June 6, 2022

Colonel Karl Jansen
U.S. Army Corps of Engineers
St Paul District
Regulatory Division
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Submitted to: **USACE-PolyMet-401a2@usace.army.mil**

Re: PolyMet Mining, Inc. Section 404 Permit
Fond du Lac Band of Lake Superior Chippewa Section 401(a)(2) Objection
MVP-1999-05528-TJH

Dear Colonel Jansen:

The Minnesota Center for Environmental Advocacy ("MCEA") is a nonprofit environmental advocacy organization with offices in St. Paul and Duluth. Since 1974, MCEA has defended Minnesota's natural resources, water, air and climate, and the health and welfare of Minnesotans. MCEA is driven by the principle that everyone has a right to a clean and healthy environment, and that decisions must be based on science and the law. MCEA is joined in this comment by Friends of the Boundary Waters Wilderness ("Friends"). For over forty years, Friends has been the leading voice for the ongoing protection, preservation, and restoration of the Boundary Waters Canoe Area Wilderness and the Superior National Forest. This comment is also submitted on behalf of the Center for Biological Diversity, Duluth for Clean Water, and MN 350. This comment is supported by two new expert reports, i.e., Myrbo (2022) and Johnson, Campbell and Stahnke (2022),[1] and other expert analysis and scientific studies as referenced and attached.

MCEA has reviewed the record supporting the PolyMet Mining, Inc. ("PolyMet") 404 permit application and the U.S. Army Corps of Engineers ("Army Corps") proposed 404 permit ("Permit"). Based on this review, MCEA supports the Fond du Lac Band of Lake Superior Chippewa's ("Band") scientific analysis and conclusion that the Army Corps must deny the Permit and that there are no conditions that could be added to the Permit that would allow it to be issued. MCEA also concludes that the Army Corps' governing authorities prohibit the issuance of the Permit based on this record.

I. LEGAL BACKGROUND

The Clean Water Act ("CWA") imposes substantive requirements on projects under consideration for permitting by the Army Corps. The purpose underlying the CWA 404(b)(1)

[1] Myrbo (2022) is Attachment 1 and Johnson, Campbell, and Stahnke (2022) is Attachment 2.

Guidelines (codified in 40 C.F.R. Part 230) is "to restore and maintain the chemical, physical, and biological integrity of waters of the United States through the control of discharges of dredged or ill material." 40 C.F.R. § 230.1(a). Accordingly, the Army Corps is prohibited from approving a project where (1) "there is a practicable alternative to the proposed discharge which would have less adverse impact on the aquatic ecosystem;"[2] (2) the discharge would cause or contribute to violations of any applicable State[3] water quality standard, applicable toxic effluent standard or prohibition, or jeopardize the continued existence of endangered or threatened species;[4] or (3) the discharge would cause or contribute to significant degradation of the waters of the United States, including significantly adverse effects of the discharge of pollutants on human health or welfare or aquatic life or other aquatic dependent wildlife, and on recreational, aesthetic, and economic values. 40 C.F.R. § 230.10(c). Similarly, under section 404(c) of the CWA, the U.S. Environmental Protection Agency ("EPA") can stop the Army Corps from issuing a permit if EPA finds that the project "will have an unacceptable adverse effect on municipal water supplies, shellfish beds and fishery areas (including spawning and breeding areas), wildlife, or recreational areas." CWA § 404(c), 33 U.S.C. § 1344(c).

The 404(b)(1) Guideline regulations state that "dredged or fill material should not be discharged into the aquatic ecosystem, unless it can be demonstrated that such a discharge will not have an unacceptable adverse impact either individually or in combination with known and/or probable impacts of other activities affecting the ecosystem of concern." 40 C.F.R. § 230.1(c). "The guiding principle should be that degradation or destruction of special sites may represent an irreversible loss of valuable aquatic resources." 40 C.F.R. § 230.1(d). "Special aquatic sites" are defined as "geographic areas, large or small, possessing special ecological characteristics of productivity, habitat, wildlife protection, or other important and easily disrupted ecological values. These areas are generally recognized as significantly influencing or positively contributing to the general overall environmental health or vitality of the entire ecosystem of a region." 40 C.F.R. § 230.43(m). Wetlands are considered a "special aquatic site" under 40 C.F.R. § 230.41.

The Army Corps cannot issue a permit until it determines that "the information in the project file" on the material to be discharged "is sufficient to provide the documentation required by [40 C.F.R.] § 230.11." 40 C.F.R. § 230.5(g). If there is a reasonable probability that the material will have chemical contamination, appropriate testing must be conducted. 40 C.F.R. § 230.5(i). Under 40 C.F.R. § 230.11, the Army Corps "shall determine in writing the potential short-term or long-term effects of a proposed discharge of dredged or fill material on the physical, chemical, and biological components of the aquatic environment in light of subparts C through F." This includes determining the degree to which the material proposed for discharge will introduce, relocate, or increase contaminants. 40 C.F.R. § 230.11(d). This determination shall consider "the material to be discharged, the aquatic environment at the proposed disposal site, and the availability of contaminants." *Id*. The determination must also consider "secondary effects" that are associated

[2] 40 C.F.R. § 230.10(a).
[3] 40 C.F.R. § 122.2 ("State" is defined to include Indian Tribes, such as the Band, given "treatment as a state status" under 40 C.F.R. § 123.31).
[4] 40 C.F.R. § 230.10(b)(1)-(3).

with a discharge of dredged or fill materials, but do not result from the actual placement of the dredged or fill material. 40 C.F.R. § 230.11(h).

Under the Army Corps' regulations, an individual permit must include "special conditions" that (a) "[i]dentify the party responsible for providing the compensatory mitigation;" (b) "[i]ncorporate, by reference, the final mitigation plan approved by the district engineer;" (c) "[s]tate the objectives, performance standards, and monitoring required for the compensatory mitigation project, unless they are provided in the approved final mitigation plan;" and (d) "[d]escribe any required financial assurances or long-term management provisions for the compensatory mitigation project, unless they are specified in the approved final mitigation plan." 33 C.F.R. § 332.3(k)(2)(i)-(iv).

II. FACTUAL BACKGROUND

PolyMet proposes to build Minnesota's first sulfide mine, based on a 32,000 ton per day/20-year mine plan. Under PolyMet's plan, target ore would be removed by open pit mining, necessitating the complete destruction of over 900 acres of surface vegetation in an area of wetlands and headwater streams, i.e., the St. Louis River Headwaters Site.[5] In a March 2007 study of the ecological significance of this site, the Minnesota Department of Natural Resources ("DNR") stated that "[t]he Headwaters Site is unique in northeastern Minnesota in several ways. The size and complexity of the peatlands in the Extensive Peatlands are unmatched in the Northern Superior Uplands Ecological Land Classification System (ECS) Section."[6] In general, headwater streams and wetlands are integral components of watersheds that are critical for biodiversity, fisheries, ecosystem functions, natural resource-based economies, and human society and culture.[7] As acknowledged by EPA, this site has a "continuous hydrologic connection to the Fond du Lac Reservation" and "scientific literature unequivocally demonstrates that streams, individually or cumulatively, exert a strong influence on the integrity of downstream waters."[8] EPA also notes that the Band's waters are at the bottom of the watershed "where the impact of cumulative loadings from the multiple sources of sulfates in the Embarrass and Partridge rivers may have an additive impact on water quality."[9] The St. Louis River estuary, including Band waters, is an "Area of Concern" because of impairments, and the St. Louis River segment at the exterior boundary of the

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[5] The site is defined as the Northern Superior Uplands/Laurentian Uplands of Lake and St. Louis Counties, including the Partridge River headwaters area at issue here. *See* DNR, *An Evaluation of the Ecological Significance of the Headwaters Site: Northern Superior Uplands Ecological Land Classification System Section; Laurentian Uplands Subsection Lake and St. Louis Counties, Minnesota* (2007). (Attachment 3).
[6] *Id.* at 1.
[7] Susan A. R. Colvin et al., *Headwater Streams and Wetlands are Critical for Sustaining Fish, Fisheries, and Ecosystem Services*, Fisheries, Feb. 2019, at 74. (Attachment 4).
[8] EPA, *Application of Region 5's CWA 401(a)(2) "May Affect" Screening Analysis for Polymet's NorthMet Mining Project*, 6 (June 2021).
[9] *Id.* at 7.

Band's reservation is listed for mercury in Minnesota's 2020 CWA section 303(d) impaired waters list.[10]

The Final Environmental Impact Statement ("FEIS") states that the NorthMet Mine would cause the permanent loss of 913.8 acres of wetlands within the St. Louis River Headwaters Site because of filling and excavation at the Plant Site and the Mine Site, and because of installation of a containment system within the wetland boundary.[11] The activity will also directly partially impact wetlands causing the loss of an additional 26.9 acres.[12] A portion of a unique large wetland area called the "One Hundred Mile Swamp" would be directly impacted to enable PolyMet to access mineral deposits by open-pit mining.[13]

In addition to direct impacts, activities related to the proposed mine would have "indirect" impacts on wetlands, including:

> 1) wetland fragmentation, 2) changes in wetland hydrology as a result of changes in the watershed area, 3) changes in wetland hydrology due to groundwater draw down from open pit mine dewatering, 4) changes in wetland hydrology from groundwater drawdown resulting from operation of the Plant site, including groundwater seepage containment, 5) changes in stream flow near Mine Site and Plant site and associated effects on abutting wetlands, [and] 6) changes in wetland water quality from atmospheric deposition of dust and rail car spillage.[14]

The FEIS calculated that mining activities would indirectly destroy and degrade either 7,694.2 acres or 6,568.8 acres of wetlands, depending on the evaluation method.[15] Approximately two-thirds of the wetlands impacted by the drawdown of the water table are minerotrophic, or groundwater fed.[16]

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[10] *Id.* at 10-11.
[11] Minnesota DNR et al., *NorthMet Mining Project and Land Exchange Final Environmental Impact Statement* (hereafter "FEIS"), ES-36 (Nov. 2015).
[12] *Id.* at ES-37.
[13] *Id.* at 5-424. Underground mining is not technically infeasible and was initially considered during environmental review as an alternative. *Id.* at 3-146. But PolyMet rejected underground mining because PolyMet claimed it was not financially feasible to recover the target minerals with this less-invasive method. *Id.* at 3-148, 3-157. The FEIS lead agencies did not dispute this assessment and eliminated the alternative. *Id.* at 2-8. *See also* https://files.dnr.state.mn.us/input/environmentalreview/polymet/feis/016_appendix_b_underground_mining_alternative_position_paper.pdf (concluding that underground mining is technically feasible but that it was economically infeasible, and therefore did not meet the "Purpose and Need" for the project.
[14] *Id.* at 5-257.
[15] *Id.*
[16] *Id.* at 5-319. Although it otherwise relies heavily on the FEIS, PolyMet now denies these statements, claiming that areas to be occupied by the mine pits and waste rock piles are ombrotrophic, i.e., they receive their water from direct precipitation. Comments of PolyMet

To "mitigate" wetlands directly impacted, PolyMet proposes to purchase wetland credits. However, PolyMet has not assessed indirect impacts to wetlands, but concludes that "the potential for water level drawdown in Mine Site wetlands is low, and the aerial extent of drawdown. . . is …minimal," relying on predictions in the environmental review documents and literature.[17] PolyMet believes that its project will reduce mercury and sulfate loading to the St. Louis River.[18] To reach this conclusion, PolyMet relies on its tailings to act as a mercury "sink" for the wastewater streams that PolyMet will dispose in the tailings basin.[19] PolyMet also relies on the efficacy of a seepage collection system that it proposes to install to intercept seepage from the tailings basin to prevent mercury and sulfate from migrating to surface waters.[20] Finally, PolyMet relies on the efficacy of its wastewater treatment system in support of its optimistic conclusion that the tailings basin seepage collection system will reduce existing contamination.[21] But, as discussed below, these conclusions are unjustified because it is highly unlikely that PolyMet will be able to construct its seepage collection system as proposed, that the level of contamination in that wastewater will be controlled as predicted, or that these controls will function at the levels required over the essentially endless time the tailings basin seepage capture system will be required to function.

III. ANALYSIS

1. Water Quality Impacts Attributable To Indirectly Impacted Wetlands Are Inadequately Studied And Have The Potential To Cause Or Contribute To Exceedances Of Band Water Quality Standards.

Mining, Inc. to EPA Regarding Downstream Water Quality-Exhibit 1: Declaration of Cliff Twaroski, 20 (April 23, 2021) (hereinafter "Twaroski Decl."). This dispute illustrates the lack of information on this important issue. But PolyMet also admits that "some wetlands near the pit rim may be affected by pit development and dewatering." *Id.* at 21. PolyMet admits that 46 acres of wetlands have a "High Likelihood" of being affected. *Id.* PolyMet attempts to downplay the significance of this (noting that it is <1% of the wetland acreage at the Mine Site) but as this is just the "High Likelihood" wetlands, and other impacts are likely, this is a weak point at best. *Id.*

[17] Twaroski Decl. at 19.

[18] Comments of PolyMet Mining, Inc. to EPA Regarding Downstream Water Quality, 9, 16 (April 30, 2021) (hereinafter "PolyMet Comments"); PolyMet Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ (hereinafter "PolyMet Testimony").

[19] Twaroski Decl. at 10-11; PolyMet Testimony.

[20] PolyMet Testimony.

[21] *Id.* PolyMet plans to use the tailings basin to store a variety of wastestreams, including water collected by the tailings basin seepage collection system. FEIS at 3-125. Although PolyMet plans to direct *treated* water to the tailings basin, many untreated wastewater streams will also be directed there, including construction mine water and runoff from the "OSLA." PolyMet Mining, *NorthMet Project Comprehensive Water and Wetland Monitoring Plan*, 7-8 (April 2022) (describing the handling of "mine water" and "construction mine water").

The Band submitted significant expert evidence that the PolyMet project's indirect impacts to wetlands are inadequately studied and that these indirect wetland impacts will cause or contribute to violation of the Band's water quality standards. The EPA agreed.[22] The commentors' experts support the Band and EPA's analysis, as described below.

A. Current information is inadequate to support issuance of the Permit.

Despite regulations requiring the Army Corps to have adequate information (40 C.F.R. § 230.11) before actions are taken that impact "special areas" such as the Headwaters Site, the Army Corps issued the Permit without obtaining information on indirect wetland impacts near the mining site. Without this information, the Army Corps lacks the data necessary to assess downstream water quality impacts, including impacts that could cause or contribute to exceedances of the Band's water quality standards, or to establish any new conditions that would ensure compliance with the Band's water quality requirements. As a result, the Army Corps must deny the Permit unless and until adequate information is developed, which would need to be analyzed and disclosed in a supplement to the FEIS.

EPA, the Minnesota Pollution Control Agency ("MPCA"), and the Army Corps itself have all admitted that there is inadequate information regarding water quality impacts from indirectly impacted wetlands. With regard to such indirect wetland impacts, EPA notes that the MPCA's 401 Certification "consist[s] of monitoring requirements and potential responses to water quality effects if and when they are detected, suggesting that MPCA thought it possible that such effects may occur."[23] MPCA candidly admits in its analysis of PolyMet's application that the data necessary to establish the limits necessary to protect these wetlands simply does not exist currently and "[t]he probability of accurately specifying the location, extent, or degree of wetland impacts from the drawdown effect of the proposed mine pit prior to construction is very low."[24] The Army Corps' Record of Decision ("ROD") supporting this action does not differ, openly acknowledging that "[i]ndirect effects caused by the discharge of dredged and fill material into wetlands, including changes to wetland hydrology, are difficult to model and accurately predict because of the complex mixes of bedrock, surficial deposits, and wetland soils at the Mine Site."[25] The Corps further admits in the ROD that impacts were not characterized other than to inform where monitoring should take place.[26] The proposed Permit only addresses these impacts in terms of monitoring for vegetative impacts and potential future mitigation in the form of "credits" for the indirectly

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[22] *See* EPA Region 5 Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ.

[23] EPA, *Application of Region 5's CWA 401(a)(2) "May Affect" Screening Analysis for Polymet's NorthMet Mining Project*, 11 (June 2021).

[24] *Id.* at 34 (quoting MPCA*, Clean Water Act Section 401 Water Quality Certification Program Fact Sheet [for PolyMet Mining, Inc.]*, at 10.).

[25] Army Corps, *Record of Decision for NorthMet*, 7.

[26] *Id.* None of the agencies credited PolyMet's "Cross-Media Analysis" as adequately identifying these impacts.

damaged wetlands.[27] Water quality impacts—including in relation to the Band's water quality standards—from these indirectly-impacted wetlands are simply not assessed at all. In similar settings, courts have rejected reliance on post-action monitoring. *See Friends of the Earth v. Hall*, 693 F. Supp. 904, 925 (W.D. Wash. 1988) (monitoring of disposal site rejected).

Dr. Amy Myrbo, an expert on the impacts of sulfate on water chemistry, has reviewed the existing scientific analysis of potential impacts from the project and concluded that analysis fails to adequately address the impacts of sulfate.[28] Based on her research, sulfate-reducing bacteria (SRB) are responsible for both the conversion of inorganic mercury to methylmercury (as described in the record for this proceeding), but also for the release of compounds released during the "mineralization" of organic matter by SRB converting sulfate to sulfide. She predicts that this "[o]rganic matter mineralization could have negative effects on several water quality parameters, including nutrients, inorganic mercury, and dissolved organic carbon."[29] She also predicts that the nutrients discharged "have the potential to cause eutrophication in the rivers and lakes to which sulfate would be discharged, and to potentially cause an exceedance of the Fond du Lac Band's water quality standards."[30]

Dr. Myrbo also notes that there is another biogeochemical factor that has not been adequately assessed with regard to mercury methylation: cobalt.[31] Cobalt has been implicated in the inorganic methylation of mercury, and "an increase in cobalt can directly cause an increase in the methylmercury production and its abundance in the environment.[32]

B. The Corps cannot approve this project on the basis of existing information.

Changes to wetland hydrology impact water quality. As detailed in existing reports prepared for the Band, PolyMet and state agencies, changes to the hydrology of wetlands can increase the discharge of mercury, which can bioaccumulate and cause exceedance of water quality standards (i.e., mercury in fish tissue) downstream from the discharge area. But, as described above, other impacts are also likely, such as an increase in nutrients caused by disruptions to the "hyporheic zones" where most nutrients are processed.[33] Headwater streams and associated wetlands both retain and transform excess nutrients, thereby preventing them from travelling downstream.[34]

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[27] Army Corp, *404 Permit Issued to PolyMet Mining, Inc.*, ¶¶ 16-33 (Mar. 21, 2019) (No. MVP-1999-05528-TJH).
[28] Myrbo (2022) Attachment 1.
[29] *Id.* at 1-2.
[30] *Id.* at 2, 3.
[31] *Id.* at. 3.
[32] *Id.*
[33] *See* Judy L. Meyer et al., *Where Rivers are Born: The Scientific Imperative for Defending Small Streams and Wetlands,* 8 (2003). (Attachment 5).
[34] *Id.* at 12-13.

These facts—coupled with agency admissions of lacking data—mean that the Permit cannot proceed. The Army Corps is allowed to use "best professional judgment" in assessing impacts to streams under 40 C.F.R. § 230.11, and the efficacy of mitigation measures to reduce impacts. *See Ohio Valley Env't Coal. v. Aracoma Coal Co.*, 556 F.3d 177, 200-201 (4th Cir. 2009) (Court will defer to Army Corps' method of assessing the structure and function of the affected aquatic ecosystem). But no case suggests that it is acceptable for the Army Corps to issue a permit based on post hoc monitoring and unspecified future mitigation. *See Friends of the Earth*, 693 F. Supp. at 937 (reliance on monitoring after-the-fact disallowed)*; Kentucky Riverkeeper, Inc. v. Rowlette*, 714 F.3d 402, 412 (6th Cir. 2013) (post-issuance mechanisms do not explain how the Army Corps arrived at its preissuance minimal cumulative-impact findings). Indeed, federal cases dealing with analogous permits establish that a permit condition that fails to define what is allowed cannot be rescued by after-the-fact monitoring and reporting requirements. *Ctr. for Biological Diversity v. Bureau of Land Mgmt.*, 422 F. Supp. 2d 1115, 1140 (N.D. Cal. 2006) (vague term defining allowable "take" of desert tortoises not improved by after-the-fact monitoring and reporting where standard required). Similarly, the proposed Permit is deficient from a procedural due process standpoint because the public cannot comment on the key plans, nor assess whether those plans would result in compliance with the Band's water quality standards or indeed state water quality standards. *See Waterkeeper All., Inc. v. U.S. Envtl. Prot. Agency*, 399 F.3d 486, 499, 503-04 (2d Cir. 2005) (nutrient management plans must be reviewable). While monitoring may be acceptable to confirm mitigation is succeeding, it is not acceptable to determine whether impacts are occurring in the first place. These impacts must be identified before permit issuance.

C. PolyMet's adaptive management plan is inadequate and does not substitute for information adequate to prevent impacts.

In defense of its Permit, PolyMet asserts that it will address any problems that are discovered through monitoring by "adaptive management." PolyMet's "adaptive management" plans should not be accorded any weight. First, as the Band pointed out in its testimony, "adaptive management" takes place only after negative impacts are detected and does not prevent those impacts. Second, although the proposed Permit makes reference to adaptive management, no adaptive management plan specific to this issue is attached to the Permit. In fact, as described in the MPCA's 401 Certification's antidegradation analysis, adaptive management consists only of more monitoring,[35] and does not include the elements necessary for a valid "adaptive management" plan. The Army Corps' own guidance on adaptive management emphasizes:

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[35]https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51hh.pdf. Section 4.B of PolyMet's 401 Certification antidegradation assessment is "Adaptive Management." https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51c.pdf It provides that "if indirect impacts are observed, additional monitoring may be developed to focus on those areas and/or to focus on a specific impact factor." Section 4.4 then notes that, after a second undefined "phase" of monitoring, the results "will be used to determine any need for additional mitigation or to develop a plan to control the changes identified in Phase I and minimize future impacts to wetlands." PolyMet complains that this monitoring exceeds other mining or industrial operations, but

> It demands the clear statement of objectives, identification of management alternatives, predictions of management consequences, and recognition of uncertainties. Stakeholder engagement, monitoring of resource response, and modeling are obligatory, as is a governance process that ensures new knowledge is operationalized through decision making.[36]

The adaptive management plan described in the Army Corps' ROD does not identify management alternatives, their consequences, and uncertainty. And there certainly has been no "stakeholder engagement" because that "stakeholder engagement" would have involved close coordination of adaptive management plan development with the Band's scientists, which simply did not happen here.

D. PolyMet's Reliance On Its Proposed Water Capture, Control And Treatment Is Unfounded.

In defense of its Permit, PolyMet testified that the Band and EPA have failed to account for the offsetting mitigation that PolyMet's tailings basin seepage capture system and wastewater treatment system will provide.[37] But PolyMet failed to tell the Army Corps that the Minnesota Supreme Court recently rejected the centerpiece of its plan to control seepage and reactivity in the tailings basin, sending PolyMet's permit to mine back to DNR for a contested case hearing. Similarly, experts who have recently examined PolyMet's proposed tailings basin seepage capture system have questioned whether it can be constructed as proposed. Until these issues are finally resolved, the Army Corps should not make any decisions with regard to this Permit.

i. The "bentonite plan" is unproven.

Both MPCA[38] and the DNR relied on PolyMet's proposal to control acid mine drainage from developing in the tailings basin by "amending" the surfaces of the tailings basin dam and

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evidently fails to recognize that, as a new mine, and as a mine proposing to mine a reactive ore with higher pollution potential, it is appropriate that it establish better data.

[36] J. Craig Fischenich et al., *A Systems Approach to Ecosystem Adaptive Management: A USACE Technical Guide*, 4 (Nov. 2019). (Attachment 6).

[37] *See* PolyMet Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ.

[38] MPCA, *National Pollutant Discharge Elimination System/State Disposal System (NPDES/SDS) Permit Program Fact Sheet* (NorthMet Project) January 31, 2018, https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51gg.pdf In its groundwater nondegradation preliminary determination, MPCA specifically identified PolyMet's bentonite amendment as an engineering control that will result in compliance with MPCA's groundwater rule, Minn. R. 7060.0400, noting "PolyMet has also proposed additional engineering controls to reduce the potential for seepage through the unlined Tailings Basin that includes the installation of bentonite amendments to the tailings dams, Tailings Basin beaches and pond bottom." MPCA, *PolyMet Mining, Inc. Groundwater Nondegradation Evaluation-Preliminary MPCA*

"beaches" and by adding bentonite to the bottom of the permanent pond PolyMet proposes to maintain after closure ("bentonite plan"). However, in its April 2021 decision, the Minnesota Supreme Court concluded that DNR did not have substantial evidence to determine whether PolyMet's bentonite plan was practical and workable or whether it satisfied rules applicable to storage of reactive mine waste. *In re NorthMet Project Permit to Mine Application ("NorthMet")*, 959 N.W.2d 731, 753-54 (Minn. 2021). The Minnesota Supreme Court concluded the following:

- DNR had failed to present evidence that the bentonite plan "has been tested" and "will be effective." In contrast, the contested case petitions included "a bevy of evidence" including statements by DNR's own experts and external consultants that contradicted the DNR's findings on effectiveness.

- The DNR wholly failed to address concerns about how the proposed sodium bentonite could react with multivalent cation species in the pond water, resulting in a cation exchange that could reduce the effectiveness of the bentonite by up to seventy percent.

- The DNR's proposed special conditions in the permit to mine, which require PolyMet to prove the effectiveness of the bentonite amendment before construction may begin on the tailings basin dam, are not an effective substitute for the substantial evidence required to support the DNR's decision.

- The effectiveness of the bentonite amendment is critical in preventing oxygen and water from reaching the stored tailings and ensuring the NorthMet project's compliance with the DNR's reactive waste rule (Minn. R. 6132.2200, subp. 2(B)(2)).

- The DNR's findings about the effectiveness of the bentonite amendment on the beaches and dam face rest on a study that is not part of the record.

- The record is entirely devoid of any evidence to support the DNR's finding that the pond-bottom bentonite cover will be effective in reducing water infiltration and maintaining a permanent pond.

Determination, 5, https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51p.pdf. MPCA then found "[t]hese combined engineering controls would abate existing pollution, maximize the possibility of rehabilitating the existing degraded groundwater, and minimize longer term effects to groundwater quality in accordance with the policies set forth in Minnesota Rule 7060.0400." *Id.* MPCA also assumed the bentonite amendment would minimize water-quality degradation consistent with MPCA's "antidegradation" rules. MPCA, *PolyMet Mining, Inc. NPDES Antidegradation Review-Preliminary MPCA Determination*, 26 (Jan. 10, 2018), https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51n.pdf (listing "[b]entonite addition to the Tailings Basin dams, beaches and pond bottom to reduce infiltration into the tailings and the amount of seepage wastewater generated" to conclude that PolyMet minimized impacts). Finally, the modeling data MPCA relied upon to evaluate the Tailings Basin's environmental controls assumed the efficacy of the bentonite amendment. FEIS 5-47. PolyMet's GoldSim model for the Plant Site includes a conductance term to simulate the bentonite amendment. *Id.* at 5-71.

See NorthMet at 731, 753–54. As a result, the Minnesota Supreme Court directed DNR to convene a contested case hearing on these issues. *Id.* at 759-60. This proceeding has begun but no trial date has been established.

If the bentonite plan does not work as intended, the tailings basin may generate leachate containing higher levels of pollutants than assumed in the FEIS. These higher pollutant levels may affect the ability of the planned treatment system to treat the wastewater as designed, but also would negatively affect PolyMet's assumptions of pollutant loadings to the Embarrass River. Because the Minnesota Supreme Court has determined that the DNR lacked substantial evidence in support of its conclusions, and this holding directly impacts MPCA's conclusions regarding water quality, PolyMet's assertion that the state permitting process supports its claims about water quality is false, and therefore the Army Corps should not issue the proposed Permit. *See* 40 C.F.R. § 230.5(g) (requiring adequate information in support of the application).

ii. The seepage collection system, even if feasible, will not work as planned.

To control seepage of polluted water from the tailings basin, PolyMet plans to construct a seepage capture system which consists of a 4.5 mile long "cut-off wall" or "slurry wall" that will be "keyed" into the bedrock to prevent seepage under the wall. PolyMet proposes to capture the polluted groundwater that the wall will (if it works) block and send it to the wastewater treatment facility *or* back into the tailings basin (see figure 1 below). PolyMet proposes to construct the "cutoff wall" using in-situ construction techniques, i.e., using equipment that mixes native soils with bentonite in a continuous process instead of pouring a prepared bentonite/soil mix into a trench.

Figure 1: PolyMet Tailings Basin Seepage Collection System Plan and Side Views[39]

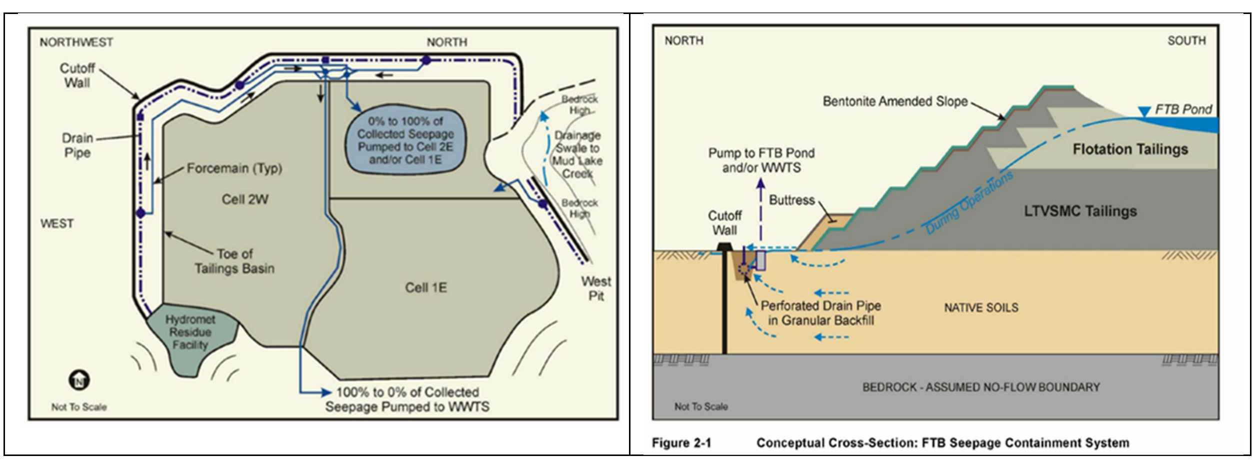

Figure 2-1 **Conceptual Cross-Section: FTB Seepage Containment System**

[39] FEIS at 3-121-2.

The performance of the seepage containment system was key to the FEIS's conclusions that seepage from the Tailing Basin would not result in destruction of natural resources, and apparently is key to PolyMet's position that its proposed project would have no impact on the Band's water quality standards.

MCEA recently requested Dr. Michael Malusis, a noted academic expert in slurry wall construction and performance, to review PolyMet's construction plans.[40] Dr. Malusis concluded that:

- The subsurface conditions along the length of the proposed cutoff wall alignment have not been adequately characterized based on industry standards. Based on the limited information available, there is significant variability in the bedrock elevation making it unlikely that the flotation tailings basin seepage containment system can be successfully keyed to the bedrock along the entire bottom of the cutoff wall, particularly given the proposed "trenchless" construction method.

- Establishing an adequate key for the cutoff wall in the fractured granite bedrock likely will not be feasible. It will be difficult, if not impossible, to achieve an adequate key of two feet or more (especially with trench cutting methods) in hard (granite) bedrock such as is present here. In fact, efforts to create the key could cause more fractures to form in the rock.[41]

In addition, Dr. Malusis observed:

- The proposed monitoring system intended to ensure that the FTB seepage containment system is functioning does not meet industry standards because the number of monitoring stations is inadequate. In addition, neither DNR nor the [MPCA] has established the regulatory standard necessary to ensure the "inward hydraulic gradient" that is required to be maintained is meaningful.

- The proposed in-situ construction method is unsuitable for the soil conditions. Using this method, native soils are incorporated into the finished wall. Based on the permit application support drawings, large amounts of organic/peaty soils are present in the subsurface along significant portions of the wall alignment, most notably in the 3,000-foot stretch of slurry wall between stations 155+00 and 185+00, where the organic layer thickness approaches 20 feet. This type of organic matter can compromise the hydraulic performance and should not be incorporated into the wall. Boulder deposits within the till will also make construction difficult, at best.[42]

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[40] Report of Michael A. Malusis, Consulting Geotechnical and Geoenvironmental Engineer, to Ann E. Cohen, Senior Staff Attorney, Minnesota Center for Environmental Advocacy (Dec. 23, 2021) (prepared in connection with the pending contested case hearing). (Attachment 7).
[41] *Id.* at 2-4.
[42] *Id.* at 3-4.

Dr. Malusis also noted that this use of a bentonite-soil cutoff wall is typically employed only as a remedial action to prevent the spread of existing subsurface contamination resulting from past releases but was here being proposed as a permanent substitute for an engineered liner system. In Dr. Malusis' opinion, the use of a remediation technology as a substitute for an engineered liner system for newly disposed waste is unprecedented and inappropriate.[43] In addition, the Army Corps should note that a much smaller slurry cut-off wall installed to control contamination from the Flambeau mine in Wisconsin appears to be failing.[44]

iii. The NPDES/SDS Permit Lacks Necessary Regulatory Terms Given PolyMet's Untried Reverse Osmosis System.

In its testimony at this hearing, EPA found that "[t]he individual CWA Section 402 permit for surface water discharges from the NorthMet project does not contain numeric water quality-based effluent limitations for mercury that would ensure compliance with the Band's water quality requirement."[45] EPA noted that "[t]he permit includes 'operating limits' on mercury at an internal monitoring station set to Minnesota's water quality standard of 1.3 ug/L, which is not sufficient to ensure compliance with the Band's downstream water quality requirements."[46] The commentors agree. The current NPDES/SDS permit lacks necessary water quality-based effluent limits, and instead relies on internal operating limits and generic conditions to prevent water quality exceedances. The NPDES/SDS permit was also issued without the analysis needed to determine whether or not permit conditions are necessary to protect surface waters from groundwater impacts, and has been remanded to MPCA to do this analysis. For this reason, the Army Corps should not rely on the NPDES/SDS permit to bolster the proposed Permit.

MPCA decided that it did not need to include water quality-based effluent limits based on the limited bench testing of PolyMet's proposed reverse-osmosis water treatment system.[47] In this hearing, PolyMet attempts to convince the Army Corps that it too should be unconcerned about the cumulative impact of pollutants in PolyMet's various discharges for the same reason. The Army Corps should not repeat MPCA's mistake. The Army Corps should instead conclude that there is simply inadequate information in the record as to whether reverse-osmosis can be successfully deployed to control pollutant levels that will be generated by this open pit mining project, where the volume, type, and pollutant concentrations can be expected to vary significantly over time. Similarly, the Army Corps must conclude that without water quality-based effluent limits in the NPDES/SDS permit there is no guarantee that water quality standards will be met, especially the Band's more-stringent water quality standards which were not considered when the NPDES/SDS permit was developed.

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[43] *Id.* at 2.
[44] *See* David M. Chambers & Kendra Zamzow, *Report on Groundwater and Surface Water Contamination at the Flambeau Mine* (2009). (Attachment 8).
[45] EPA Region 5 Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ.
[46] *Id.*
[47] See NPDES/SDS Permit Fact Sheet, https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-51gg.pdf.

In its hearing testimony, PolyMet cited to Michigan's Eagle Mine and its use of reverse-osmosis technology as supporting the claim that this technology is "proven" and will result in effluent that is "nine times cleaner than rainwater."[48] In particular, PolyMet cited the Eagle Mine as using the same technology and achieving good mercury control.[49] However, as the Band noted in its rebuttal testimony, the Eagle Mine is a far-smaller underground mine—processing only 2,000 metric tons of ore per day at a mine site covering roughly 150 acres and storing its reactive tailings in a geologically-stable flooded mine pit.[50] The Eagle Mine does not present the same water management issues as PolyMet's proposed open-pit/above-ground tailings basin mine, with its far-greater volumes and more variable wastewater streams all requiring management and treatment.

E. PolyMet's Reliance On Wetland Destruction To Offset Indirect Mercury Impacts From Remaining Wetlands Is Unfounded.

In defense of its Permit, PolyMet's experts testified that any indirect impacts from mercury releases will be offset by its massive destruction of wetlands at the mine site because that destruction will remove areas where mercury is currently being methylated and discharged.[51] PolyMet fails to note that the massive wetland destruction authorized by this Permit will result in a vast and uncontrolled "pulse" of mercury, methylated mercury and sulfate that is currently sequestered in those peatlands/wetlands. This mercury, once liberated by PolyMet's actions, will make its way downstream to enter other wetlands (including those on the Band's reservation) where it will cause or contribute to exceedances of the Band's water quality standard.[52]

The FEIS contains only vague descriptions of how PolyMet will manage the water that will be generated when it removes "overburden" from the mine site. "Stormwater" from pit construction will be managed by "small dikes," and shallow groundwater seepage by "compressing the peat with earthen dike materials to create a low-permeability layer" or by creating a soil cutoff trench, slurry wall, or sheetpile wall.[53] The FEIS does not specify where the "stormwater," which will likely include ionic pollutants such as sulfate or dissolved pollutants such as methylmercury, will be controlled or captured. To the extent that more detailed plans exist, they are not public because PolyMet has applied for coverage under the MPCA's "general permit" governing construction stormwater. PolyMet plans to store "unsaturated" overburden and peat in the unlined

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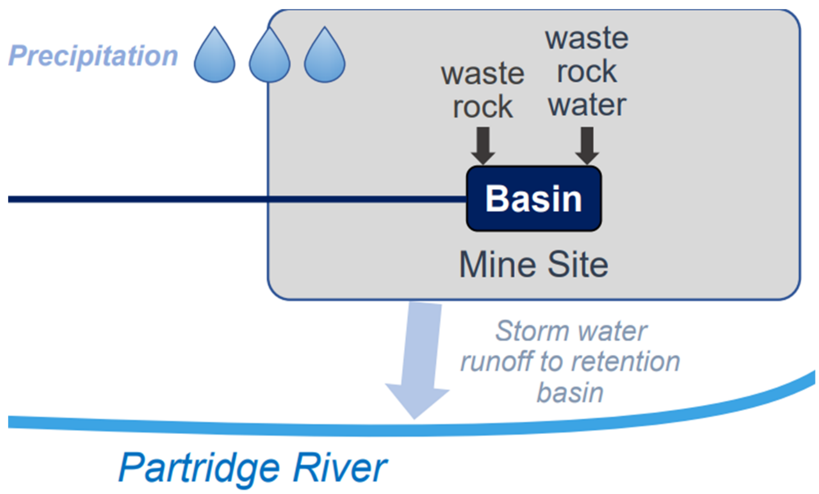
[48] PolyMet Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ.
[49] *Id.*
[50] *See About Us*, EAGLE MINE, (May 26, 2022), https://www.eaglemine.com/about; *see also Our Operations*, EAGLE MINE (May 26, 2022) https://www.eaglemine.com/operations.
[51] PolyMet Testimony (May 4, 2022), https://www.youtube.com/playlist?list=PLKn9TM2TouWSMx3xulypKiBdqcQ6rcFnJ.
[52] PolyMet also fails to note or discuss that its planned mitigation—wetland creation—will result in the same mercury discharges that its planned wetland destruction will theoretically eliminate.
[53] FEIS at 3-52.

Overburden Storage and Laydown Area; "saturated" materials will be directed to the lined Category 2/3 and 4 stockpiles and commingled with waste rock until backfilling.[54]

PolyMet's planned stormwater controls, which are designed to prevent sediment from moving, will not prevent water containing mercury, methylmercury and sulfate from leaving the saturated organic material as it is moved to the laydown area or 2/3 stockpile area. PolyMet will direct this stormwater to a "retention basin" as shown in this diagram:

Figure 2: Mine Site Storm Water Management (from PolyMet presentation)



A construction stormwater permit is designed to prevent sediment from escaping construction sites and to control erosional forces, not to limit the dissolved chemical constituents in water that is discharged.[55] As the EPA observed in its April 29, 2022, evaluation and recommendation, the general permit contains no limits on pollutant discharges.[56] A "retention basin" is designed to discharge, meaning that any dissolved pollutants (such as sulfate) that were sequestered in the "overburden" will be discharged from the retention basin during storm events.[57] Further, as commenters noted during environmental review and permitting, the drier material PolyMet plans to deliver to the unlined overburden laydown and storage area ("OSLA") will be subject to repeated rewetting, which will likely result in repeated discharges of methylmercury and inorganic mercury.[58]

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[54] FEIS at 3-45.
[55] *See* MPCA, *Construction Stormwater General Permit*, 14-15 ¶¶ 18.1-10 (Aug. 1, 2018), https://www.pca.state.mn.us/sites/default/files/wq-strm2-80a.pdf.
[56] EPA, *Clean Water Act Section 401(a)(2) Evaluation and Recommendations with respect to the Fond du Lac Band's Objection to the Proposed Clean Water Act Section 404 Permit for the NorthMet Mine Project*, 15-16 (April 29, 2022).
[57] *See* https://stormwater.pca.state.mn.us/index.php/Design_criteria_for_stormwater_ponds.
[58] Technical Memorandum from Tom Myers, Hydrologic Consultant, to Minnesota Center for Environmental Advocacy, 6-7 (Feb. 19, 2018). (Attachment 9). *See also* Coleman-Wasik et al 2015. "The continuous process of drying and rewetting of overburden peat stockpiled in laydown

2. Regulatory agencies have failed to consider water quality impacts from the use of waste rock and tailings for "fill" under the Permit.

In addition to lacking adequate information on "secondary impacts," the Army Corps also lacks adequate information on the chemical contamination associated with the material the Permit allows PolyMet to use as "fill" and the Permit has established no conditions on use of that fill. The Permit allows PolyMet to use "any dredged and fill material" as fill by submitting various plans, including a plan to discharge "Category 1" waste rock which otherwise is required to be managed at sites that have seepage collection systems.[59] Although the Army Corps retains the authority to approve these plans, the proposed Permit establishes no standards for such approvals other than it must be "suitable for discharge into waters of the United States."[60]

By not specifying the characteristics of the materials that PolyMet would be allowed to use for fill or how contaminants will be controlled, the proposed Permit fails to control sources of water pollution that have the potential to cause exceedances of Band water quality standards. Even where the Permit does specify characteristics (i.e., sulfate content of Category 1 material) the Army Corps should note that experts opining on PolyMet's permit to mine have stated that it will be very difficult for PolyMet to ensure that waste rock removed after blasting is moved to the correct stockpile, and as a result, the supposedly less-reactive waste rock may be more reactive than assumed, as discussed below.

During the public comment period on the permit to mine, Dr. Ann Maest, an expert in geochemistry, commented that PolyMet and DNR analyzed an inadequate number of samples for acid-base accounting, whole rock chemistry, and mineralogy based on industry standards.[61] In particular, Dr. Maest opined that PolyMet's assumptions about the sulfide content of the Category

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areas may not only continue to release inorganic mercury, but may also continuously regenerate sulfate, and in anaerobic locations, promote methylmercury formation." (p. 21)

[59] *See* Army Corp, *404 Permit Issued to PolyMet Mining, Inc.*, ¶¶ 7-10 (Mar. 21, 2019) (No. MVP-1999-05528-TJH).

[60] *See Id*. The Permit does not specify what PolyMet will use the Category 1 and other waste materials for. Based on the FEIS, PolyMet proposes to use waste rock to fill one exhausted mine pit. FEIS at 3-64. PolyMet also plans to use "fill material" to support the proposed tailings basin dam buttress (following excavation of incompetent materials such as peat), for waste rock stockpile support, and to fill on-site stormwater management ponds. *Id.* at 3-105, 3-45, 3-71. The FEIS identifies the fill material as "Cat1 rock" or LTV tailings. *Id.* As summarized by the Band, "PolyMet will discharge dredged or fill material into wetlands, which would then either be removed and replaced by mine pits or excavated and replaced with fill material discharged to construct overburden and waste rock storage facilities, roads, storm and mine water management systems, tailings basin buttresses, the tailings basin seepage capture system, and utility corridors." Notice of Objection from Fond du Lac Band of Lake Superior Chippewa Reservation Business Committee to EPA, Army Corps, 10 (Aug. 3, 2021).

[61] Technical Memorandum of Ann S. Maest, Geochemist, Buka Environmental, to Kevin Lee, Minnesota Center for Environmental Advocacy, 1 (Feb. 27, 2018). (Attachment 10).

1 wastes are unreliable.[62] Dr. Maest also commented that "the consistent separation of Category 1 wastes from waste and ore with higher sulfide content during operations will be difficult, if not impossible, leading to a greater potential for pollutants to be generated in the unlined Category 1 storage pile than PolyMet assumes."[63]

Recent analysis by experts Bruce Johnson, Fred Campbell, and Gerald Stahnke[64] ("Geology Experts") affirms Dr. Maest's earlier conclusions, noting the heterogeneity of the Duluth Complex's rocks and the fact that variations in composition can occur over stratigraphic thicknesses less than ten feet, conditions that would be reflected in the Category 1 waste rock.[65] These conditions would make proper sampling of the Category 1 waste rock "technically and financially impossible."[66] As a result, high sulfur inclusions missed during the evaluation can be predicted to release acid, sulfate and metals from water infiltration.[67] The Geology Experts predict that use of Category 1 material as on-site fill would impact surrounding waters with undetermined concentrations of leachates.[68] The Geology Experts also conclude that mine site water quality assessment is based on erroneous assumptions about rock characterizations and chemistry based on inadequate sampling and testing, affirming Dr. Maest's earlier observations.[69] Thus, they conclude that the Category 1 waste rock piles will almost certainly result in discharges that greatly exceed surface water standards and that may cause or contribute to exceedance of the Band's water quality standards, and should not be used as fill.[70] The Geology Experts observe that PolyMet's predictions of leachate concentrations/volumes from the permanent Category 1 waste rock stockpile are based on the assumption that this waste rock does not become acidic and thus will not discharge toxic chemistries.[71] Because these assumptions are unfounded, the Geology Experts conclude it should not be used as construction material, as currently allowed under the Permit.[72]

The Permit's lack of standards governing the use of the waste rock materials as fill is in violation of applicable law.[73] Under 40 C.F.R. § 230.11, the Army Corps "shall determine in writing the potential short-term or long-term effects of a proposed discharge of dredged or fill material on the physical, chemical, and biological components of the aquatic environment in light

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[62] *Id.*
[63] *Id.* at 2.
[64] Johnson, Campbell, Stahnke (2022) (Attachment 2).
[65] *Id.* at 3.
[66] *Id.*
[67] *Id.* at 4.
[68] *Id.*
[69] *Id.* at 5.
[70] *Id.* at 6.
[71] *Id.* at 8.
[72] *Id.*
[73] DNR's permit to mine does not make up for these deficiencies. DNR's permit to mine authorizes waste rock to be used as construction fill and for other construction purposes. *See, e.g.*, DNR, *Permit to Mine and Assignment for NorthMet Mining Project*, ¶¶ 23, 45b, 38, (Nov. 1, 2018) (allowing BIF and LTV tailings to be used for "construction" subject to DNR approval). But no standards are established for when DNR approval will be granted.

of subparts C through F." This requirement includes determining the degree to which the material proposed for discharge will introduce, relocate, or increase contaminants. 40 C.F.R. § 230.11(d). This determination shall consider "the material to be discharged, the aquatic environment at the proposed disposal site, and the availability of contaminants." *Id.* The 404(b)(1) Guidelines state that "dredged or fill material should not be discharged into the aquatic ecosystem, unless it can be demonstrated that such a discharge will not have an unacceptable adverse impact either individually or in combination with known and/or probable impacts of other activities affecting the ecosystem of concern." 40 C.F.R. § 230.1(c).

In a similar circumstance, a court has rejected an Army Corps' decision because of a lack of testing data on fill materials. *See Friends of the Earth*, 693 F. Supp. at 927-935 (also noting failure of EIS to contain opposing views). Similarly, by not including either testing protocols or standards for approval of the fill allowed under the proposed Permit, the Army Corps has "in effect, prevented the public from commenting on the single most important feature" of this proposed Permit. *Id.* at 948. The proposed Permit is deficient from a procedural due process standpoint because the public cannot comment on the key plans, nor assess whether those plans would result incompliance with the Band's water quality standards or indeed state water quality standards. *See Waterkeeper All., Inc.*, 399 F.3d at 499, 503-04 (nutrient management plans must be reviewable).

3. PolyMet's proposed mine is not needed to support the "Green Economy."

In its May 4, 2022, presentation, PolyMet implies that its project should be approved because the metals produced at the NorthMet mine would be used in the clean energy transition and therefore the mine is necessary to address the climate crisis. PolyMet's argument ignores the impact that the mine would have on biodiversity, which has also been degraded by human activity to crisis levels.[74] Similarly, PolyMet also ignores the climate impact that issuance of the Permit would cause because the mine would produce carbon, and the Permit would allow PolyMet to destroy peatlands and wetlands that sequester vast amounts of carbon.[75] Setting aside these impacts, PolyMet's case for the need for the metals it would produce is unsupported.

The metals that PolyMet proposes to produce are not necessary for the clean energy transition. Copper, the project's primary target, is not on the 2022 List of Critical Minerals, because it does not meet the threshold for supply risk and importance to economic and national security.[76]

[74] *See What is the Triple Planetary Crisis?*, UNITED NATIONS CLIMATE CHANGE (April 13, 2022), https://unfccc.int/blog/what-is-the-triple-planetary-crisis.

[75] *See* FEIS at 5-842 (stating that NorthMet would emit at least 15,790,752 CO_2e over a 20-year operating lifetime). As MCEA detailed in its September 28, 2016, letter to Doug Bruner, Project Manager, U.S. Army Corps of Engineers and Michael Jimenez, Minerals NEPA Project Manager, Superior National Forest, this figure is likely an underestimate, in part because no environmental review document adequately analyzed the destruction of high-quality wetlands and the consequent loss of absorbed carbon as emissions.

[76] *See* U.S. Geological Survey ("USGS"), *2022 Final List of Critical Minerals*, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/2022%20Final%20List%20of%20Critical%20Minerals%20Federal%20Regist

And if built, PolyMet would produce only a small amount of copper compared to both U.S. and global production. PolyMet's projected annual recovered copper production of 54.8 million lbs.,[77] or 24,856 metric tons, would contribute 2% to the 1,200,000 metric tons of copper produced by U.S. mines in 2021, or 0.12% to the 21,000,000 metric tons produced worldwide in 2021.[78] If permitted, PolyMet would have lower production capacity than 16 of the 17 leading copper-producing mines in the U.S., which represent over 99% of domestic production.[79]

In fact, an increase in the copper recycling rate in the U.S. *by just 1%* would produce the amount of copper that PolyMet projects that its NorthMet mine would produce.[80] Similarly, PolyMet's nickel production could be achieved by increasing the nickel recycling rate by 1.2%.[81] Copper and nickel are readily and infinitely recyclable.

Neither can PolyMet prove that its projected production would support domestic clean energy supply chains. PolyMet would not be obligated, under any enforceable document that commentors are aware of, to prioritize sale to domestic buyers at any point in the project, or to use metals for clean energy technologies. In fact, Swiss-owned Glencore currently holds offtake agreements with PolyMet for copper-nickel concentrate production.[82] NorthMet ore would likely

er%20Notice_2222022-F.pdf; U.S. Geological Survey, *Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List* (2021), https://pubs.usgs.gov/of/2021/1045/ofr20211045.pdf.

[77] Zachary J. Black et al., *Form NI 43-101F1 Technical Report for the NorthMet Project*, 26 (Mar. 26, 2018), https://polymetmining.com/wp-content/uploads/2018/10/PN150163-PolyMet-NI-43-101-Technical-Report-2018_03_26_Rev0.pdf.

[78] *See* USGS, *Mineral Commodity Summaries January 2022-Copp*er, (2022), https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf.

[79] *See* USGS, *2017 Minerals Handbook – Copper* (Oct. 2021), https://pubs.usgs.gov/myb/vol1/2017/myb1-2017-copper.pdf.

[80] According to 2018 data from the USGS, 861,000 metric tons of copper were recycled; 2,510,000 metric tons were available for recycling; and the recycling rate was 34%. Increasing the recycling rate by 1% would result in 25,100 more metric tons recycled, which exceeds PolyMet's annual copper production of 24,856 metric tons, converted from 54.8 million lbs. *See* USGS, *2018 Minerals Yearbook—Recycling Metals* (April 2022), https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-recycling.pdf

[81] According to 2018 data from the USGS, 124,000 metric tons of nickel were recycled; 259,000 metric tons were available for recycling; and the recycling rate was 48%. Increasing the recycling rate by 1.2% would require 3,108 more metric tons to be recycled, which exceeds PolyMet's annual nickel production of 2,994 metric tons, converted from 6.6 million lbs. Zachary J. Black et al., *Form NI 43-101F1 Technical Report for the NorthMet Project*, 26 (Mar. 26, 2018), https://polymetmining.com/wp-content/uploads/2018/10/PN150163-PolyMet-NI-43-101-Technical-Report-2018_03_26_Rev0.pdf.

[82] *See* PolyMet Mining, *Minnesota Commitment, Global Opportunity*, 14 (2016), http://www.polymetmining.com/wp-content/uploads/2013/02/2016-PolyMet-Corporate-Presentation-14pg.-6.22.2016pptx.pdf.

be refined at a Glencore smelting facility in Canada,[83] then sold on the global market. In contrast with the low likelihood PolyMet would contribute to domestic clean energy supply chains that would reduce carbon emissions, it is certain the NorthMet mine, if permitted, would contribute to climate change.

4. Federal Agencies Must Supplement the FEIS Pursuant to the National Environmental Policy Act.

As noted above, PolyMet proposed a 32,000 tpd/20-year project, and the FEIS bases its assessment of environmental impacts on that mining plan. However, if the rate of mining changes, or the duration of the mining changes, impacts from the project will increase, including water quality impacts with the potential to cause or contribute to exceedances of the Band's water quality standards.

On June 8, 2018, MCEA, Friends and CBD served a petition for a Supplement to the FEIS on the U.S. Forest Service, the Army Corps, the MPCA, and the DNR ("Petition").[84] The Petition was prompted by PolyMet's issuance of a new securities filing—a NI43-101 Technical Report ("Technical Report"). In the 2018 Technical Report, PolyMet chose to include two "Preliminary Economic Assessments" or "PEAs" of two expanded mining scenarios with ore throughputs of 59,000 and 118,000 tpd. Based on PolyMet's analysis, the PEA scenarios would yield significantly higher profits. Under Canadian securities regulations, a PEA "is generally the first signal to the public that a mineral project has potential viability. Given the significance of this milestone in the evolution of any mineral project, the market views PEA results as important information."[85] Although the Minnesota Court of Appeals initially upheld DNR's decision to deny the Petition, it later determined that the Petition information is probative of PolyMet's intent to expand after the current mine is permitted and has ordered MPCA to adopt findings addressing the impact of PolyMet's Technical Report on MPCA's air permitting decision, which was based on the assumption that PolyMet would operate as a "synthetic minor" source. *See In re Air Emissions Permit No. 13700345-101 for Polymet Mining, Inc.*, 965 N.W.2d 1, 9-10, 12 (Minn. App. 2021). Despite the Court's conclusion, MPCA has refused to investigate PolyMet's expansion plans. As a result, MCEA and others have been forced to appeal MPCA's latest "hear no evil" decision. *See* Pet. for Writ of Cert., *In re MPCA Issuance of Air Individual Permit No. 13700345-101 to PolyMet Mining, Inc.*, No. A22-0068 (appeal docketed Jan. 18, 2022).

Since the Petition was filed, PolyMet has continued to take actions consistent with the expansion/accelerated plans described in the Technical Report and actions consistent with a

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[83] *See Metals & Minerals: Copper*, GLENCORE CANADA (May 27, 2022), https://www.glencore.ca/en/What-we-do/Metals-and-minerals/Copper.

[84] At the time this 2018 Petition was filed, the land exchange granting PolyMet rights to the surface of the land, as necessary for an open-pit mine, had not closed, nor had the Army Corps issued the Permit.

[85] Canadian Securities Administrators, *CSA Staff Notice 43-307 Mining Technical Reports – Preliminary Economic Assessments*, 1 (Aug. 16, 2012), https://mrmr.cim.org/media/1026/csa-staff-notice-43-307.pdf.

significantly longer mine life than the 20-year mine life the FEIS examined.[86] In November 2019, PolyMet announced the results of its 2018-2019 drilling program ("2019 Drilling Announcement").[87] PolyMet announced that "Proven and Probable Reserves increased by 14% to 290 million tons" and "Measured and Indicated Resources increased by 22% to 795 million tons."[88] The 2019 Drilling Announcement quoted PolyMet president and CEO Jon Cherry, who stated, "we also continue to identify opportunities to optimize and deliver the project in the most economic way possible."[89] PolyMet's November 2021 investor presentation continues to tout the greater profits to be made from the PEA expanded and accelerated mining scenarios, and the expansion of the mine beyond the "20 Year Pit Shell."[90] Indeed, PolyMet notes the "regional exploration opportunity" consisting of "high grade, near mine, legacy intercepts" and "untested strike to NE and SW of ore body."[91]

Friends and MCEA have challenged the Army Corps' failure to prepare a supplement to the FEIS examining the impacts of PolyMet's expansion plans in the federal district court. *See Friends of the Boundary Waters Wilderness et al., v. U.S. Army Corps of Engineers*, No. 0:19-cv-02493 (D. Minn. filed Sept. 10, 2019). In addition to the reasons stated in the Petition, the Army Corps must supplement the FEIS with the information necessary to determine whether the PolyMet project's indirect impacts on wetlands will cause or contribute to exceedances of the Band's water quality standards.

CONCLUSION

The current suspended Permit, if reinstated, would cause or contribute to exceedances of applicable water quality requirements within the Band's downstream waters based on the available scientific information. The information that PolyMet relies on to support issuance of the Permit has been deemed unreliable by the Minnesota Supreme Court and a variety of experts. Given the lack of information about the indirect impacts and the impacts from fill material, the Army Corps lacks the information required both to issue this Permit or to determine whether there are new conditions that would ensure compliance with the Band's water quality standards. As a result, there are no new conditions that could be added to the Permit that would ensure compliance.

PolyMet seeks to construct the proposed mine to make money. The Band seeks to defend its homeland and treaty rights to preserve its culture. The Army Corps has the duty to protect "special places" such as the St. Louis River Headwaters Site, and a special responsibility to ensure

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[86] The FEIS agencies refused to examine a longer-mine life scenario despite the fact that PolyMet's reason for not disposing of the Category 1 was rock in the West Pit is also to allow future mining.
[87] Press Release, PolyMet Mining, Inc., *PolyMet drilling program results in additions to NorthMet Mineral Resources and Reserves* (Nov. 19, 2019) (hereinafter "2019 Drilling Program Announcement"). (Attachment 11).
[88] *Id.* at 1.
[89] *Id.* at 2.
[90] *See* PolyMet Mining, *Minnesota Commitment, Global Opportunity* (Nov. 2021). (Attachment 12).
[91] *Id.* at 20, 23.

that permits do not violate the treaties that the U.S. Government and Tribe signed many years ago. Under these circumstances, all doubts must be resolved in favor of the Band.

Sincerely,

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June 6, 2022

The undersigned submits this report in support of the comments of the Minnesota Center for Environmental Advocacy in the U.S. Army Corps of Engineers proceeding titled Fond du Lac Band of Lake Superior Chippewa Section 401(a)(2) Objection/MVP-1999-05528-TJH.

Expert qualifications of Dr. Amy Myrbo

I hold a B.A. in English Literature and a Ph.D. in Geology from the University of Minnesota (UMN). My dissertation focused on the biogeochemistry of lakes and lake sediments in Minnesota, especially lakes experiencing human impacts. I was the lead investigator for the UMN Twin Cities Campus under contract from the Minnesota Pollution Control Agency (MPCA) for their Field Survey for the Sulfate Standard to Protect Wild Rice (2011-2015). I was lead author on two of the publications that resulted from that work, published in the American Geophysical Union's *Journal of Geophysical Research - Biogeochemistry* in 2017, and a coauthor on two additional resulting publications. I have authored or co-authored 28 other peer-reviewed publications. My relevant professional work has also included the study of the chemistry, sedimentology, and history of wild rice lakes in Minnesota. I am a Fellow of the UMN Institute on the Environment and was a member of the UMN Vice President for Research Wild Rice Advisory Committee 2017-2018. Since 2019 I have been an independent consultant (Amiable Consulting), and am a part-time Assistant Scientist at the St. Croix Watershed Research Station, Science Museum of Minnesota.

Additional dangers of sulfate pollution: Eutrophication, inorganic mercury release, and water clarity

The release of sulfate to fresh waters causes numerous deleterious environmental effects. Two of these have been discussed in materials submitted to date: (1) sulfate is converted to sulfide, which poisons wild rice and other aquatic plants (Pastor et al., 2017; Myrbo et al., 2017a and references therein); and (2) during the conversion of sulfate to sulfide, inorganic mercury is converted to methylmercury, the highly toxic form of mercury that bioaccumulates in organisms (e.g., Gilmour et al., 1992; Myrbo et al., 2017b). Sulfate-reducing bacteria (SRB) are responsible for both processes.

Yet there is a third negative outcome that has not to our knowledge been considered in the FEIS or materials submitted at this hearing: the compounds released during the "mineralization" of organic matter by SRB converting sulfate to sulfide. Organic matter mineralization could have negative effects on several water quality parameters, including nutrients, inorganic mercury, and dissolved organic carbon. These effects were recently demonstrated in a large experiment in northeastern Minnesota (Myrbo et al., 2017b), and are described in more detail below.

<u>Nutrients.</u> In order to convert sulfate to sulfide (to "reduce" sulfate, in chemical terms), SRB oxidize the organic matter in lake and river sediments. Oxidation "mineralizes" or decomposes organic matter into its constituent components - predominantly carbon, nitrogen, and phosphorus compounds (equation 1). These dissolved compounds are released to the sediment pore waters, and can then diffuse or advect into the water column, affecting water quality. As shown in Eqn. 1, ammonium (NH_3) and phosphate (H_3PO_4), plant nutrients that are readily taken up by primary producers such as algae, are products of this coupled sulfate reduction and organic matter mineralization. These nutrients have the potential to cause eutrophication in the rivers and lakes to which sulfate would be discharged, and to potentially cause an exceedance of the Fond du Lac Band's water quality standards.

$$2(CH_2O)_x(NH_3)_y(H_3PO_4)_z + {}_xSO_4^{2-} \rightarrow 2xHCO_3^- + xH_2S + 2yNH_3 + 2zH_3PO_4 \qquad (1)$$

In other words: Organic matter + sulfate *are converted to* alkalinity + sulfide + nutrients (ammonium+phosphate).

<u>Inorganic mercury.</u> In addition to the components of organic matter, mineralization releases the inorganic mercury that is adsorbed onto that organic matter (Regnell and Hammar 2004; Myrbo et al., 2017b). This inorganic mercury is then available to be methylated, rather than being buried in the sediments. In the presence of elevated sulfate, SRB thus cause a "double whammy" of increased inorganic mercury plus increased methylation of that mercury - which could dramatically increase methylmercury in fish, otters, eagles, and other fish-eating wildlife; birds, bats, and other insect- and spider-eating wildlife; and of course, the human consumers of fish from impacted waters.

<u>Dissolved organic carbon.</u> In Eqn. 1, the carbon on the right side of the equation is shown completely oxidized to bicarbonate (HCO_3^-). Bicarbonate affects the buffering of aqueous systems, so could have an effect on downstream ecosystems. If oxidation is not complete, the carbon in Eqn. 1 will instead be in the form of dissolved organic carbon (DOC), the molecules that give some of the waters of northeastern Minnesota their brown tint. An increase in DOC makes water less transparent, which could affect the growth of aquatic plants and the relative populations of rooted plants vs. algae, especially in concert with nutrient releases identified above. DOC also interacts strongly with inorganic mercury and methylmercury (Ravichandran, 2004; Myrbo et al. 2017b), and could increase transport of both forms of mercury, as well as decreasing potential photodemethylation of mercury by attenuating sunlight.

The effects of sulfate reduction have the potential to cause these deleterious effects out of proportion to the amount of sulfate released to the ecosystem, because each sulfur molecule can be recycled many times. Sulfate is reduced to sulfide, then can be re-oxidized to sulfate (e.g., as sulfide diffuses out of anoxic pore waters), then reduced again to sulfide and oxidized to sulfate, ad infinitum, in what is known as the "cryptic sulfur cycle" (Canfield et al., 2010). Each time it is reduced from sulfate to sulfide, more organic matter is mineralized and more nutrients, mercury, and DOC are released.

In the analysis conducted in support of the 404 Permit, it does not appear that the impacts described above have been taken into consideration. The release of nutrients and inorganic mercury as the result of the project has the potential to violate the Band's nutrient water quality standards (FDL Band 1998).

<u>The role of cobalt in mercury methylation</u>

Another biogeochemical factor that has not been adequately addressed is the role of cobalt in mercury methylation. PolyMet recognizes that cobalt will be emitted by mining activities but does not consider the effects of this addition of cobalt on the methylation of mercury by SRB and abiotically. Cobalt can be limiting to mercury-methylating SRB (Ekstrom and Morel 2008), meaning that an increase in cobalt can directly cause an increase in methylmercury production and its abundance in the environment. Cobalt has also been implicated in the inorganic methylation of mercury.

The critical role of cobalt in mercury methylation by the SRB *Desulfovibrio desulfuricans* was first identified in the early 1990s (Berman et al 1990), and Choi and Bartha (1993) verified cobalamin, a coordination complex of cobalt, as the molecule that transfers a methyl group to the mercuric ion as SRB convert sulfate to sulfide. Ekstrom and Morel (2008) found that mercury methylation by *Desulfococcus multivorans,* another SRB, was a factor of 3 to 5 lower in the absence of cobalt.

Work by Bertilsson and Neujahr (1971) and Imura et al (1971) also demonstrated spontaneous mercury methylation by free cobalamin. Although this process may be relatively minor compared to methylation by SRB, "its influence may be increased in organic-rich lakes," according to Ullrich et al (2001). The lakes of northeastern Minnesota are organic-rich, and thus may be susceptible to spontaneous mercury methylation by free cobalamin, the abundance of which may in turn be increased by deposition of cobalt from mining activities.

In addition to mercury methylation by SRB and spontaneously by free cobalamin, abiotic methylation may occur due to the presence of inorganic dissolved cobalt (Munson et al 2018). These authors et al found a "dramatic" increase in mercury methylation when they added dissolved inorganic cobalt to filtered seawater, and suggested that this increase may be due to "competition between Co(II) and Hg(II) for organic ligand binding that could increase Hg(II) substrate availability for methylation" (Munson et al 2018).

SRB may also acquire Co directly from solid cobalt sulfide, CoS (Ekstrom and Morel 2008), which is the likely form of cobalt in fugitive dust from the proposed PolyMet mine site; if this is the case, CoS particles may enhance mercury methylation even if they do not dissolve into water in wetlands, lakes, and rivers.

In the analysis conducted in support of the 404 Permit, it does not appear that the impacts described above have been taken into consideration. The effects of potential cobalt contamination on mercury methylation in addition to the direct toxicity of cobalt in the

environment must be considered before any conclusions are made related to the 404 Permit.

Disposal of the waste from the reverse-osmosis process

Sulfate salts are highly soluble, and the removal of dissolved sulfate and mercury from mining water using reverse osmosis (RO) is tremendously expensive, and energy- and carbon-intensive. Even if PolyMet were able to economically treat all of the water it will discharge, it would then face the immense problem of the resulting toxic waste: the sulfate and other salts, and the mercury and other metals removed and highly concentrated by RO, which must then be disposed of as solids or liquid products, such as sulfate brines and precipitated minerals (Kinnunen et al., 2018). What landfill will accept a concentrated, soluble, and reactive sulfate and mercury slurry?

Amy Myrbo, Ph.D.

June 2, 2022

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The undersigned submit this report in support of the comments of Friends of the Boundary Waters Wilderness in the U.S. Army Corps of Engineers proceeding titled Fond du Lac Band of Lake Superior Chippewa Section 401(a)(2) Objection/MVP-1999-05528-TJH.

Expert Qualifications

Fred Campbell:
I have a Bachelor of Arts degree in Geology from Macalester College, and a Master's degree in Geology from the University of Minnesota-Duluth. My professional career included work in both the private and the public sector. At the Minnesota Department of Natural Resources, I worked on the Regional Copper-Nickel Study, and contributed to Report 93 (Mineral Resources Of A Portion Of The Duluth Complex And Adjacent Rocks In St. Louis And Lake Counties, Northeastern Minnesota). At AMAX Exploration, Inc., I worked on the Minnamax (now Teck) copper-nickel deposit, mainly logging and sampling drillcore. Later, I worked on several mineral exploration projects in northeastern Minnesota for E.K. Lehman and Associates, and for Meridian Land and Minerals (then a subsidiary of Burlington Northern Railroad). After additional education at the University of Minnesota (Minneapolis) and Century College, I worked for the Minnesota Department of Transportation (Water Quality Unit), the Minnesota Geological Survey, and the Minnesota Pollution Control Agency (MPCA). At the MPCA, I worked as a hydrogeologist in the Superfund Program for approximately 29 years, and I retired in 2017. The Superfund work included oversight and enforcement of investigation and cleanup activities at several major projects involving soil, groundwater, and surface water contamination at sites operated by General Mills, Honeywell, 3M and other companies.

Bruce Johnson:
I have over 30 years of experience in water quality and environmental toxicology in Minnesota, with a great deal of this in Northeast Minnesota. My professional experience has direct connections to the Duluth Complex and its associated environmental chemistry and toxicology. My Bachelor of Arts degree is in Biology and Chemistry from Winona State University with emphasis in biochemistry and physiology. I initially worked for USEPA with the Shagawa Lake Restoration Project assessing the effects of sewage remediation on Shagawa Lake near Ely, Minnesota. I was next the field chemist in charge of the metal pathways portion of the Regional Copper Nickel Study. In this position, my staff and I studied potential water quality impacts from Duluth Complex waste rock, primarily from the LTV Dunka Mine. Later as the DNR field chemist stationed within Minnamax, I managed one of the on-site waste rock and tailing field leaching studies. At the MPCA, as technical lead for three staff for NPDES industrial enforcement, I enforced permits, including mining. In that position, I drafted the first enforcement document requiring Erie Mining Company to resolve years of violations from the Duluth Complex leachates emanating from the mine's waste rock stockpiles.

Other related experience:
- I am certified hazardous materials manager at the Masters level (retired);
- I was a member of the Academy of Sciences Transportation Research Boards Environmental Maintenance Subcommittee;
- I was invited by the Umwelt Bundes Amt (German Federal EPA) to work 6 weeks in Berlin Germany for an information exchange; and

- I have authored and co-authored ten publications.

Gerald Stahnke: From 1974 to 1979, I was an aquatic biologist working for Barr Engineering on behalf of the State of Minnesota Department of Natural Resources. During this time, I was taking water quality samples of groundwater and surface water at copper-nickel projects, including the Minnamax (now Teck) deposit. I also conducted biota sampling of the Dunka and Partridge Rivers, and took multiple samples of leachate from a tailings basin designed to investigate the quantity and quality of leachate that would result from the disposal of waste rock from the Minnamax copper-nickel deposit.

In 1979, I began working for the MPCA Solid Waste Division, conducting enforcement actions at landfills. At that time, I was attending the University of Minnesota School of Public Health, with an emphasis on Water Hygiene. I worked in enforcement until 1983, when I was involved in rewriting the State's Solid Waste Rules. From 1984 to 1986, I was the Dakota County (Minnesota) Senior Environmental Health Specialist and County Solid Waste Officer.

After two years, I returned to the MPCA to establish the Voluntary Investigation and Cleanup (VIC) Program, where I oversaw hundreds of cleanups and redevelopments at sites. I remained in the Superfund Program until I retired in 2016. In recognition for my work in the VIC Program, I was awarded Minnesota Brownfields' first-ever Mac Hyde Brownfield Leadership Award.

Executive Summary

The proposed 404 Permit proposes to allow the use of Category 1 waste rock as "fill." The PolyMet Final Environmental Impact Statement (FEIS) and its associated documents, including the 401 and 404 permits, contains significant errors and omissions in the basic data acquisition and analysis, such that the impacts of Category 1 waste rock use as fill in wetlands cannot be predicted.

Based on the insufficient characterization of the rocks at the PolyMet deposit, impacts from a number of potentially toxic releases from the project to the St. Louis River watershed and wetland complexes cannot be determined sufficiently to demonstrate that releases of chemical parameters will not cause or contribute to exceedances of the Fond du Lac Band's water quality standards.

As a result of these errors and omissions in the PolyMet FEIS and its associated documents, any possible future modification of the existing 404 Permit would be insufficient to be protective of the St. Louis River watershed, the project site or nearby wetlands, or the Fond du Lac Band's waters.

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5. Wastewater Treatment

Introduction

Our comments are limited to documented environmentally conservative elements/mixtures that have been omitted or otherwise erroneously evaluated in the FEIS. This is not to indicate other major elements or mixtures have been adequately addressed to be protective of the downstream resources.

Discussion

1. Sampling and Analysis Plan

Published literature on the petrology and mineralogy of the basal Duluth Complex contains numerous references to the heterogeneity of these rocks (e.g., Severson, 1994). For example, the basal Duluth Complex, because it is actually a series of intrusions, contains rock types ranging in composition from peridotite to anorthosite. The variations in composition can occur over stratigraphic thicknesses less than ten feet. In addition, the basal Complex contains numerous xenoliths (i.e., inclusions, see definition from Bates, 1983, below) of the Virginia Formation and the Biwabik Iron Formation. These inclusions sometimes contain significant concentrations of sulfides, often as pyrite and/or pyrrhotite (Miller et al, 2002).

In addition, it is important to emphasize that any waste rock has a large amount of surface area, which makes it susceptible to leaching by infiltrating precipitation or circulating fluids (including leachate). In particular, sand-sized, or finer grained material has a huge amount of surface area, and would represent a large potential source for mobile contaminants. Since Category 1 waste rock is compositionally heterogeneous, it will likely be heterogeneous in grain size too. As a result, obtaining representative samples for chemical analyses would be difficult, if not impossible.

Because of the heterogeneous nature of these materials, any material initially identified as Category 1 waste rock would certainly exhibit similar heterogeneity. Any plan to properly and adequately sample and analyze this waste would require many individual samples (i.e., not composite samples) and many different analyses, often requiring very low reporting and/or detection limits. Therefore, a properly designed and adequate sampling and analysis plan for this waste rock would be technically and financially impossible.

High sulfur inclusions missed during the evaluation can be predicted to release acid, sulfate and metals from water infiltration. This acid contacts surrounding low sulfur rocks and releases sulfate and metals. Gradually the acid is buffered by the rock and the pH is raised, yet the dissolved metals and sulfate remain. The water continues to dissolve metals and sulfate from lower concentration rock at less intensity. Ultimately neutral pH seepages exit the piles with elevated metals and sulfate concentrations that have been determined to be chronically or acutely toxic.

The use of Category 1 material as on-site fill would impact surrounding waters with undermined concentrations of leachates.

2. Waste Rock Characterization

Mine Site water quality assessment is based on erroneous assumptions about rock characterization and chemistry. Category 1 waste rock, as with many portions of the Duluth Complex and its adjacent formations, is heterogeneous, and may contain localized areas with high sulfide content. Because these sulfides may be primarily pyrite and/or pyrrhotite, they contain little or no copper, nickel, or other elements of economic interest. Thus, some waste rock may contain high concentrations of sulfides, and determining which waste rock meets the requirements for Category 1 would require an impossibly complex and expensive sampling and analysis program (see above).

As a result, Category 1 waste rock piles will almost certainly create acidic pore water and leach high volumes of sulfates and toxic metals, and other contaminants. Thus, this waste rock has a high potential for generating leachate containing concentrations of metals, sulfate and major ions that will greatly exceed surface water standards and the Fond du Lac Band's water quality standards, and should not be used for construction or fill.

The discussion of a Category 1 waste rock sulfur cutoff of 0.12% sulfur (FEIS, p. 3-46) contains faulty model inputs from the results and conclusions of PolyMet's 2013 Waste Characterization Data Package due to small sample size and composite sampling or averaging to design waste rock humidity cell tests.

The FEIS humidity cell testing lacks the rigor necessary to predict sulfur content of the waste rock stockpiles. It is well documented in the geologic literature that the Duluth Complex mineralogy is highly heterogeneous. This variation in mineralogy is demonstrated in both reports and drill core analyses (Patelke and Severson, 2005). For example, Patelke and Severson discuss a report on a bulk sample collected by Teck Cominco, at site B1-321:

> *Thus, one lesson to be learned here is that if the grade is important it is imperative to conduct detailed drilling of a site to establish the boundaries of the future bulk sample! The extreme variability of the Unit 1, both in geology and mineralization style, can produce dramatic changes within a few tens of feet (both horizontally and vertically).*

The report documents that the Duluth Complex contains inclusions of Virginia formation (Patelke and Severson, 2005). An inclusion is defined as "a fragment of older rock within an igneous rock to which it may or may not be genetically related" (Bates, 1983). The Virginia formation often contains high sulfur and other metals (Miller et al, 2002). The inclusions vary from large ones, that may be identified by coring, to rather small inclusions (a few inches to multiple feet in size) that are environmentally significant but are easily missed with drill cores. (Geerts et al, 1990).

The Partridge River intrusion, where the proposed PolyMet mine site is located, is highly heterogeneous as well. As a result, both the mineralogy and the concentrations of elements of environmental concern vary significantly throughout the intrusion and the PolyMet mine site.

The variability of sulfide concentrations can be observed in drill cores (Patelke and Severson, 2005, p. 74) (SRK, RS53/RS42 – Waste Rock Characteristics/Waste Water Quality Modeling – Waste Rock and Lean Ore - NorthMet Project. Draft 01. Prepared for PolyMet Mining Inc. March 9, 2007, FEIS reference SRK 2007b, Appendix c.2.) and are also described in the published literature (e.g., Miller et al, 2002). The SRK RS53/RS42 document describes the humidity cell process, stating 89 samples were used to categorize waste rock, representing a total of 309 million tons of waste rock (NorthMet Project Waste Characterization Data Package V. 9, March 7, 2013, SDEIS, reference PolyMet 2013, section 4.3, not referenced in the FEIS). This sample size is statistically and scientifically inadequate for characterization of such a massive amount of waste rock.

The humidity cell test rock was separated by rock type (i.e., by geological units). In describing the process for the selection of the test cores, the document states that cores were determined by "knowledge" to select representative samples of each unit (SRK, RS78 – Block Ore and Waste March 2, 2007, SDEIS reference SRK 2007a, p. 8, not referenced in the FEIS). In such an important evaluation, an accepted statistical protocol, such as use of a random number generator, must be used to select cores. The cores used in the testing were not selected using a scientifically valid statistical procedure. This likely skews the predicted sulfide and metals concentrations in the tests.

The selected core intervals were divided into their geological units. Each unit was composited, and the sulfur content for each unit was averaged. The average concentration was used for the humidity testing. However, averaging ignores the effect of actual isolated high sulfur concentrations within the waste rock, and by default assumes all waste rock sulfur concentrations will be as well mixed within the Category 1 waste rock stockpile as in the test cells. Only under these waste rock well-mixed conditions would the resultant leachate be similar to the humidity cell results.

From an environmental standpoint, using average concentrations fails to adequately address environmental impacts. High sulfur "seed" inclusions (Geerts et al, 1990) are of environmental concern (SDEIS reference SRK 2007a, p. 6., not referenced in the FEIS). This humidity cell testing procedure, by default, assumes all waste rock sulfur concentrations will be as well-mixed within the stockpile as they were in the test cells. Thus, in theory, the leachate observed in the field will be similar to the humidity cell results. However, in practice the waste rock will not be well mixed and numerous seed quantities of sulfur much greater than 0.12% will be within the stockpile. These seeds will initiate acid and leach both its high sulfur waste rock and also the lower sulfur rock in its drainage path. The acid may exit the stockpile or may be neutralized before exit, but either way it will carry out a load of dissolved metals and sulfate (Robertson et al, 1987).

Thus, the ore block model may be excellent for assessing the economic value of a resource for production purposes, but it will not upscale adequately to meet environmental, chemical and toxicological requirements. Separation of the very heterogeneous waste rock containing high sulfide inclusions, such as those described in Miller et al, 2002, using an average concentration block model will not prevent higher concentration sulfide-bearing rock from being placed in lower concentration waste rock stockpiles (Eger et al, 1980).

The up-scaling of theoretical modeling and/or laboratory testing results to field operations will unavoidably result in high concentration inclusions (seed quantities) of sulfur being placed in lower sulfur (i.e., Category 1) stockpiles. These high sulfur inclusions will produce pockets of acidic leachates within the piles. These acidic leachates will drain and leach other low sulfur materials below. If neutralizing rock is not sufficiently present, over time, the leachate will remain acidic, and contain metals and other contaminants. Even if the acidic leachate were to be neutralized to some degree before it exits the stockpile, the drainage will carry out a load of dissolved metals and sulfate. Leached metals and sulfate will not be adsorbed by the host rock in the pile and will result in much higher leachate concentrations than those predicted by the model. The higher the stockpile, the higher the concentration of leachate that will be produced. (Eger et al, 1980).

> **Category 1 waste rock piles will almost certainly create acidic pore water and leach high volumes of sulfates and toxic metals, and other contaminants. Thus, this waste rock has a high potential for generating leachate containing concentrations of metals, sulfate and major ions that will result in discharges that greatly exceed surface water standards and that may cause or contribute to exceedances of the Fond du Lac Band's water quality standards, and should not be used for construction or fill.**

3. **Waste Rock Segregation**

   a. **Sorting waste rock stockpiles will not be possible to the degree presumed in the FEIS.**

The FEIS proposes to use block modeling to separate heterogeneous waste rock into four classes based on the predicted/calculated sulfur concentrations EIS, p, 3-46). This modeling cannot be consistently applied during the physical action of loading trucks from the windrowed blast rock. Since the mineral deposit is mostly in the form of disseminated sulfides, and the blocks are averaged, localized areas with high levels of sulfur will be unidentified and unaccounted within a block. In addition, adjacent block averages could vary significantly in sulfur concentration. The entire permanent, unlined Category 1 waste rock stockpile is classified as less than or equal to 0.12% sulfur (FEIS, p. 3-46). In practice the block modeling and sorting process will result in blocks or portions of blocks with high concentrations placed into the Category 1 pile.

The block model was designed to estimate ore resources for production purposes. It averages the nearest 10-foot drill core analyses to the 20-foot height of the block, and then averages all nearby drill core averages adjusted by distance to determine a number for sulfur content in the 50 x 50 x 20 feet block (PolyMet Rock and Overburden Management Plan V. 5, December 28, 2012, SDEIS reference PolyMet 2012s, Section 2.3, not referenced in the FEIS). There are 436 drill cores in the mine area. The economic portion of the mine is 528 acres. This calculates to an average of less than one drill core per acre. The mine area is divided into 133,000 blocks (SDEIS, pp. 3-39, 40, not referenced in the FEIS).

This process of determining the block's average sulfur content will not reflect the highest concentration found in the nearest drill core. As noted previously, mine site drill core logs demonstrate large variability of sulfur, even between analyses completed at 10-foot intervals, which demonstrates the severe heterogeneous nature of the rock (Patelke and Severson, 2005, Fig. 24, p. 66). Thus, waste rock will definitely contain "seed quantities" of sulfur much greater than 0.12% and will generate acid that will leach metals from the high sulfur material and from other rock in its drainage path. Any block may contain rocks with much higher sulfur than what is calculated as the average.

This process of waste rock characterization is further adulterated by the gross separation of waste rock by category during the extraction process. Consider that over 13 years, the Category 1 stockpile will contain 167,922,000 tons of waste rock (FEIS p. 3-44). Each blast will remove 250,000 to 300,000 tons of rock (FEIS, p. 3-42). Thus, each blast will remove approximately 85 blocks. A block weighs 3,518 tons (PolyMet, Rock and Overburden Management Plan, SDEIS reference PolyMet 2012s, p 39. not found in the FEIS reference) and each truck holds 240 tons of rock. Therefore, each block contains approximately 15 truckloads. Blocks or portions of blocks with higher sulfur seed concentrations will be transported to the Category 1 pile. If one block from a blast is mis-characterized and transported to Category 1, more subsequent trucks moving the blasted rock may replicate this error. The Plan states they will use GPS tracking to assist in separating rock types (FEIS Reference PolyMet 2015h, p. 33). GPS use cannot resolve the issue of averages underestimating sulfur concentrations in some rocks.

As a result of these practical constraints, the proposed block evaluation process will result in stockpiles that will not uniformly meet proposed cutoff concentrations, resulting in much higher concentrations of metals, sulfate and major ions in leachate than those predicted in the FEIS. These elevated concentrations in leachate will impact surface water, groundwater, and wetlands (Myrbo et al, 2017).

Approaches to determining stockpile sorting were considered in FEIS Reference SRK 2007b. While discussing models, this document noted on page 4:

> "*Northwest Geochem (1991) comprehensively reviewed modeling methods to predict the chemistry of waste rock stockpile drainage and concluded that 'no model exists which can even generally simulate the most critical physical, geochemical, and biological processes in waste-rock piles.' Subsequently, MEND (2000) concluded that 'If assessments of the behavior of waste rock stockpiles are required, it should be realized that no reliable modeling approaches are available. Advances have been made in understanding and modeling the various processes (e.g. flow in unsaturated materials, pyrite oxidation) but reliably coupling the models remains primarily a topic of research.'*"

Other theoretical and empirical approaches were discussed, and the decision was made to use the current block model approach, but the block model cannot escape the faults enumerated in both the FEIS Reference SRK 2007b and this review.

Although the SDEIS acknowledges that much higher rates of leaching would result if waste rock piles were to become acidic, up to a factor of 8.2 times the predicted concentrations/volumes (SDEIS, p. 5-51), in the FEIS, PolyMet's predictions of leachate

concentrations/volumes from the permanent Category 1 waste rock stockpile are based on humidity testing. As a result of that testing, Polymet assumes Category 1 waste rock will *not* become acidic and thus will not discharge toxic chemistries (FEIS, Polymet 2015h). The USACE states its approval to use Category 1 waste rock for construction material (USACE, Record of Decision 2022 p. 45), and this use is allowed under the proposed 404 permit. However, this material must be considered reactive waste under Minn. Rules 6132.0200 Subp 28, which states:

> ***Reactive mine waste means waste that is shown through characterization studies to release substances that adversely impact natural resources.***

Category 1 has a high potential for leaching of metals, sulfate and major ions beyond surface water standards and should not be used as construction material, acidic or not.

b. Gaps in Characterization of Waste Rock Parameters

The FEIS uses block modeling, originally used to predict the amount of profitable resource, to separate very heterogeneous waste rock into four classes based on the sulfur concentrations.

In general, elements of both economic and non-economic interest within the Duluth Complex are widely dispersed but locally concentrated. Copper, nickel, cobalt, zinc, mercury, arsenic, sulfur, chlorides, as well as major ion concentrations vary within the host rocks. These elements also vary in their relative economic and metallurgical value and in the significance of their relative environmental concentrations. As proposed by PolyMet, waste rock will not be blended to an average concentration, as it must be for the beneficiation process. Even after blending, anomalous concentrations of unwanted contaminants, such as pyrite and/or pyrrhotite, chloride, arsenic, and mercury will be processed and discharged as tailings.

The previously completed humidity testing sampling focused only on the presence of sulfides in its core- and geologic unit selection process, so the sampling and analyses were limited to parameters closely associated with the sulfide-bearing minerals. (FEIS Reference PolyMet 2015q, pp.7-1F). This sampling and analysis process failed to address concentrations of other parameters that exist within the non-sulfide-bearing host rock. Non-sulfide parameters and major ions are also of environmental concern.

During humidity cell testing, numerous parameters from the PolyMet test rocks demonstrated releases of leachate at near-neutral-to basic pH (FEIS Reference SRK2007b, App. H.2.). These releases can be expected to be at environmentally elevated concentrations, regardless of the circumneutral leachate pH. Humidity testing was designed to separate acid leachates from non-acid leachates using sulfur as the only parameter needed for rock stockpile classification. The assumption then followed that category 1 waste rock could be contained by less expensive containment and could be used as fill. This ignores the fact that non-acid leachates have demonstrated to remain acutely toxic to test organisms at the Dunka mine. And major ions through elevated specific conductance have also been demonstrated to be toxic to aquatic invertebrates. Thus, the only benefit of separation is to somewhat reduce toxicity, not to determine it is non-toxic and thus requires less extensive management and can be used as fill.

As discussed previously, high-sulfide concentration inclusions (seed quantities) will produce pockets of acid leachate within the piles, leaching metals along the drainage path. If neutralizing rock is not sufficiently present, the leachate will be acidic and contain metals and other contaminants. If neutralizing rock is sufficiently present, circumneutral leachate will still contain metals, especially nickel, which is environmentally mobile, sulfate, and other contaminants. As in the humidity testing to predict sulfates, use of the block modeling averages underestimates metals leachate production.

Unlike many other copper (Cu) deposits in the United States, the PolyMet deposit contains significant quantities of nickel, potentially significant quantities of cobalt, platinum, and gold (Co, Pt, Au) and also contains other associated elements, including but not limited to arsenic and mercury (As, Hg). Rock from the Duluth Complex in this area contains disseminated mineralization, that may or may not produce acidic leachate, but will still leach heavy metals far above surface water standards at potentially toxic levels (Lapakko et al, 1980). The release of Cu can be reduced by adjustments to a circumneutral pH (pH 6.7 to 7.2), by adding limestone to waste rock piles, but this is not true for Ni, Co, and Zn, which are readily released in near neutral pH (+/- pH 7) (Lapakko et al, 1980; Rinker et al, 1999; MEQB, 1977; Eisenreich et al, 1976). Unlike the PolyMet FEIS, which did not discuss circumneutral impacts which clearly fall under the definition of a reactive waste in Minn. Rules 6132.0200 Subp 28, the Regional Cu-Ni Study states that leachate impacts of nickel, cobalt and zinc are of great significance (Minnesota Planning Agency,1979).

Acid rock drainage related to copper and sulfur is not a sufficient indicator for determining how much leaching of toxic metals will occur, since there are numerous reports on the Duluth Complex in the area demonstrating significant releases of Ni, Co, and Zn at circumneutral pH. (Eisenreich et al, 1977, p. 27; Lapakko 1980, p. 3; Eger et al, 1980, pp 9-10).

Pilot testing has demonstrated at the former LTVSMC's Dunka mine that only a 10 percent reduction in Ni releases resulted from the use of limestone in the Dunka Mine Duluth Complex waste rock seepage site (Eisenreich, 1977). The use of limestone also increases major ion concentrations in an environment that is naturally very low in major ion concentrations is toxic to sensitive invertebrates (Johnson, 2015, Cormier, 2016).

Elevated releases were toxic from Cu, Ni, Co, and Zn at near neutral pH, from the Duluth Complex stockpiles at the LTV Dunka Taconite Mine (a.k.a. Cliffs Erie Dunka Mine). The AMAX test site (now Teck) and Spruce Road Bulk Sample Site (now Twin Metals) demonstrated similar chemistries. Cliffs Erie required a variance from Minnesota water quality standards with respect to acute toxicity for its 2001 Dunka Mine NPDES Permit MN0042579, (Northshore, 1970's to present, pp. 11-15).

Minnesota's Regional Cu-Ni Study data showed that Duluth Complex waste rock leachates have a high probability of aquatic toxicity (Eger et al, 1980, p. 197). The median trace metal concentrations (Ni, Cu, Zn and Co) from Dunka Mine stockpiles with circumneutral pH had leachate seepages that ranged from 10 to 10,000 times the natural background levels of streams in the area (Lapakko et al, 1980, p.3). In August 1988, the Minnesota Pollution Control Agency (MPCA) determined all of these discharges to be acutely toxic. The leachates were found toxic to *Ceriodaphnia dubia* in as low as 3 to 14 percent dilutions. These discharges are the most acutely toxic discharges known in the state (MDNR, 1983; Johnson et al, 1989; Northshore/MPCA, since 1970s). Copper, nickel, cobalt and zinc metals are all highly toxic to aquatic life at low levels (micrograms per liter), and may have negative human health effects at marginally higher levels. For example, the U.S. Environmental Protection Agency (EPA) has determined that some forms of nickel are human carcinogens (ATSDR, 2005).

The average annual precipitation for the Project area is 28.4 inches. The 855.9 acres of stockpiles projected for the PolyMet mine site can be expected to receive 660,008,592 gallons of precipitation in an average year. Uncovered AMAX test plots indicated 50 to 60 percent of precipitation was released as leachate (Eger, P. et al, 1979). In an *average* year, a rough estimate would predict PolyMet stockpiles will produce 330,000,000 to 396,000,000 gallons of leachate, containing metals and sulfides.

Both acid and circumneutral leaching must be anticipated from all stockpiles of mineralized Duluth Complex waste rock (Eger et al, 1980; Lapakko et al, 1980; MEQB, 1977; Eisenreich, 1976, p. 27). This leaching would far exceed surface water standards and should be expected to be acutely toxic (Northshore/MPCA, since 1970's; MDNR, 1983, Johnson 1989). Experience suggests that toxic metal releases of Ni, Co and Zn exceeding surface water standards can be expected indefinitely, if not in perpetuity, in the Partridge River Watershed. Category 1 stockpile rock will likely have the same chemical concentrations at a neutral pH as the low sulfur stockpile piles at Dunka and MinnAmax. The use of Cat 1 waste rock for fill can be expected to release toxic leachates.

PolyMet's proposed mine pit sidewalls would likely contain not only rocks from the Duluth Complex, but also rocks from the Virginia- and Biwabik Iron Formation. These underlying and included rock formations will also produce acidic leachate and metals concentrations that are orders of magnitude above surface water standards. This was documented in the Cu-Ni Study sampling of the U.S. Steel bulk sample pit at the Filson Creek site. A 33-day laboratory test of the Duluth Complex rock resulted in elevated metals releases in water, with increased releases as the water's oxygen content increased (Eger et al, 1980, pp. 108,110). In the Cu-Ni Study, the Minnesota Department of Natural Resources (MDNR) also expressed concerns over mine pit sidewall leaching (Eger et al, 1980, p. 263).

> **The use of a block model intended to predict the amount of profitable resource to determine concentrations of other parameters does not accurately predict potentially toxic waste rock leachates. This error will compound the inaccuracies resulting from the averaging of the sulfate mineralogy from the humidity testing. Predictions of metal leachate species, volumes, and concentrations in the FEIS are likely to be underestimated. Additional mass balance analysis of non-production metals should be required, particularly for environmental parameters of concern, especially, but not limited to arsenic, mercury, zinc, chlorides, and major ions.**

4. <u>Gaps in Tailings Analysis</u>

In the PolyMet FEIS and supporting documents, no testing of beneficiation processing occurred and no tailings wastes were tested for total leachate chemistry. The lack of this testing leaves gaps in the list of chemical constituents that ultimately are used to predict leachate chemistry.

PolyMet's sulfate leachate predictions ignored the significant contribution of pyrite and pyrrhotite (iron sulfides) that will not be beneficiated, and thus will be deposited in the tailings basin. Over a period of three years, the Minnamax tailings produced sulfate leachates with a maximum concentration of 3,950 mg/l and averaged concentrations of 1,752 mg/l, far higher than the FEIS predictions.

PolyMet's chloride predictions were also extremely low, given the fact that high concentrations of chloride brines are found within the serpentinized ultramafic rocks (e.g., peridotite) of the Duluth Complex. (Dalberg, 1991; Pasteris, 1995). At both the PolyMet and Twin Metals deposits, these serpentinized rocks often contain potentially economic concentrations of the platinum group metals in addition to copper and nickel sulfides (Miller et al, 2002).

PolyMet's FEIS failed to mention that data from the Minnamax (now Teck) deposit showed elevated chlorides during the dewatering and tailings testing processes. Shaft water testing by MDNR demonstrated chlorides in the closed Minnamax shaft ranging from 462 mg/l to 667 mg/l from 1' to 300' deep (MDNR, 1985). Over a period of three years, the Minnamax tailings testing showed that tailings produced chloride leachates with a maximum concentration of 4,690 mg/l and averaged 890 mg/l (MDNR 2004), far higher than the FEIS predictions.

> **The FEIS failed to use bulk sampling beneficiation tailings to predict leachate chemistry and concentrations. The leachate chemistry in the FEIS ignores existing data that suggests PolyMet's leachates will be significantly more chemically concentrated than predicted. In the selection of chemical parameters for tailings leachate sampling and analysis, the FEIS ignored existing tailings leachate data and impacts from the Minnamax (now Teck) deposit that is also located in the Partridge River Intrusion. The PolyMet tailings analysis also failed to use actual waste from the final PolyMet beneficiation process to analyze leachate chemistry. This resulted in a total inability to predict the chemical species and their concentrations that will escape containment and be released into the St. Louis River watershed, wetlands, and Fond Du Lac Reservation waters. As a result, predictions of impacts to these areas cannot be determined, and the 404 Permit must be rescinded.**

5. <u>Gaps in Wastewater Treatment System Evaluation</u>

Wastewater treatment systems must go through laboratory treatment testing to determine the effectiveness of the treatment to meet goals and operate efficiently, as well as determining the chemistry of waste that will be produced. It is critical in the successful design and operation of any treatment system that the volume of waste and the chemicals involved, as well as each of the chemical's concentrations are identified. Once these factors/parameters are identified, a preliminary system design can be made. No such testing has been performed in support of the PolyMet project's wastewater treatment system.

PolyMet's proposed wastewater treatment design cannot be validated due to the following omissions and oversights:

1. Limited testing of waste rock leachates;
2. The inability to prevent elevated sulfide-bearing materials from being included within or added to Category 1 stockpiles;
3. The inability to chemically assess all tailings leachate chemistry and concentrations;
4. The inability to accurately predict the chemicals and concentrations of leachates collected by the hydrometallurgical facility lined lagoon collection system;
5. It is not possible to predict the design success of a wastewater filtration system to meet any of the stated output goals; and
6. It is also not possible to determine chemistry of the reject water such that it can be disposed in compliance with all existing environmental regulations.

> **The proposed wastewater treatment system lacks critical chemical analyses and chemical concentrations, as shown in each of the above sections. Additionally, the lack of relevant inflow chemistry data precludes any realistic prediction of the reject water chemical concentrations. The wastewater treatment system uses a series filtration systems to remove chemical contaminates. These filters become plugged. To unplug the filters clean water is back flushed through the filters. The backflush consisting of all the filtered chemicals and water is called reject water and requires appropriate disposal. The chemical concentrations of waste rock tailings or smelting wastes are not sufficiently known to be able to design a facility to meet the goals. Lagoon leakage chemistry and concentrations cannot be predicted until this information is known. Since complete chemical analyses and the chemical's concentrations and regulatory status remain unknown, impacts of chemicals escaping containment and released into the St. Louis River watershed, wetlands, and Fond Du Lac Reservation waters cannot be determined. As a result, predictions of impacts to these areas cannot be determined, and the 404 Permit must be rescinded.**

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An Evaluation of the Ecological Significance of the

Headwaters Site

Northern Superior Uplands Ecological Land Classification System Section;
Laurentian Uplands Subsection
Lake and St. Louis Counties, Minnesota

Prepared by:
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March, 2007

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SUMMARY

DATE: January 2007 **AUTHORS:** Chel Anderson and Ethan Perry

NAME OF SITE: Headwaters **COUNTY:** St. Louis and Lake

STATEWIDE BIODIVERSITY RANK: Outstanding

ECS REGION: Northern Superior Uplands Section; Laurentian Uplands Subsection (Figure 1)

DNR QUAD CODES (USGS QUADS): H22d, H23c (Babbitt SE, Greenwood Lake West)
H23b (Slate Lake West)

LEGAL DESCRIPTION: T58N R12W Sec 1-4, 9-16, 21
T59N R12W Sec 1, 11-15, 22-28, 33-36
T58N R11W Sec 3-10, 16-18
T59N R11W Sec 4-12, 14-23, 27-34

APPROXIMATE ACREAGE: 38,713

OWNERSHIP: U.S. Forest Service, State of Minnesota, St. Louis and Lake counties, private inholdings (Figure 2; Table 7)

ECOLOGICAL SIGNIFICANCE

Overview

The Headwaters Site straddles the continental divide, with water from the Site flowing both east through the Great Lakes to the Atlantic Ocean and north to the Arctic Ocean. Paradoxically, the divide runs through a peatland. Although the peatland appears flat, water flows out of it from all sides, forming the ultimate source of rivers that eventually reach two different oceans. The Site is the headwaters of four rivers: Stony River, Dunka River, South Branch Partridge River, and the St. Louis River, which is the second largest tributary to Lake Superior (Figure 3 page 83).

The Headwaters Site encompasses vast peatlands on its eastern side, unfragmented upland forests in the west, and broad transition zones between them. Within the Site are two distinct areas, referred to in the document as the "Extensive Peatlands" and the "Big Lake Area," which are linked hydrologically as part of the Upper St. Louis River watershed. The Extensive Peatlands area is a mosaic of open and forested wetland communities and includes forested upland islands and peninsulas. The Big Lake Area, in the southwestern quarter of the Site, includes Big Lake and surrounding unfragmented upland forest interspersed with small wetlands.

The Headwaters Site is unique in northeastern Minnesota in several ways. The size and complexity of the peatlands in the Extensive Peatlands are unmatched in the Northern Superior Uplands Ecological Land Classification System (ECS) Section. The Sand Lake Peatland Scientific and Natural Area (SNA), established by the Wetlands Conservation Act of 1991, protects one of the

15 most significant peatlands in the state, and it is by far the largest SNA in the Section (MN DNR 1984).

The Nature Conservancy's (TNC) Superior Mixed Forest (SMF) Ecoregion Plan identifies the Sand Lake/Seven Beavers (SL7B) conservation area, including the entire Headwaters Site, as one of 51 conservation areas in the Ecoregion[1] that best represent the ecosystems and species of the Ecoregion, and serve as a blueprint for conservation action (The Nature Conservancy and Nature Conservancy Canada 2002). According to the SMF Ecoregion Plan, these conservation areas are the best opportunities for conserving the full diversity of terrestrial and aquatic ecosystems and globally rare or declining species.[2] The SMF Ecoregion Plan identifies these areas as critical places for conserving biodiversity (SMF Plan - Section 7.5) and outlines the threats to conservation and conservation targets for these areas (SMF Plan - Appendix F), recognizing that more detailed site planning is needed to address how to implement conservation efforts (Section 7.5).

The Minnesota Pollution Control Agency has ranked the Upper St. Louis River watershed in the second highest category in the Lake Superior Basin for watershed integrity (Minnesota Pollution Control Agency 2003). The Headwaters Site is among the highest quality areas within the watershed. The upland forest surrounding Big Lake is among the largest, if not the largest, unfragmented, predominantly upland forest in the North Shore Highlands, Toimi Uplands, and Laurentian Uplands (NTL) ECS Subsections. The upland forest area covers 7,920 acres (including 788-acre Big Lake). This high-quality, fire-dependent forest has not been logged in recent decades, except for two stands totaling 140 acres, along the northern edge of the Site.

Covering an area roughly 11 to 12 miles (from northeast to southwest) by 7 to 8 miles (from northwest to southeast), the Headwaters Site is a mosaic of high-quality native plant communities that have functioned under relatively undisturbed conditions since the nineteenth and early twentieth century, when parts of the Site were logged and then burned by wildfires. A corridor containing a railroad grade and power line crosses this vast area, representing the only major permanent conversion of the natural landscape. Minnesota County Biological Survey (MCBS) sites bordering about two-thirds of the Site's boundary have been assigned High or Moderate statewide Biodiversity Significance (Figure 4, page 85). The lack of roads, absence of recent large-scale logging, and large size of the Site allow for natural functioning of ecological processes. These processes include disturbances such as wind, fire, and flooding, as well as plant species competition, nutrient cycling, and hydrology. Natural landscape patterns, such as patch size of the various plant communities, have not been altered, in comparison with most other parts of northeastern Minnesota (White and Host 2003). Minimal recent human disturbance also results in a landscape with very few populations of exotic or invasive species.

The predominant upland forest native plant community in the Big Lake Area is Aspen - Birch Forest [FDn43b], with inclusions of Upland White Cedar Forest [FDn43c] and White Pine - Red

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[1] The SMF Ecoregion is located near Lake Superior and includes portions of Michigan, Wisconsin, Minnesota, Manitoba and Ontario.

[2] The Sand Lake Seven Beavers terrestrial conservation area intersects with the Sand Lake Complex/St. Louis River headwaters and the Upper Cloquet River aquatic conservation areas, identified in the Great Lakes Ecoregion Plan (The Nature Conservancy 2000).

Pine Forest [FDn43a] (Figure 5, page 87)[3]. Isolated wetlands within the Big Lake Area's upland forest support a variety of native plant communities, including Northern Poor Conifer Swamp [APn81], Northern Rich Spruce Swamp (Basin) [FPn62], White Cedar Swamp (FPn63a), Northern Alder Swamp [FPn73a], and Black Ash - Conifer Swamp [WFn64a]. (See Native Plant Communities below for descriptions, and Relevés, Appendix 2, page 61.)

The Extensive Peatlands are composed of a complex of native plant communities, including Northern Cedar Swamp [FPn63]; Northern Rich Spruce Swamp (Basin) [FPn62]; Northern Alder Swamp [FPn73]; Northern Rich Tamarack Swamp (Water Track) [FPn81]; Northern Rich Fen (Water Track) [OPn91]; Northern Rich Fen (Basin) [OPn92]; Northern Shrub Shore Fen [OPn81]; Northern Spruce Bog [APn80]; Northern Poor Conifer Swamp [APn81]; Northern Open Bog [APn90]; and Northern Poor Fen [APn91]. The many upland islands in this portion of the Site provide additional native plant community diversity, supporting community types in the Northern Dry-Mesic Mixed Woodland [FDn33] and White Pine-Red Pine Forest [FDn43] classes (Figure 5). (See Native Plant Communities below for descriptions and Relevés, Appendix 2.) The Headwaters Site supports healthy known populations of eight state-listed plant species, all of which are listed as Special Concern (SPC) in Minnesota: coastal sedge *(Carex exilis)*, Michaux's sedge *(Carex michauxiana)*, English sundew *(Drosera anglica)*, bog rush *(Juncus stygius)*, small green wood orchid *(Platanthera clavellata)*, Lapland buttercup *(Ranunculus lapponicus)*, sooty-colored beak rush *(Rhynchospora fusca)*, pedicelled woolgrass *(Scirpus cyperinus/S. pedicellatus)*, and Torrey's mannagrass *(Puccinellia pallida)* (see Table 3, page 26, and Element Occurrence Records, Appendix 1, page 49). The unfragmented complex of high-quality native plant communities within and across the Site's landforms provide excellent habitat for a wide variety of animal species distinctive of the landscape, including moose, gray wolf, sandhill cranes, American bitterns, boreal and great gray owls, and numerous amphibians, butterflies, and small mammals.

In 2005 and 2006 the Minnesota County Biological Survey of the MN DNR conducted rare plant and native plant community fieldwork, mapped the native plant communities and completed this Ecological Evaluation of the Headwaters Site. Based on the natural features and conditions revealed through this recent work and that of others since the 1980s, MCBS recommends the primary management objective for the Headwaters Site be to protect, enhance, or restore ecological processes and native plant community composition and structure. In accordance with this objective, the site or portions of the site may be identified by landowners or land management agencies for conservation activities such as special vegetation management, including ecologically based silviculture and forest development activities,[4] or for designation as a park (city, county, state, or private), research natural area, non-motorized recreation area, scientific and natural area, or other reserve. This Ecological Evaluation has been written to characterize the ecological significance of the MCBS Site as a whole and to serve as a guide for conservation action by the various landowners.

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[3] The native plant community names and codes used in this document generally refer to the plant community classification presented and described in MN DNR (2003).

[4] Examples of ecologically based silviculture are described in the strategic direction document of the North Shore Highlands, Toimi Uplands, and Laurentian Uplands Subsection Forest Resource Management Plan, which includes management direction, strategies, and goals for vegetation management of state forestlands administered by the Department of Natural Resources, divisions of Forestry, Fish and Wildlife, and Trails and Waterways within the North Shore Highlands, Toimi Uplands, and Laurentian Uplands subsections (MN DNR 2004b).

Geologic Context and Features

The Headwaters Site is within the Laurentian Uplands Subsection of the Northern Superior Uplands Section of the Ecological Classification System (see Figure 1, page 81). ECS Sections are divided into Subsections, which are further divided into Land Type Associations (LTAs).[5] The bedrock of the Site is of Precambrian age (1.6 billion to 600 million years old); Duluth Complex igneous rocks related to the Mid-continent Rift System underlie the Site (Green 1982). The surficial geology (Figure 6, page 89) expressed at the Site is the result of activity of the Rainy and Superior lobes of the Late Wisconsin Glaciation, which ended 10,000 to 12,000 years ago (Ojakangas and Matsch 1982).

Landforms left by these glacial lobes are described by Hobbs and Goebel (1982) and the University of Minnesota-Duluth (1997). The uplands in the western and northern parts of the Site, including the Big Lake Area, are part of end and ground moraines associated with the eastern end of the Big-Bird Lake Moraine LTA and the southern edge of the Isabella Moraine LTA. Rainy Lobe deposits constitute most of these features, but Superior Lobe deposits occur in the far northern part of the Site. The Rainy Lobe till plain, characterized by low topographical relief and many wetlands, is located west and north of Big Lake. Two areas of glacial drift with somewhat more topographic relief are present to the east and northeast of Big Lake (Rainy Lobe) and in the Isabella Moraine LTA (Superior Lobe). Within the Greenwood Lake Till Plain LTA, Rainy Lobe ground moraine fringes the Site's southern boundary and two fingers of Rainy Lobe outwash project into the Site's east-central boundary. Eskers run throughout the Site, generally from southwest to northeast (parallel to flow of the Rainy Lobe), including along the eastern shore of Big Lake. Elevations in the Site range from about 1,630 feet, where the Dunka River leaves the Site, to about 1,760 feet at the top of the esker deposits at the south end of Big Lake.

Outside of the Big Lake Area, the Site's soils are principally peat (Holocene) of the Seven Beavers Peatland LTA. Peat formation likely began at the Headwaters Site 5,000 to 6,000 years ago. Peat depth ranges from 15 to 53+ inches. Within the Extensive Peatlands, movement of water, which is typically imperceptible on the ground, sculpts raised bogs, water tracks, and swamps. Drumlin and esker islands of loamy till, one to fifty-five acres in size, break the peatland's flat to very gently sloping relief.

The U. S. Forest Service has mapped approximately 42% (16,800 acres) of the land within the Headwaters Site to Ecological Land Types (ELT) 1, 2, 5, 6, 7, 9, 13, and 14 and Land Type Phases (LTP) 4, 7, 10A, 10B, 13B, 13C, 16A, 24, 30A, 30B, 30C, 31A, 32, 44A, 44B, 44C, and 47, for which the agency has comprehensive descriptions of landform associations, soil properties, and suitability analyses for a variety of land management and development activities (B. Luelling, pers. comm. 2005). The glacial drift is more than 40 inches and less than 100 feet thick. Typically, mineral soils on ground moraines, end moraines, and till plains are sandy loams over gravelly sandy loam, often with a hardpan below these layers. In areas of outwash, which are less common in the Site, soils are fine sand over sand and gravel. On steep to gently sloping terrain, mineral soils are typically derived from till associated with ridges with convex, concave, or nearly linear slopes. Upland mineral soils are typically of moderate fertility, dry and warm during the growing season, and with a rapid rate of infiltration and permeability. Exceptions are lower concave side slopes transitioning to wetlands, and drainages, where soils are cooler, typically with mesic to wet-mesic conditions.

[5] See MN DNR (2003) or Minnesota DNR website (http://www.dnr.state.mn.us/ecs/212L/index.html) for a description of the Ecological Land Classification System and units (sections and subsections) in Minnesota,

Hydrologic Context and Features

As mentioned above, the Headwaters Site straddles the continental divide, with water from the Site flowing both east through the Great Lakes to the Atlantic Ocean and north to the Arctic Ocean. Paradoxically, the divide runs through a peatland. Although the peatland appears flat, water flows out of it from all sides, forming the ultimate source of rivers that eventually reach two different oceans. The Site is the headwaters of four rivers: Stony River, Dunka River, South Branch Partridge River, and the St. Louis River (Figure 3, page 83). The largest river leaving the Site is the North River, which flows south into Seven Beavers Lake, the source of the St. Louis River. Water from Big Lake flows west into the Partridge River system, which later joins the St. Louis River on its way to Lake Superior. These two sixth-level sub-watersheds constitute the headwaters of the St. Louis River watershed; the St. Louis River is the second largest tributary to Lake Superior. Water from the northwestern part of the peatland flows out the Dunka River to Birch Lake and eventually to the Rainy River and the Arctic Ocean. The northeastern-most part of the Site is also part of the Rainy River drainage, by way of Nip Creek and Sand River to the Stony River, and Birch Lake.

Upper St. Louis River Watershed

The Minnesota Pollution Control Agency has conducted a ranked assessment of the integrity of minor watersheds in Minnesota's portion of the Lake Superior Basin (Minnesota Pollution Control Agency 2003). Ranking was based on condition parameters, including stressors or disturbances within the watershed; and on vulnerability parameters, including values at risk that can be affected by management activities. Overall, the Upper St. Louis River watershed ranked in the second highest of five categories of condition among the minor watersheds in Minnesota's portion of the Lake Superior basin. Although no similar ranking of the Rainy River basin watersheds has been done, the quality of the native plant communities and undeveloped character of the Upper Rainy River minor watersheds within the Headwaters Site suggests a similar condition.

Streams

Within the Headwaters Site, the generally flat landscape and high percentage of lakes and wetlands combine to create an area with relatively few streams. Streams in the area are generally unconfined, sinuous, and have low gradients. Annual low flows typically occur during the winter, from December through March. Annual peak flows can occur anytime between March and November, but most often are associated with snowmelt in early April (Fedora 2005).

Stream flow response to precipitation is highly influenced by water table elevations in the surrounding wetlands. When water tables are high, precipitation moves quickly through the undecomposed surface layers of peat to become streamflow. When water tables are low, rainfall first raises the water table, and little water becomes available for streamflow until the water table is recharged. Generally, low flows in the Site's streams are likely to be lower than in surrounding watersheds except in those streams that intercept regional groundwater tables. The pH of streams in the Site reflects the differing degrees of groundwater influence.

The North River is the major stream of the Headwaters Site. Along with its tributary, Ridgepole Creek, it drains the majority of the Extensive Peatlands into Seven Beavers Lake, following a mostly sinuous, low-gradient channel. For most of its length the width is only a few yards, widening to 30 yards at the mouth (Fedora 2005). The substrate is predominantly silt, with a sand component in places. At low water, mudflats along the shore are extremely soft. Devil crayfish *(Cambarus diogenes)* burrows were observed in these mudflats; this native species appears to be declining in number in parts of its range as a result of insecticide use and a decrease in suitable habitat (Michigan Department of Natural Resources). Inlets along the North River, where channels sometimes drain water into the river, have mud flats with spikerushes *(Eleocharis* spp.), narrow-panicled rush (Juncus brevicaudatus), mare's tail *(Hippuris vulgaris)*, arrowheads (*Sagittaria* spp.), scheuchzeria *(Scheuchzeria palustris)*, buckbean *(Menyanthes trifoliata)*, and even a few spatulate-leaved sundew *(Drosera intermedia)*. The vegetated bank is about 16 inches above normal water level. The floodplain is dominated by extensive open rich fens, primarily Northern Rich Fen [OPn92], sometimes with *Sphagnum* moss and sometimes without. These fens contain a very large population of Michaux's sedge *(Carex michauxiana)*, listed as Special Concern in Minnesota. There are a few small patches of Northern Shrub Shore Fen [OPn81] within the rich fens; these areas have greater cover of sweet gale *(Myrica gale)* and leatherleaf *(Chamaedaphne calyculata)*. A few places along the river also tend toward Sedge Meadow [WMn82b], which has less fen wiregrass sedge *(Carex lasiocarpa)* and more beaked sedge *(Carex utriculata)* and lake sedge *(Carex lacustris)* compared to rich fen communities. (See Native Plant Communities below for more detailed descriptions of these communities.)

The dominant plants growing in the river channel are yellow pond lily *(Nuphar variegata)*, small yellow waterlily *(Nuphar microphylla)*, white waterlily *(Nymphaea odorata)*, and floating bur reed *(Sparganium fluctuans)*. These species never cover extensive areas. There are scattered patches of Torrey's mannagrass *(Puccinellia pallida)*, listed as Special Concern in Minnesota, along the water's edge.

The lower stretch of the North River flows without obstruction, but above Ridgepole Creek the gradient is almost entirely controlled by small beaver dams, which have been built to the top of the channel (Fedora 2005). According to Fedora (2005), historical aerial photos revealed that the pattern of stream meanders remains remarkably unchanged since 1934, despite historical logging and road construction activities. Although no trees currently grow near the banks of the lower North River, there are some dead tree stumps, suggesting that water levels have fluctuated significantly in the past. A 1934 aerial photo shows a higher water level than subsequent photos, which show a stable level that matches current conditions.

Nip Creek is part of the Rainy River watershed. This state-designated trout stream flows northward along the Site's northern boundary from its headwaters in a wetland-and-upland-island complex in the east-central portion of the Site.

Two unnamed creeks, tributaries of the Dunka River (in the Rainy River watershed), flow to the northwest from the Site. One of these originates from a large bog and fen complex and the other originates from the highly heterogeneous mosaic of wetlands and uplands in the northeast corner of the Site. Both have narrow, sinuous, low-gradient channels, with width generally less than 26 feet. Active and abandoned beaver dams and flooding are common. Ponds are also common. Along much of the southern extent of these tributaries there are bands of open, low-shrub and graminoid-dominated vegetation adjacent to the channels. Where observed by MCBS ecologists, the substrate along these tributaries is predominantly silt.

Lakes
Lakes of the Headwaters Site are rich in dissolved minerals, with circumneutral pH as evidenced by water chemistry sampling and abundant presence of aquatic species typical of circumneutral waters, such as wild rice and water lilies. Origin of lake water is unknown, but the most likely sources are groundwater springs and streams where present. These waters have significant influence on adjacent native plant communities, depending on how excess water leaves the lake (see discussion below in Peatlands Hydrology).

Big Lake lies within the upland forest landscape of the western part of the Site. At 788 acres, its maximum depth is 30 feet and it has very little emergent or floating vegetation or wetland fringe compared to nearby large lakes. Almost the entire shoreline is thickly forested. Unlike Seven Beavers Lake, it has no significant tributaries, but it is the source of the South Branch Partridge River. Minnesota Department of Natural Resources (MN DNR) Fisheries mid-summer measurements of the lake between 1979 and 1993 documented a pH range of 7.34–7.8 (J. Geis, pers. comm. 2005). The only shoreline development is a single private cabin set well above the southern shore and accessed by all-terrain vehicle (ATV) or snowmobile, and a boat landing where several boats are stored at the southern tip, which is accessed by an ATV trail across the railroad tracks.

Peatland Lakes
Swamp Lake is a small lake ringed by a 30–100 foot band of Low Shrub Poor Fen [APn91a] vegetation. The fen consists of a mat of *Sphagnum* moss, floating near the water's edge but firm near the surrounding forested peatland. Mounds of *Sphagnum* are covered with the low shrub, leatherleaf. Other species common in the fen include Labrador tea *(Ledum groenlandicum),* small cranberry *(Vaccinium oxycoccos),* scheuchzeria, marsh St. John's wort *(Triadenum fraseri),* pitcher plant *(Sarracenia purpurea),* marsh cinquefoil *(Potentilla palustris),* bog wiregrass, and poor sedge *(Carex paupercula).* There has been recent ATV traffic on federal land along the northwestern shore, which has left deep tracks in the fen vegetation. A single boat was observed, on St. Louis County land, on the southern shore where a trail leads to a county-lease cabin 755 feet away on the closest upland outside the Headwaters Site.

The Extensive Peatlands complex includes eleven lakes, three 10 acres or less in size and the rest ranging from 30 to 160 acres. All the lakes support some floating-leaved aquatic vegetation. Lake-filling—the gradual process of vegetation growing over lakes—has likely already occurred in the Headwaters peatlands, eliminating and effectively masking the past presence of other lakes. Current evidence of this process is found in Bonga, Continental, Ridgepole, and Fools lakes, and to a lesser extent in three unnamed lakes northwest of Lobo Lake, where floating peat mats occur along all or parts of lake edges. Except in the case of Ridgepole Lake, where an open fen mat 30–130 feet wide rings the entire lake, the mats are discontinuous. All of the lakeshore mats support open fen communities [OPn81, APn91], but the shore along Bonga Lake also supports some bands of Cattail - Sedge Marsh [MRn83a].

The absence of a floating peat margin on Culkin Lake, Lobo Lake, and a small-unnamed lake north of Bonga Lake is evidence of strong groundwater discharge to these lakes.

Peatlands Hydrology
Peatlands in the Headwaters Site are nutrient poor, reflecting the amount, source, and movement

of water in the flat to very gently sloping landscape. The peatlands have three sources of water: precipitation, groundwater, and runoff. Bogs, the poorest peatland communities, receive water only from precipitation. Surface water in bogs flows away from or around areas where domes of peat have developed (usually downslope from flow obstructions or over minor drainage divides), limiting pH to less than 4.2. While the water table is often at or near the surface in these areas, significant drawdowns are common. In fens, influence by groundwater or runoff raises surface water pH above 4.2. Underlying substrates and adjacent uplands influence the presence and abundance of mineral-rich groundwater, with direct effects on water chemistry and native plant communities.

In the Extensive Peatlands portion of the Site, run-off from uplands and raised-peat landforms drains down-slope and coalesces into water tracks, which terminate in tributary streams to the North River at the down-slope margin of the peatland. The pH increases to 5.5 or higher in the water tracks, depending on the amount and chemistry of surface run-off and groundwater inputs. The water table is near the surface and stable, with little seasonal variability; both conditions directly affect plant composition of wetland communities in the Extensive Peatlands. Figure 3 (page 83) illustrates the general direction of surface water movement in the peatland complex.

The Site's medium to coarse, loamy upland soils permit rapid infiltration of water from rainfall and snowmelt, which then flows laterally into adjacent peatlands or downward into the groundwater aquifer. Water moving to the peatlands from upland landforms, including islands, accumulates minerals and creates distinctive environmental gradients that are reflected in the vegetation. There are wide gradients of white cedar *(Thuja occidentalis)* ([Northern Cedar Swamp (Northeastern)][FPn63a]) or speckled alder *(Alnus incana)* ([Alder – (Maple – Loosestrife) Swamp] [FPn73a]) where water is moving downslope in the large peatlands. Narrower gradients are present on the upstream side of the peatlands or of islands within it, where there is very little water movement.

The Site's peatland lakes also have significant influence on adjacent vegetation, depending on the water chemistry of the lake and how excess water leaves the lake. In lakes with stream outlets, abrupt environmental gradients often exist between the lake, whose water is rich in minerals and near neutral in pH, and adjacent acid peatland plant communities. On the margins of these lakes this narrow gradient is often occupied by sweet gale. In lakes without stream outlets, excess water tends to move downstream from the lake over a broad area. This mineral-rich water fans out through the peat along some part of the lake edge, supporting rich peatland forest in areas near the lake. With increasing distance from the lake, the mineral content of the water is diluted, the ecological gradient diminishes, and the vegetation becomes dominated by acid peatland communities. The Lobo and Continental lakes areas have good examples of water fans and of abrupt gradients between bogs and swamps (Figure 3, page 83 and Figure 5, page 87).

Historic Vegetation

According to Marschner's map of past vegetation of Minnesota (Marschner, date unknown), vegetation prior to European settlement around Big Lake was dominated by Aspen-Birch (trending to Conifers) with interspersed Conifer Bogs and Swamps. Current vegetation is similar. The northwestern part of the Headwaters Site on the Superior Lobe glacial drift was Jack Pine Barrens and Openings according to Marschner, but Public Land Survey (PLS) line notes

(1873–1894) indicate a dense forest with jack pine *(Pinus banksiana)* as a component. Aspen (Populus tremuloides and P. grandidentata) and birch *(Betula papyrifera)* currently dominate this area. Pines south of Big Lake, as indicated by PLS bearing trees, are no longer present, but north of Big Lake they are still present, along with white cedars. The PLS line notes for the entire area around Big Lake include tamarack *(Larix laricina)* as a component, but this species no longer appears to be present in the uplands.

In the Extensive Peatlands, both Marschner and the PLS line notes describe the presettlement vegetation as principally wetlands of spruce and tamarack with islands of upland forest, and adjacent uplands in the north with mixed white and red pine forests on the Rainy and Superior Lobe drift. A dense understory of beaked hazelnut and balsam fir in the uplands, and alder and cedar in wetlands are also mentioned in the PLS general descriptions. With the possible exception of the loss of tamarack from the upland communities, little about the vegetation has changed in this portion of the Site.

Natural Disturbance History and Forest Development

In the past, fire was the dominant natural disturbance in the forests of the Headwaters Site and fire-scarred stumps are abundant in pine-dominated upland islands in the Extensive Peatlands. In the transitional zone between the uplands around Big Lake and the peatlands to the east, there has been some recent wind damage to mixed stands of aspen, balsam fir *(Abies balsamea),* and black spruce *(Picea mariana).* The damage was not evident on 1997 MN DNR color-infra-red photography of the area, but occurred before 2003 Farm Service Agency photography, possibly part of the wide-ranging blowdown of July 4, 1999. Conditions in these 20–25 patches of blowdown—which are mostly less than one to two acres, with the largest about five acres—provide sites for establishment of long-lived conifers from nearby pine and spruce seed sources. Even within the blowdown areas there are still some standing trees.

Other natural disturbances to forest ecosystems are caused by insects and parasites, such as spruce budworm *(Choristoneura fumiferana)*, larch sawfly (*Pristiphora erichsonii)*, eastern larch beetle *(Dendroctonus simplex),* and dwarf mistletoe *(Arceuthobium pusillum).* Spruce budworm, a moth larva that favors balsam fir, has not had any recent impact on the Headwaters Site. Larch sawfly larvae can defoliate tamaracks. In Minnesota old tamaracks are rare because of huge sawfly outbreaks in the first half of the 1900s (MN DNR Division of Forestry 1997). Since the 1970s, when two species of European wasps that parasitize sawflies were introduced, outbreaks have been small (Seybold et al. 2002, Barzen 2002). Larch beetles, which can kill tamaracks by boring into their phloem, continue to affect tamaracks in Minnesota, but mortality was not observed in the Headwaters Site. Dwarf mistletoe is a parasitic plant that favors black spruce and can cause tree mortality over large areas, but in the Headwaters Site infestations are small. When a canopy of nearly pure black spruce is opened, other tree species, particularly tamarack, often regenerate, along with black spruce stunted by the parasite.

An analysis of Public Land Survey records completed by the MN DNR reports an average rotation of catastrophic fire in Northern Mesic Mixed Forest [FDn43] in northern Minnesota, the predominate forest class of the Headwaters Site, of about 220 years (MN DNR 2003). This forest class includes both white pine *(Pinus strobus)* – red pine *(Pinus resinosa)* forests and aspen – birch forests. The rotation of severe surface fires was about 260 years, resulting in an estimated combined rotation for catastrophic and surface fires of 115 years (J. Almendinger, pers. com. 2006). In a report to the Minnesota Forest Resources Council, Frelich (1999) used information from several studies to estimate a rotation of stand-replacing fire of 150–300 years for white pine–red pine forest and 100–200 years for birch-aspen-spruce-balsam fir forest. White pine–red pine forests had additional surface fires every 40 years on average. Both analyses reported rotations of stand-leveling windthrow of over 1,000 years. Partial windthrow was of course much more frequent.

Native plant communities in the Acid Peatlands and Forested Rich Peatlands Systems dominate the extensive forested peatlands of the Headwaters Site, including Northern Spruce Bogs [APn80], Northern Poor Conifer Swamps [APn81], Northern Rich Spruce Swamps (Basin) [FPn62], and Northern Rich Tamarack Swamp (Water Track) [FPn81]. Bogs and poor swamps have much longer rotations of catastrophic fire than the upland forests (greater than 1,000 years for [APn80] and about 570 years for [APn81]) and shorter surface fire rotations (120 and 90 years, respectively) (MN DNR 2003). The effects of fire on these peatlands are described as ranging from black spruce mortality and maintenance of nearly continuous leatherleaf cover to conversion to open bog, depending on fire intensity (MN DNR 2003). Fire frequency in rich spruce swamps [FPn62] is similar to that in the upland forests (about 220 years), probably because the swamps are often embedded within upland landscapes that determine the overall fire rotation for the area. This may be true in the area around Big Lake, but the rich spruce stands to the east within the extensive peatland probably burned less frequently. Stand-leveling windthrow is uncommon in all three forested peatland types: 700 years for [APn80], 500 years for [APn81], and greater than 1,000 years for [FPn62].

In Carlson's study (2001) of a wildfire in the Border Lakes Subsection, intermixed wet forests and upland forests both burned, but a larger proportion of the wetlands were left unburned. The amount of tree canopy cover left after the fire was variable across the landscape, even within the uplands. In the aspen-birch cover type, very little forest was untouched by fire: roughly 60–70% of the area lost more than 75% of its canopy, and roughly 20–30% of the area lost 6–50%. More than half the white pine – red pine type lost 25–75% of its canopy, while the rest was burned either more severely or less severely. The patch sizes of the severity classes were also variable, averaging about 2.5 acres. This study is only one example of fire effects on forest patterns. Differences in Land Type Associations within the subsection would likely result in different fire behavior. However, these patterns provide a picture of what the upland forest in the Headwaters Site might have looked like after a natural disturbance. Natural disturbance patterns in the Headwaters landscape may also account, in part, for the presence of the transitional communities described below (see Forested Peatland/Upland Transition Complex [FPT_CX], page 24).

In the open peatland communities, environmental conditions, including cycles of inundation and drawdown, are very consistent. Under natural conditions succession is gradual and related to vegetation changes in response to changing water chemistry and quantity rather than catastrophic disturbance. Some natural disturbance occurs at a small scale, for example moose wallows and narrow (less than 20 inches wide) linear tracks of peat disturbance created by moose travel.

Native Plant Communities (see Figure 5, page 87)

The earliest plant community research in the Headwaters Site, conducted between 1978 and

1981, focused on the peatlands as part of the MN DNR's Peat Program (Wright et al. 1992). Field surveys of both upland and wetland native plant communities were conducted by MCBS plant ecologists during the summer of 2005 and a map of plant communities was prepared for the Site in 2006. The various plant communities in the Headwaters Site are principally communities represented in the Fire-Dependent Forest, Forested Rich Peatland, and Acid Peatland systems. Open Rich Peatland System communities cover less area. (More description of systems and the MN DNR's native plant community classification and additional information on community ecology can be found in MN DNR [2003] and on the MN DNR website [http://www.dnr.state.mn.us/npc/index.html].)

The Headwaters Site's native plant communities are typically high quality due to their size (relative to the size at which they occur naturally), condition, and landscape context. They also reflect the range of environmental gradients, ecological conditions, and repeatable patterns of the LTAs. Most of the native plant communities are functioning under relatively undisturbed conditions and provide habitat for rare species. The statewide conservation ranking of the communities in the Site ranges from S2 to S5, and several of those ranked as S3, S4, or S5 appear to be rare or unique in the Laurentian Uplands Subsection (MN DNR 2004a; see also Native Plant Community Ranking and Assessment below for definitions of S-Ranks).

Extensive Peatlands Native Plant Communities

The native plant communities of the Acid and Open Peatland systems that form the extensive patterned peatlands in the northern and eastern part of the Site are unique in the Northern Superior Uplands Section and among the highest quality in the state, with fine examples of many of the characteristic peatland landforms, including forested raised bogs, which in Minnesota are at the southern edge of their continental range (MN DNR 1984). The Acid and Open Peatland communities of the Extensive Peatlands area are interspersed with communities of the Forested Rich Peatland and Wet Meadow/Carr systems, as well as islands of upland mesic mixed forest from the Fire-Dependent Forest/Woodland System.

Big Lake Area Native Plant Communities

In the Big Lake Area, upland fire-dependent communities are dominant, with interspersed peatlands. The communities in this area occur in patches larger on average than those in most of the Laurentian Uplands Subsection. The uplands and peatlands in this area are linked by many examples of distinct transitional vegetation that do not cleanly fit the plant communities in the MN DNR's native plant community classification. A detailed description of these communities is presented below in Forested Peatland/Upland Transition Complex [FPT_CX], on page 24.

Native Plant Community Ranking and Assessment

Minnesota's native plant communities have been evaluated and assigned ranks based on the Natural Heritage Conservation Status Rank (S-Rank) system developed by NatureServe (2002). The resulting community S-Rank is a value (S1 to S5) assigned to a native plant community type (or subtype) that best characterizes the relative rarity or endangerment of high-quality examples of the community statewide. These ranks are defined in the table below and appear with the community descriptions in the text.

Table 1. Statewide Natural Heritage Conservation Ranks (S-Ranks) for Native Plant Community (NPC)Types (MN DNR 2004a)

NPC Type S-Rank	Definition
S1	Critically imperiled.
S2	Imperiled.
S3	Rare or uncommon.
S4	Widespread, abundant, and apparently secure, but with cause for long-term concern.
S5	Demonstrably widespread, abundant, and secure.

Native Plant Community Descriptions

In the community classification described in the MN DNR's Field Guide to the Native Plant Communities of Minnesota: The Laurentian Mixed Forest Province (MN DNR 2003), vegetation types are arranged hierarchically within Systems. Plant community classes (such as [FDn43]) are divided into types (such as [FDn43a], [FDn43b], and [FDn43c]), and types are often divided into subtypes (such as [FDn43b1] and [FDn43b2]). Descriptions for each of the native plant community and community complex map units used in Figure 5 are found in this section under a brief description of the associated System. See the Field Guide to the Native Plant Communities of Minnesota: The Laurentian Mixed Forest Province (MN DNR 2003) for further information concerning the System level of the classification.

<u>Fire-Dependent Forest/Woodland System</u>

Fire-Dependent Forest/Woodland communities are dominated by species adapted to survive repeated fires and regenerate successfully after fires. Evergreens are prevalent, most visibly pines and other conifers. These communities are strongly influenced by fires that periodically remove the litter, duff, and organic material, and that can have significant effect on nutrient cycling and availability. In the Laurentian Mixed Forest Province, fire-dependent communities occur on well-drained or thin soils over bedrock. The random behavior of wildfires causes nutrient availability in these communities to be episodic and unpredictable. Prior to fire suppression, because the rotation period for surface fires was equal to or longer than that for stand-regenerating fires, Northern Fire-Dependent [FDn] communities in this system tended to become multi-aged as they matured, with fairly constant recruitment of shade-tolerant species.

Northern Mesic Mixed Forest Class [FDn43] 5689 Acres

In the Headwaters the canopies of mesic forests are most often mixed, but range from solely coniferous to solely deciduous. White, red, and jack pine, aspen, paper birch, white cedar, white spruce *(Picea glauca),* black spruce, and balsam fir are all important canopy species. Within the Site this community occurs in landscape settings ranging from small isolated islands within the Extensive Peatlands (often remnant eskers), to large patches on morainal landforms, particularly in the upland-dominated Big Lake Area. The shrub layer is dominated by deciduous species and variable in cover. Beaked hazelnut *(Corylus cornuta),* bush honeysuckle *(Diervilla Lonicera),* and mountain maple *(Acer spicatum)* are common shrubs. In the patchy to continuous cover of ground-layer plants, Canada mayflower *(Maianthemum canadense),* bunchberry *(Cornus canadensis),* wild sarsaparilla *(Aralia nudicaulis),* bluebead lily *(Clintonia borealis),* and large-leaved aster *(Aster macrophyllus)* are common. Mosses and lichens are common on exposed rock, tree boles, and coarse woody debris.

White Pine – Red Pine Forest [FDn43a] S2/ 1128 Acres
Pine forests occur as inclusions within the Headwaters Site's widespread [FDn43b1] forests (described below) and are prevalent on islands within the Extensive Peatlands, including eskers. Some stands have nearly pure canopies of red pine or jack pine, while others are dominated by white pine or a mix of species. Many pines are in the 14–18 inch diameter-at-breast-height (dbh) range, and old charred snags are common on some islands. Some stands have an open understory; others have thick stands of young balsam fir, or a dense understory of tall shrubs (e.g., mountain maple and beaked hazelnut). Ground-layer vegetation is similar to that in [FDn43b1], but is often sparser and sometimes includes species of drier environments, such as bush juniper *(Juniperus communis),* snowberry *(Symphoricarpos albus),* and pipsissewa *(Chimaphila umbellata).*

Old-growth white pine and red pine stands in T59N R12W, SW¼ Section 13 have been designated as old-growth by the state, or evaluated for old-growth qualities by the U.S. Forest Service. The adjacent forest in Section 14 is of similar composition, and although some cutting is evident on 1948 aerial photos, it retains some old-growth qualities. In the two sections, old pine forest totals about 112 acres. Additionally, one high-quality twenty-five acre stand in the U.S. Forest Service candidate Research Natural Area (T58N R12W, S½ Section 12) is dominated by white pines averaging 14–16 inches dbh (one pine near this stand measured 37 inches dbh), mixed with 10–12 inch dbh black spruce (of the same height as the pines) and a few white cedars. U.S. Forest Service inventory data estimate the stand origin year as 1896, but selective cutting is apparent on 1948 aerial photos. Natural origin mesic pine communities dominated by white, red, or jack pine also occur on peatland islands in T59N R12 Sections 13 and 24 and T59N R11W, Sections 7, 8, 9, 10, 18, and 19 (some designated old growth).

In the Big Lake Area ecologists have visited two small pine stands. One 3-acre stand is predominantly red pine averaging 16 inches dbh mixed with birch, aspen, and balsam fir (T59N R12W, SW¼ SW¼ Section 35). The other, observed by Puchalski (1995) in T59N R12W, SE¼ Section 28 and NE¼ Section 33, is dominated by large white pines, some over 30 inches. Puchalski noted significant white pine seedling regeneration in the area. In addition, a jack pine dominated stand was observed in T59N R12W SE¼ Section 28 during a 2005 helicopter overflight.

Aspen – Birch Forest Balsam Fir Subtype [FDn43b1] S4/ 2031 Acres
The predominant upland forests at the Site are mixed hardwood and conifer forests [FDn43b1] with a variable conifer component, mostly spruces and balsam fir, with conifer abundance typically increasing near peatland communities. In the Big Lake Area black spruce is more abundant than white spruce. According to 1998 MN DNR timber appraisal reports for T59N R12W Section 36, black spruce makes up 75–80% of all spruce trees. These forests are generally even-aged with trees averaging 12 inches dbh and with some (especially aspen) up to 18 inches dbh. There have been some recent blowdowns up to 5 acres in size near the upland-peatland transition east of Big Lake. In the northwestern part of the Site jack pine is a minor component of this forest community. Red maple *(Acer rubrum)* is also a significant component.

The understory of [FDn43b1] is typical of the community type [FDn43b], and includes beaked hazelnut, mountain maple, fly honeysuckle *(Lonicera canadensis),* dwarf raspberry *(Rubus* *pubescens)*, large-leaved aster, bluebead lily, bunchberry, Canada mayflower, wild sarsaparilla, starflower *(Trientalis borealis)*, rose twisted stalk *(Streptopus lanceolatus)*, woodland horsetail *(Equisetum sylvaticum)*, sweet-scented bedstraw *(Galium triflorum)*, lady fern *(Athyrium filix-femina)*, spinulose shield fern *(Dryopteris carthusiana)*, common oak fern *(Gymnocarpium dryopteris)*, shining firmoss *(Huperzia lucidula)*, round-branched groundpine *(Lycopodium dendroideum)*, pointed woodrush *(Luzula acuminata)*, mountain rice grass *(Oryzopsis asperifolia)*, false melic grass *(Schizachne purpurascens)*, long-stalked sedge *(Carex pedunculata)*, and drooping wood sedge *(Carex arctata)*.

Some small areas in low spots have wetter soil than the dominant forest. These areas often hold temporary puddles, or seasonal pools, but the vegetation only occasionally includes wetland indicators, such as black ash *(Fraxinus nigra)*. The tree canopy is often open.

Upland White Cedar Forest [FDn43c] S3/ 816 Acres
Upland White Cedar Forests have been documented at several places in the Site. The MN DNR has a 31-acre designated old-growth upland cedar stand in T59N R11W, SW¼ NW¼ Section 20. In his survey for the U.S. Forest Service, Puchalski (1995) observed upland cedar forest in T58N R12W, NW¼ SE¼ Section 10, and T59N R12W, N½ SE¼ Section 27, and noted sugar maple *(Acer saccharum)* as a canopy component. [Note: Puchalski also mentioned an area of young sugar maple forest in T59N R12W, NW¼ NW¼ Section 36. These maple trees are not readily differentiated from the surrounding forest on color infrared aerial photos, but they indicate the possibility of a small patch of mesic hardwood forest, such as [MHn35 (S3) or MHn45b (S2).] A large block of upland white cedar occurs in the central area of the Site north of the railroad tracks, associated with a large area of uplands of low relief within the Extensive Peatland. During an overflight in 2005, significant areas of white cedar were observed in T59N R12W Sections 27, 33, and 34. There is also upland cedar along the northeastern shore of Big Lake, where patches of Canada yew *(Taxus canadensis)* were observed in 2005. White cedar was also often observed as a canopy species component of other [FDn43] forest types within the Site, such as [FDn43a and FDn43b1]. In general, the understory of upland cedar forest is sparse, but includes the species listed above for [FDn43b1] and often also has mesic species like naked miterwort *(Mitella nuda)* and goldthread *(Coptis trifolia)*.

Wet Forest System

Wet Forest communities in the Headwaters Site occur along riparian corridors or in shallow basins where there is a steady supply of groundwater, but which does not inundate the mineral soil for long periods of the growing season. Variations in microtopography and groundwater supply are essential to sustaining these communities.

Lowland White Cedar Forest [WFn53a] S3/ 53 Acres
Occurring in only a few small patches in the area north of Big Lake, wet cedar forests are similar to black ash-conifer swamps [WFn64a], but with greater canopy cover of white cedars and often with greater moss ground cover. The community grows on shallow peat or mineral muck. Ecologists visited only two patches (at the northeast end of Big Lake) during MCBS surveying. The others were classified by aerial photography interpretation, so they may actually be northern cedar swamps [FPn63a], which also has a cedar-dominated canopy. Classification was based on the presence of black ash in the canopy or proximity to rich wetland types. In addition

to the species of [WFn64a], wet cedar forests often contain twinflower, creeping snowberry *(Gaultheria hispidula)*, and long-stalked sedge.

Northern Wet Ash Swamp Class [WFn55] 20 Acres
A handful of examples of Northern Wet Ash Swamps have been mapped in the Headwaters Site based on aerial photography interpretation. Ecologists visited none of them during MCBS surveying. This community is richer and drier than Black Ash - Conifer Swamp [WFn64a]. It occurs adjacent to beaver-influenced wetlands (and Big Lake) where groundwater is richer in nutrients than in most of the Site.

Black Ash – Conifer Swamp [WFn64a] S4/ 77 Acres
Although not a common community type in the Site, there are small isolated depressions of Black Ash – Conifer Swamp within upland regions. Strongly influenced by groundwater, the community is the richest in nutrients of all the forested wetland types in the Site. Black ash is the dominant tree species (sometimes with cedar or tamarack) and there is often a dense shrub layer of mountain maple, speckled alder, swamp red currant *(Ribes triste),* and swamp gooseberry *(Ribes hirtellum),* among others. The forb layer is very diverse, including dwarf raspberry, naked miterwort, alpine enchanter's nightshade *(Circaea alpina)*, goldthread, woodland horsetail, three-leaved false Solomon's seal *(Smilacina trifolia)*, lady fern, spinulose shield fern, sensitive fern *(Onoclea sensibilis),* common oak fern, rough bedstraw *(Galium asprellum),* sweet-scented bedstraw, northern bugleweed *(Lycopus uniflorus)*, mad dog skullcap *(Scutellaria lateriflora),* willow-herbs *(Epilobium* spp.), marsh marigold *(Caltha palustris),* spotted Joe pye weed *(Eupatorium maculatum)*, flat-topped aster *(Aster umbellatus)*, red-stemmed aster *(Aster puniceus),* tall Northern bog orchid *(Platanthera hyperborea)*, and swamp thistle *(Cirsium muticum).* Common graminoids include fowl manna grass *(Glyceria striata)*, Canada blue-joint *(Calamagrostis canadensis),* drooping woodreed *(Cinna latifolia)*, graceful sedge *(Carex gracillima)*, bladder sedge *(Carex intumescens)*, bristle-stalked sedge (*Carex leptalea),* soft-leaved sedge *(Carex disperma),* and brownish sedge *(Carex brunnescens).*

Forested Rich Peatland System

Forested Rich Peatland communities within the Headwaters Site occur on deep (>15 inches) peat. They derive the majority of their water from mineral-rich groundwater and have surface-water pH of 5.5 to 7.5. In these rich peatlands, stagnant groundwater tables are typically below the peat surface, especially during the summer. During periods of high water-table levels, pools often form at the surface in hollows that are common among the hummocks around trees bases.

Rich Spruce Swamp (Basin) [FPn62a] S3/ 4234 Acres
Rich Spruce Swamp is a common peatland type in the Site. The community occurs as a component of the Extensive Peatlands in the east and in isolated depressions within the Big Lake Area uplands. The largest expanses are in the southern part of the Site, on either side of the North River corridor. This area was clearcut in the 1940s, so is now nearly pure, even-aged black spruce about 60–70 years old and averaging about 6 inches dbh. Tamarack was probably a larger component in the past. There are open patches of dwarf mistletoe *(Arceuthobium pusillum)* damage, but these are not extensive. In general, the tree canopy is very dense, the shrub layer sparse, and there is a continuous mat of *Sphagnum* and other mosses. Common shrubs are speckled alder, Labrador tea, leatherleaf, willows, and bog laurel *(Kalmia polifolia).* Ground-

layer species include creeping snowberry, small cranberry, three-leaved false Solomon's seal, twinflower, woodland horsetail, bunchberry, bluebead lily, starflower, dwarf raspberry, bristly clubmoss, three-seeded bog sedge *(Carex trisperma),* and occasional northern comandra *(Geocaulon lividum).*

One species of Special Concern was observed in this community type, Lapland buttercup.

Northern Cedar Swamp Northeast [FPn63a] S4/ 1802 Acres
Cedar swamps are common as patches within the uplands around Big Lake and near the edges of the Extensive Peatlands farther east. The largest examples are near the railroad track along the western edge of the Headwaters Site and at the northeast end of Big Lake. This community is richer than other peatland types, such as Rich Spruce Swamp [FPn62], but poorer than Black Ash - Conifer Swamps [WFn64]. It develops on shallow to deep peat.

Balsam fir and black spruce often join white cedar in the tree canopy. Pools are common, and a continuous carpet of mosses, especially *Sphagnum* mosses, covers most of the rest of the ground. The shrub layer is variable, often including speckled alder, red-osier dogwood *(Cornus sericea),* dwarf alder *(Rhamnus alnifolia),* Labrador tea, fly honeysuckle, and swamp fly honeysuckle *(Lonicera oblongifolia).* The ground-layer vegetation includes dwarf raspberry, twinflower *(Linnaea borealis),* creeping snowberry, goldthread, naked miterwort, starflower, bunchberry, bluebead lily, wild sarsaparilla, red-stemmed aster, northern bugleweed, three-leaved false Solomon's seal, woodland horsetail, crested fern *(Dryopteris cristata),* spinulose shield fern, cinnamon fern *(Osmunda cinnamomea),* long beech fern *(Phegopteris connectilis),* common oak fern, lesser rattlesnake plantain *(Goodyera repens),* bristly clubmoss *(Lycopodium annotinum),* shining firmoss, small northern bog orchid *(Platanthera obtusata),* and heart-leaved twayblade *(Listera cordata).* Graminoids include bluejoint, bladder sedge, soft-leaved sedge, bristle-stalked sedge, three-seeded bog sedge, and graceful sedge.

Lapland buttercup *(Ranunculus lapponicus),* a species listed as Special Concern, was observed in the Site's rich spruce swamp, but it is actually more typical of cedar swamps and likely occurs in them.

Alder Swamp [FPn73a] S5/ 106 Acres
Alder Swamp is not extensive in the Site, but patches are interspersed with other peatland types. Some alder swamps are not peatlands and do not have a layer of *Sphagnum* moss, but these are rare in the area. Only one tiny example was observed in the Site, at the northern tip of Big Lake. Most alder swamps grow on peat with hummocks of *Sphagnum*. Although there are often stunted balsam fir, white cedar, and black spruce in the community type, they constitute <25% canopy cover, while shrubs are the dominant vegetation, including speckled alder, willows *(Salix* spp.), red-osier dogwood, Labrador tea, bog birch *(Betula pumila),* red raspberry *(Rubus idaeus),* and various gooseberries and currants *(Ribes* spp.). Ground-layer vegetation includes dwarf raspberry, goldthread, spotted touch-me-not *(Impatiens capensis),* northern bugleweed, tufted loosestrife *(Lysimachia thyrsiflora),* three-leaved false Solomon's seal, wild calla *(Calla palustris),* northern blue flag *(Iris versicolor),* red-stemmed aster, flat-topped aster, bog goldenrod *(Solidago uliginosa),* spotted Joe pye weed, tall northern bog orchid, crested fern, spinulose shield fern, Canada mayflower, and bunchberry. Graminoids include bluejoint,

fowl manna grass, soft-leaved sedge, bristle-stalked sedge, three-seeded bog sedge, silvery sedge *(Carex canescens)*, and sometimes lake sedge.

Northern Rich Tamarack Swamp Class (Water Track) [FPn81] 363 Acres
Northern Rich Tamarack Swamp is a part of the Extensive Peatlands complex in landscape settings of deep peat, influenced by lateral flow of groundwater in water tracks originating from two of the peatlands lakes. Surface pH is >5.5. Feather and *Sphagnum* mosses typically have greater than 50% cover, and hummocks and water-filled hollows are common. Cover of forbs, grasses and sedges is sparse but diverse, including marsh cinquefoil, pitcher plant, three-leaved false Solomon's seal, soft-leaved sedge, bristle-stalked sedge and poor sedge. The cover of shrubs varies, relying on hummocks that rise above the water table for suitable habitat. Dominant low shrubs are ericaceous species such as Labrador tea, small cranberry, leatherleaf, and bog rosemary *(Andromeda glaucophylla)*. Dominant tall shrubs are usually bog birch and willows. In the Headwaters, tamarack, along with scattered black spruce and white cedar, comprise the patchy canopy.

Rich Tamarack – (Alder) Swamp [FPn82a] S5/ 2430 Acres
Rich Tamarack – (Alder) Swamp occurs as part of the Extensive Peatlands complex and embedded within fire-dependent communities in the Big Lake area. Feather and *Sphagnum* mosses typically have > 50% cover, and hummocks and water-filled hollows are common. Mixed with the tamarack are white cedar, black spruce, and balsam fir trees, forming an interrupted canopy. The shrub layer is often very dense and diverse, including speckled alder, willows, bog birch, Labrador tea, red-osier dogwood, swamp fly honeysuckle, winterberry *(Ilex verticillata)*, dwarf alder, gooseberries and currants, and red raspberry. Cover of forbs, grasses and sedges is variable. Ground-layer species include small cranberry, bog rosemary *(Andromeda glaucophylla)*, dwarf raspberry, goldthread, bunchberry, bluebead lily, woodland horsetail, field horsetail *(Equisetum arvense)*, three-leaved false Solomon's seal, red-stemmed aster, northern blue flag, buckbean, cinnamon fern, and crested fern.

Open Rich Peatland System

Open Rich Peatland communities within the Headwaters Site occur on deep (>15 inches) peat. They derive the majority of their water from mineral-rich groundwater and have surface-water pH of 5.5 to 7.5. Shore fens along the margins of ponds and lakes are influenced also by pond or lake water, and shore fens in laggs are influenced also by run-off from adjacent uplands. In all of these locations, inundation is also often a regular occurrence. Open rich fen water tracks are highly influenced by groundwater, which creates surface flow poor in nutrients, but rich enough in minerals to maintain a pH >5.5. The water supply and level is typically stable near the peat surface, with little seasonal variability (Boelter and Verry 1977; MN DNR 2003).

Northern Shrub Shore Fen Class [OPn81] 12 Acres
Shrub shore fen communities within the Site are typically of small extent and narrow, occurring on floating mats of peat at the margins of peatland lakes, ponds, and streams, or in laggs at the edges of peatlands. Moss cover is usually high and dominated by *Sphagnum*. Cover of ericaceous shrubs is usually high. Cover of grasses is variable and that of forbs and trees is sparse. These communities are influenced by circumneutral water from an adjacent water body, or by runoff from adjacent uplands, which maintains a pH of >5.5. Plants in these communities are adapted to low nutrients and periodic flooding.

Bog Birch – Alder Shore Fen [OPn81a] S5/ 114 Acres

Bog Birch – Alder Shore Fen [OPn81a] occurs in the Headwaters Site in lagg zones at the edges of peatlands, including along the edges of islands within the peatlands. The shrubs bog birch and speckled alder are typically dense, mosses are patchy, and forbs and grasses have little presence. This community also occurs along low-gradient streams, especially tributaries to the North River. These occurrences are mapped as part of the Shrub Shore Fen/Low Gradient Stream Complex [SFS_CX] described below.

Leatherleaf – Sweet Gale Shore Fen [OPn81b] S-5

Leatherleaf – Sweet Gale Shore Fen [OPn81b] occurs along low-gradient streams, especially tributaries to the North River. These occurrences are mapped as part of the Shrub Shore Fen/ Low Gradient Stream Complex [SFS_CX] described below. Leatherleaf – Sweet Gale Shore Fen also occurs on floating mats too narrow to map along the edges of lakes and ponds. In this community, mosses, especially *Sphagnum*, carpet the surface, and shrubs such as sweet gale and leatherleaf are common. Tamarack and black spruce are sparse, and stunted when present. Grasses and forbs are not prominent, but beaked sedge, lake sedge, fen wiregrass sedge, blue-joint, and tussock sedge were commonly observed.

Shrub Rich Fen (Water Track) [OPn91a] S5/ 65 Acres

Shrub Rich Fens at the Site have up to 75% cover of bog birch over a continuous, saturated *Sphagnum* carpet. Occasional low hummocks commonly support fen wiregrass sedge and three-leaved false Solomon's seal, and less often leatherleaf, Labrador tea, stunted tamarack, and black spruce. Small patches of buckbean are common. The community is present over large areas of the featureless water tracks in the northern half of the site.

Graminoid Rich Fen (Water Track) [OPn91b] S4/ 104 Acres

Graminoid Rich Fen (Water Track) is part of the open peatland mosaic. In the Headwaters Site it is characterized by wet lawns of fine-leaved sedges such as fen wiregrass sedge, lead-colored sedge *(Carex livida)*, lantern sedge *(Carex limosa)*, coastal sedge *(Carex exilis)*(listed as Special Concern in Minnesota), and tufted bulrush (Scirpus cespitosus), with occasional subtle hollows dominated by brown mosses and peat-bottomed pools. These pools, oriented perpendicular to groundwater flow, harbor characteristic aquatic species such as lesser bladderwort *(Utricularia minor),* seaside arrow grass *(Triglochin maritima),* and lead-colored sedge. Shrubs such as bog rosemary, leatherleaf, small cranberry, bog birch, and sweet gale are often perched on drier hummocks that sometimes punctuate the graminoid lawns, but have <25% cover. Scattered tamaracks and white cedar less than 20 inches tall also grow on these mounds. Forbs commonly observed in this community include pitcher plant, round-leaved sundew *(Drosera rotundifolia),* northern white violet *(Viola macloskeyi),* water horsetail *(Equisetum fluviatile),* rose pogonia *(Pogonia ophioglossoides),* and bog goldenrod.

Graminoid Rich Fen (Basin) [OPn92a] S4/ 34 Acres

Communities in this class are open rich fens that appear to be transitional between Northern Rich Fen (Water Track) and Northern Wet Meadow/Carr communities. Both types in the class, Graminoid Rich Fen [OPn92a] and Graminoid – Sphagnum Rich Fen [OPn92b] are present in the Site and often intermingle with each other. They are found primarily along the North River, where they grow in floodplain soil saturated by a moderately fluctuating water table associated with the river. In Graminoid Rich Fen (Basin) communities the cover of *Sphagnum* is typically < 25%. Common graminoids include fen wiregrass sedge, beaked sedge, bluejoint, rattlesnake grass *(Glyceria canadensis)*, cottongrasses *(Eriophorum* spp.), white beak rush *(Rhynchospora alba)*, three-way sedge *(Dulichium arundinaceum)*, and winter bentgrass *(Agrostis scabra)*. Michaux's sedge, a species of Special Concern, is also common along the North River and is actually a dominant species in some areas. Another species of Special Concern, pedicelled woolgrass, is also documented from the river shore. Other species in the community include water horsetail, pitcher plant, round-leaved sundew, marsh cinquefoil, bog aster *(Aster borealis)*, marsh St. John's wort, northern bugleweed, marsh bellflower *(Campanula aparinoides)*, tufted loosestrife, willow herbs, northern marsh fern *(Thelypteris palustris)*, and northern blue flag. Scattered, stunted tamaracks are common.

Graminoid – Sphagnum Rich Fen (Basin) [OPn92b] S4/ 47 Acres
Communities in this class are open rich fens that appear to be transitional between Northern Rich Fen (Watertrack) and Northern Wet Meadow/Carr communities. Both types in the class, Graminoid Rich Fen [OPn92a] and Graminoid – Sphagnum Rich Fen [OPn92b] are present in the Site and often intermingle with each other. They are found primarily along the North River, where they grow in floodplain soil saturated by a moderately fluctuating water table associated with the river. The cover of *Sphagnum* in Graminoid – Sphagnum Rich Fen (Basin) communities is > 50%. These fens have modest amounts of sweet gale, bog willow *(Salix pedicellaris)*, and leatherleaf. Common graminoids include fen wiregrass sedge, beaked sedge, bluejoint, rattlesnake grass *(Glyceria canadensis)*, cottongrasses *(Eriophorum* spp.), white beak rush *(Rhynchospora alba)*, three-way sedge *(Dulichium arundinaceum)*, and winter bentgrass *(Agrostis scabra)*. Other species in the community include small cranberry, bog rosemary, water horsetail, pitcher plant, round-leaved sundew, marsh cinquefoil, bog goldenrod, bog aster *(Aster borealis)*, marsh St. John's wort, northern bugleweed, marsh bellflower *(Campanula aparinoides)*, tufted loosestrife, northern marsh fern *(Thelypteris palustris)*, and northern blue flag. Scattered, stunted tamaracks are common.

Acid Peatland System

Raised acid peatlands such as open bogs [APn90] and semi-treed bogs [APn80] occupy large areas of the Headwaters Site's extensive peatland area. They occur on deep (>15 inches) peat and are dependent on precipitation because the *Sphagnum* substrate elevates the community above the flood level of runoff from surrounding uplands and groundwater cannot move through the dense accumulation of peat. As a consequence, water flows away from or around the peat surface, limiting additions of nutrients and minerals. *Sphagnum*-induced chemical changes in the stagnant surface water lowers pH values of these acidic peatlands communities to <4.2. The water table is usually near the surface, but large drawdowns of the water table are common. Poor conifer swamp communities [APn81] are typically transitional between bogs and fens, rich swamps, or uplands. Their surface pH lies between 4.2 and 5.5 as they receive some minerotrophic ground or surface water. These communities experience some water-table fluctuations, but not as severe as the raised bogs. Bogs and poor conifer swamps in the Site are usually dominated by black spruce, which has suffered some mortality from dwarf mistletoe, but not extensive damage. Poor fens [APn91] have developed on the fringes of some of the raised bogs, in characteristic water tracks with a higher, but still acidic pH of up to 5.5. In some instances, these water tracks gradually transition into rich fens.

Black Spruce Bog [APn80a] S5/ 2108 Acres
Portions of the Headwaters site mapped as Black Spruce Bog include areas where the [APn80a1] and [APn80a2] subtypes are intermingled and not readily mapped as separate entities, and areas where the canopy cover does not clearly indicate one or the other of the subtypes. The structure and composition of the areas mapped as [APn80a] are similar to those of the subtypes described below.

Black Spruce Bog (Treed Subtype) [APn80a1] S5/ 1307 Acres
The Treed Subtype of Black Spruce Bog is prominent in the patterned peatlands of the Headwaters Site, particularly north of the railroad tracks in T59N R11W Sections 15 and 22. Here, the community is present on linear crests where it is readily discernible in aerial photos and from the ground as a radiating linear pattern of black spruce following the subtly sloping concave sides. On upper portions of the bog crests, shading cover of black spruce provides habitat for shade-tolerant species such as velvet-leaved blueberry *(Vaccinium myrtilloides)*, Indian pipe *(Monotropa uniflora)*, and heart-leaved twayblade. Other occurrences of [APn80a1] lacking the pattern of linear treed crests are present throughout the large peatland complex. High, well-developed hummocks of *Sphagnum* and mats of *Pleurozium* moss are typical in these communities, supporting Labrador tea, leatherleaf, creeping snowberry, small cranberry, three-seeded bog sedge, and few-fruited sedge *(Carex pauciflora)*.

Black Spruce Bog (Semi-Treed Subtype) [APn80a2] S5/ 740 Acres
The Semi-Treed Subtype of Black Spruce Bog occurs in patterned peatlands at the bases of bog crests and near the tops of drains, where the water table is high enough to limit tree cover to scattered, stunted black spruce. More tamarack, few-fruited sedge, pitcher plant, and tussock cottongrass *(Eriophorum vaginatum)* are present in this community than in [APn80a1], in response to sparser tree cover of black spruce and higher light conditions. High, well-developed hummocks of *Sphagnum* and mats of *Pleurozium* moss are typical in these communities, supporting Labrador tea, leatherleaf, creeping snowberry, small cranberry, and three-seeded bog sedge.

Northern Poor Conifer Swamp Class [APn81]/ 1294 Acres
Poor Conifer Swamps occur throughout the Headwaters site. Moss cover is continuous and dominated by *Sphagnum* species. Low hummocks and hollows are common. Forbs are sparse, and graminoid cover is < 25%, with fine-leaved species being the most important. Ericaceous species dominate the low shrub layer, and the tall shrub layer typically includes minerotrophic indicators such as bog birch, speckled alder, and willows. The patchy canopy is dominated by stunted black spruce or tamarack. Species diversity is relatively low, but includes minerotrophic indicators.

Poor Black Spruce Swamp [APn81a] S4/ 471 Acres
Poor Black Spruce Swamp occurs in the Headwaters Site in small patches (relative to the other peatland communities), typically in transitional settings between bogs and richer peatland community types or uplands. Cover of stunted black spruce is greater than 50% and occasionally the community has a tall, closed-canopy structure. The ericaceous shrubs Labrador tea and leatherleaf dominate the low shrub layer, which also includes cranberries *(Vaccinium macrocarpon* or *V. oxycoccos)*, velvet-leaved blueberry, bog rosemary, creeping snowberry, and bog

laurel. Tall shrubs like speckled alder, willow, and bog birch are occasional. Low hummocks and shallow hollows support a moderate sedge cover including three-fruited bog sedge and creeping sedge, and a sparse forb cover including three-leaved false Solomon's seal, pitcher plant, buckbean, marsh cinquefoil, Pyrola species, round-leaved sundew, and tall white bog orchid *(Platanthera dilatata).*

Poor Tamarack – Black Spruce Swamp (APn81b) S4/ 1641 Acres
Poor Tamarack – Black Spruce Swamp occurs in the Headwaters Site in small patches (relative to the other peatland communities), typically in transitional settings similar to those of poor black spruce swamp, although slightly wetter. Tree cover ranges from 25% to 50% and consists of stunted black spruce with occasional tamarack or vise versa. The ericaceous shrubs Labrador tea and leatherleaf dominate the low shrub layer, which also includes cranberries, velvet-leaved blueberry, bog rosemary, creeping snowberry, and bog laurel. Tall shrubs such as speckled alder, willow, and bog birch are occasional. Low hummocks and shallow hollows support a moderate sedge cover including three-fruited bog sedge and creeping sedge, and a sparse forb cover including three-leaved false Solomon's seal, pitcher plant, buckbean, marsh cinquefoil, Pyrola species, round-leaved sundew, and tall white bog orchid.

Poor Tamarack – Black Spruce Swamp (Black Spruce Subtype) [APn81b1] S4/ 193 Acres
In this subtype, black spruce dominates the canopy with the occasional tamarack. Round-leaved sundew, few-fruited sedge, and buckbean are more often associated with this subtype than with [APn81b2].

Poor Tamarack – Black Spruce Swamp (Tamarack Subtype) [APn81b2] S4/ 159 Acres
Dominated by tamarack and typically with black spruce, this subtype has a slightly more open canopy than APn81b1. Lowbush blueberry *(Vaccinium angustifolium)* is found in the understory, and leatherleaf and bog rosemary are more abundant than in APn81b1.

Northern Open Bog Class [APn90] 239 Acres
Northern Open Bog is present in the Headwaters Site on the sides of raised bog crests, at the upper ends of water tracks, and in the interiors of basins isolated or peripheral to the large patterned peatland. The peat surface is elevated and isolated from groundwater, with a pH of <4.2. Saturation and fast growth of *Sphagnum* severely limit black spruce and tamarack growth. Microtopography is often pronounced, with deep hollows, low *Sphagnum* carpets, and well-developed hummocks.

Low Shrub Bog [APn90a] S5/ 475 Acres
Deep hollows and high hummocks are common in Low Shrub Bogs. Hummocks are dry enough to support a moderate to dense cover of Labrador tea, leatherleaf, bog rosemary, creeping snowberry, and bog laurel, as well as scattered stunted black spruce and tamarack. Forbs such as pitcher plant and round-leaved sundew are typically restricted to small openings among the shrubs and have sparse cover.

Graminoid Bog (Typic Subtype) [APn90b1] S4/ 85 Acres
The Typic Subtype of Graminoid Bog is associated with the large, crested, raised bogs in the patterned peatlands, forming incipient water tracks of wet *Sphagnum* carpets with low hummocks. Bog wiregrass sedge *(Carex oligosperma)*, few-fruited sedge, tussock cottongrass, tall

cottongrass *(Eriophorum polystachion),* and lake sedge dominate the hollows and mats, ornamented with pitcher plants and scheuchzeria. Ericaceous shrubs dominate the hummocks, with scattered pitcher plants and round-leaved sundew.

Northern Poor Fen Class [APn91] 139 Acres
Northern Poor Fens are a common aspect of the large patterned peatland portion of the Site and have pH ranging from 4.2 to 5.5.The largest occurrences of the community types in this class are associated with the lower sides of crested raised bogs where they develop as recognizable drains and water tracks that gradually transition into rich fens. Smaller occurrences are associated with floating peat mats on the margins of several of the Site's lakes and ponds.

Low Shrub Poor Fen [APn91a] S5/ 1484 Acres
Low Shrub Poor Fens occur either on floating mats or as part of the peatlands complex. They are characterized by *Sphagnum* hummocks with a relatively homogeneous and dominant cover of leatherleaf and bog birch. Hollows are rare, as are forbs and grasses. This community also develops on the distinct peat ridges, or "strings", adjacent to the "flarks" [APn91c2] described below. Together, strings and flarks create the distinctive pattern characteristic of the "ribbed fens" found in some portions of water tracks.

Graminoid Poor Fen (Basin) [APn91b] S3/ 80 Acres
Graminoid Poor Fen (Basin) occurs on floating mats at the edges of some peatland lakes and ponds and at the edges of the large peatlands complex. Bog wiregrass, few-fruited sedge, and tussock cottongrass dominate the *Sphagnum* carpet, with white beak rush, scheuchzeria, and lantern sedge common in wet hollows.

Graminoid Poor Fen (Featureless Watertrack Subtype) [APn91c1] S4/ 664 Acres
The Featureless Watertrack Subtype of Graminoid Poor Fen is characterized by leatherleaf, bog birch, bog willow, and stunted black spruce and tamarack present on scattered low hummocks. Fen wiregrass sedge and coastal sedge dominate the flora, which also includes creeping sedge, bristle-stalked sedge, lantern sedge, and slender sedge *(Carex echinata).* Forbs such as pitcher plant and buckbean are frequent, along with lesser amounts of small green wood orchid, a species listed as Special Concern. Additional species such as lead-colored sedge, white beak rush, Scheuchzeria, and bog rush are found in shallow wet hollows.

Graminoid Poor Fen (Flark Subtype) [APn91c2] S4/ 279 Acres
The Flark Subtype of Graminoid Poor Fen is a fen dominated by the graminoid species present in [APn91c1], but has well-differentiated peat-bottom pools lying perpendicular to the flow of groundwater and framed by drier moss hummocks that form strings of rich or poor shrub fen. The pools are habitat for aquatic species, such as horned bladderwort *(Utricularia cornuta),* not found in [APn91c1], as well as spatulate-leaved sundew, lead-colored sedge, white beak rush, scheuchzeria, and bog rush.

Wet Meadow/Carr System
Wet Meadow/Carr communities are shrub- or graminoid-dominated wetlands annually subject to inundation flowing spring thaw and heavy rains and to periodic drawdowns during the summer. Broad-leaved graminoids are common, but shrubs often dominate drier sites. Although

peak water levels are high enough and persist long enough to prevent trees (and often shrubs) from becoming established, there may be little to no standing water during much of the growing season. Surface water, derived from run-off, stream flow, or ground water, is circumneutral, with pH 6.0–8.0, and has high mineral and nutrient content. These communities are associated with wetland basins, stream and drainage ways, drained beaver ponds, and shallow bays, or are present as semi-floating mats on sheltered lakeshores.

Northern Wet Meadow/Carr Class [WMn82] 113 Acres
Communities in the Wet Meadow/Carr class occur as small wetland patches dominated by dense graminoids such as bluejoint, lake sedge, and tussock sedge *(Carex stricta)*; tall shrubs such as willows, speckled alder, and red-osier dogwood; or a combination of these.

Willow – Dogwood Shrub Swamp [WMn82a] S4/ 56 Acres
Willow – Dogwood Shrub Swamps are circumneutral (pH 6.0–8.0) open wetland communities. They occur in small patches within the large peatlands complex, near the margin of the peatlands and in shallow drains. Water levels vary over the growing season, with both inundation and drawdown common. Moss cover and species composition varies both within and among communities. Dominant vascular plant cover varies from tall shrubs such as speckled alder, red-osier dogwood, willows, bog birch, and meadowsweet *(Spiraea alba)*, to a variety of graminoids, including lake sedge, beaked sedge, bluejoint, tussock sedge, fowl manna grass, soft-leaved sedge, bristle-stalked sedge, and three-seeded bog sedge. Forbs are a significant component of the community’s flora, including bog goldenrod, dwarf raspberry, three-leaved false Solomon’s seal, red-stemmed aster, flat-topped aster, northern blue flag, violets, willow herb species, and crested fern. Frequent inundation limits tree cover to scattered black spruce and balsam fir.

Sedge Meadow [WMn82b] S5/ 54 Acres
Beaked sedge, lake sedge, bluejoint, and tussock sedge typically dominate or share dominance in this community, which occurs in the wetland complex along the North River, as small patches near the margin of the patterned peatlands, and as small strips of sedge meadow at the northeast end of Big Lake. Water levels vary over the growing season, with both inundation and drawdown common. pH ranges from 6.0–8.0. Willows, speckled alder, meadowsweet, and red-osier dogwood are sometimes present but typically have <25% combined cover. Forbs such as marsh bellflower, marsh skullcap *(Scutellaria galericulata)*, willow herb species, great water dock *(Rumex orbiculatus)*, and marsh cinquefoil grow among the dense sedge and grass cover.

Marsh System

Tall forbs, grasses, and sedges dominate Marsh communities in wetlands with standing water. Where marshes are adjacent to streams, slow-moving water is present during most of the growing season. Marsh communities may be rooted in mineral soil or floating mats. Stability of water level is dependent on whether inputs include groundwater as a source. If drawdown occurs, it coincides with drought cycles, and is not seasonal. Nutrient levels are usually high, and pH of water is typically circumneutral to basic, but dependent on properties of the substrates in the surrounding landscape.

Northern Mixed Cattail Marsh (Northern) [MRn83] S4/ 3 Acres
Mixed Cattail Marshes are emergent marsh communities typically dominated by cattails *(Typha*

spp.) but with a significant component of graminoids including sedges, woolgrass, and bluejoint. Shrubs are uncommon. In addition to cattails, marsh cinquefoil, tufted loosestrife, and linear-leaved willow-herb *(Epilobium leptophyllum)* are common forbs. Cover of floating-leaved and submergent aquatic plants is sparse. The scattered, small occurrences of this community are on floating mats along some peatland lakes and rooted in mineral soil in a few shallow wetland basins.

Native Plant Community Complex Descriptions

Alder Swamp/Forested Peatland Complex [AFP_CX] 868 Acres

This complex encompasses areas of Northern Rich Alder Swamp [FPn73] intermixed with various Forested Peatland classes, including Northern Rich Spruce Swamp [FPn62], Northern Cedar Swamp [FPn63], and Northern Rich Tamarack Swamp [FPn82]. It also occurs where Northern Rich Alder Swamp and Northern Wet Cedar Forest [WFn53] are intermixed. In areas mapped as [AFP_CX], individual native plant communities are difficult to assign for two reasons: 1) the communities are too small or convoluted to map accurately; and 2) the boundaries between communities are gradual, ecotonal, or vague. Tree cover is variable, typically about 25%, with small, scattered patches sometimes approaching 75% cover. Common tree species are black spruce, white cedar, tamarack, and balsam fir, with lesser amounts of paper birch, quaking aspen, and balsam poplar. Open areas have a shrub canopy of nearly pure alder with scattered individual trees and small clumps.

Shrub Shore Fen/Low Gradient Stream Complex [SFS_CX] 60 Acres

This complex includes long, linear occurrences of Bog Birch – Alder Shore Fen [OPn81a] and Leatherleaf – Sweet Gale Shore Fen [OPn81b] communities (described above) and their associated streams, where the streams are too narrow to map and/or where open water appears to be intermittent.

Beaver Wetland Complex [BW_CX] 513 Acres

This mapping complex is used to represent small to medium-sized wetlands whose character has been altered or is influenced by beaver-created impoundments, usually along watershed drainages. These are generally unforested wetlands, although trees and shrubs may have been common prior to beaver impoundment. Standing dead trees (snags) and shrubs and downed wood are common in many of these wetlands. Patches of open water occur directly behind the dam (often mapped separately as open water). Cattails, lake sedge, and other tussock-forming sedges are often dominant in the wettest zones near the dam. Slightly drier zones often support speckled alder, ericaceous shrubs, or bluejoint. Remnants of the wetland communities present before flooding by beaver dams are sometimes found at higher elevations in the watershed. Wetland community types that are frequently inundated by beavers include alder swamp, wet meadow, poor and rich fen, wet cedar forest, tamarack swamp, and black spruce swamp.

Forested Peatland/Upland Transition Complex [FPT_CX] 1530 Acres

This mapping unit identifies areas where a similar tree canopy occurs on adjacent forested peatlands and upland forests, making mapping by aerial photo difficult. The edges between these uplands and peatlands often support distinct transitional communities that do not clearly fit the plant communities described in the MN DNR's Field Guide to the Native Plant Communities of Minnesota (MN DNR 2003). This complex of upland, peatland, and transitional zones occurs where there are minor variations in elevation, either in a matrix of swamp with low islands of upland/semi-upland forest, or where large uplands are adjacent to large peatlands. The soils of the transition zones are moderately- to well-drained sandy loam with or without a clay hardpan and no evidence of gleying. Soils are typically cobbly or shallow to bedrock, with ground cover a mix of *Sphagnum*, *Pleurozium*, and other mosses. Various upland and peatland community classes can occur together in this complex, depending on the location, including Northern Rich Spruce Swamp [FPn62], Northern Cedar Swamp [FPn63], Northern Wet Cedar Forest [WFn53], Northern Mesic Mixed Forest [FDn43], and Northern Poor Dry-Mesic Mixed Woodland [FDn32].

In the Headwaters Site the peatlands and transition zones of this complex are dominated by black spruce, while the uplands have mixed black spruce, balsam fir, aspen, birch, and white pine. Tree cover is typically dense (>75%), but occasional openings are created by budworm mortality to balsam firs or mistletoe mortality to spruces. The two dominant community classes that grade into each other are Northern Rich Spruce Swamp [FPn62] and Northern Mesic Mixed Forest [FDn43]. In the transition zones between them, shrubs and herbaceous vegetation combine species typical of both peatlands and uplands, including those listed in Table 2. The transitional communities are associated with Ecological Land Types 13 and 2 (mapped by the U.S. Forest Service) and perhaps others.

Table 2. Examples of Species from Transition Zones

Peatland Species
Labrador tea, swamp fly honeysuckle, three-leaved false Solomon's seal, purple-leaved willow-herb *(Epilobium coloratum)*, goldthread, soft-leaved sedge, three-fruited bog sedge
Upland Species
prickly wild rose *(Rosa acicularis)*, mountain ashes *(Sorbus* spp.), beaked hazelnut, red-berried elder *(Sambucus racemosa)*, mountain maple, velvet-leaved blueberry, rose twisted stalk, cow wheat *(Melampyrum lineare)*, twinflower, starflower, wild sarsaparilla, Canada mayflower, bunchberry, common wood sorrel *(Oxalis acetosella)*, lady fern, spinulose shield fern, bristly clubmoss, round-branched ground pine, pointed woodrush, mountain rice grass , false melic grass *(Schizachne purpurascens)*, drooping wood sedge

Young Forest Complex [YF_CX] 983 Acres
Regenerating (<30 years old) upland and wetland forest communities within the Headwaters site. These areas are typically the result of timber harvest, but in some instances are forests regenerating after windthrow or spruce budworm mortality.

Rare Plants

The Headwaters Site's rare plant species data are stored in the MN DNR Natural Heritage Information System. Table 3 (below) lists the Site's rare plant occurrences recorded to date. The first data on rare plant populations were collected from the peatland complex in the 1980s during assessments conducted for the MN DNR's Minerals Division Task Force on Peatlands of Special Interest (MN DNR 1984). Puchalski (1995) conducted a search for rare plants around Big Lake in preparation for a proposed U.S. Forest Service timber harvest (which never occurred). He covered 5,000 acres with varying intensity and found no plant species listed by the State of Minnesota as Endangered, Threatened, or Special Concern. He found one occurrence of matricary grapefern *(Botrychium matricariifolium)*, which is tracked by the state but not listed, on MN DNR land (T59N R12W NWNW36). Judith Jones, working for The Nature Conservancy, also collected rare species data (Jones 1999).

MCBS plant ecologists and botanists have surveyed many parts of the Site, including significant survey work in 2005. Yet the Site has been far from thoroughly searched and native plant communities whose type and quality are similar to those supporting rare populations need additional survey.

Table 3. Rare plant occurrences in the Headwater's Site recorded to date.

Scientific Name	Common Name	Status	Location	Notes
Arethusa bulbosa	dragon's mouth	Tracked (not listed)	Peatlands	One very large population; numerous other individuals and small populations
Botrychium matricari-ifolium	Matricary grape-fern	Tracked (not listed)	T59NR12W NWNW36	Single plant found in 1995
Carex exilis	Coastal sedge	Special Concern	Patterned peatland	Large populations
Carex michauxiana	Michaux's sedge	Special Concern	Lower North River; and many other populations	One extremely large population; numerous viable populations
Drosera anglica	English sundew	Special Concern	Patterned peatland	Numerous populations
Juncus stygius var. *americanus*	Bog rush	Special Concern	Patterned peatland, and peatland pond edges	Numerous populations
Platanthera clavellata	Small green wood orchid	Special Concern	Peatlands	Scattered
Ranunculus lapponicus	Lapland buttercup	Special Concern	T58N R11W SWNW6	Scattered within 25 m2
Rhynchospora fusca	Sooty-colored beak-rush	Special Concern	Patterned peatland	Several populations of varying size
Scirpus cyperinus/ S. pedicellatus	Pedicelled wool-grass	Tracked (not listed)	Along North River	Scattered patches
Puccinellia pallida	Torrey's mannagrass	Special Concern	Along North River	Scattered patches

Animals

Information regarding the presence of and use of habitats in the Headwaters Site by individual animal species is more limited than that available for plants. No comprehensive animal surveys, except for birds, have been conducted to date in the Site. However, beginning in the late 1970s, considerable study of patterned peatlands in Minnesota was conducted as part of the Minnesota Peat Program and included animal species and their habitat use of these ecosystems. Applicable information from that work is referenced here to give a more complete picture of these facets of the Site and their significance.

Federally listed species
The U.S. Fish and Wildlife Service currently lists the gray wolf *(Canis lupus)*, Canada lynx *(Lynx canadensis)*, and bald eagle *(Haliaeetus leucocephalus)*, which have been documented in northeastern Minnesota, as “Threatened.” Bald eagles (which are also listed by the State of Minnesota as a species of Special Concern) have a documented nesting site on the western side of Big Lake. Gray wolf sign was observed in the Site by MCBS ecologists in 2005. Lying within the Superior National Forest, the Site is considered by the U.S. Fish and Wildlife Service to provide habitat for the Canada lynx.

Birds
MCBS conducted a breeding bird survey in the Sand Lake Peatland on June 3–5, 2003. Except where otherwise noted, the birds in Table 4 were observed during that survey. No other focused bird survey work has been done, although observations from the Site by knowledgeable MN DNR staff have been included in the table. None are listed as Endangered, Threatened, or Special Concern. Other bird species are also likely to breed in the Site.

Table 4. Breeding Birds Observed in or near the Headwaters Site

Habitat	Common Name	Scientific Name	Remarks
Water	Canada Goose	*Branta canadensis*	
Water	Mallard	*Anas platyrhynchos*	
Water	Black Duck	*Anas rubripes*	Observed Sept. 2005 in North River; may have been migrants
Water	Ring-necked Duck	*Aythya collaris*	
Water	Common Loon	*Gavia immer*	
Conifer	Spruce Grouse	*Canachites canadensis*	Observed in 1987 (S. Wilson, pers. comm.)
Conifer	Great Gray Owl	*Strix nebulosa*	
Conifer	Black-backed Woodpecker	*Picoides arcticus*	
Conifer	Olive-sided Flycatcher	*Contopus cooperi*	
Conifer	Yellow-bellied Flycatcher	*Empidonax flaviventris*	
Conifer	Blue-headed Vireo	*Vireo solitarius*	
Conifer	Gray Jay	*Perisoreus canadensis*	
Conifer	Boreal Chickadee	*Parus hudsonicus*	Observed by MCBS near Site and probably occurs within it
Conifer	Golden-crowned Kinglet	*Regulus satrapa*	Observed by MCBS near Site and probably occurs within it
Conifer	Swainson’s Thrush	*Catharus ustulatus*	
Conifer	Northern Parula	*Parula americana*	
Conifer	Magnolia Warbler	*Dendroica magnolia*	
Conifer	Yellow-rumped Warbler	*Dendroica coronata*	
Conifer	Pine Warbler	*Dendroica pinus*	Observed by MCBS near Site; uncommon in this part of state
Conifer	Palm Warbler	*Dendroica palmarum*	
Conifer	Connecticut Warbler	*Oporornis agilis*	

Table 4. Breeding Birds Observed in or near the Headwaters Site continued

Habitat	Common Name	Scientific Name	Remarks
Conifer	Lincoln's Sparrow	*Melospiza lincolnii*	
Conifer	Dark-eyed Junco	*Junco hyemalis*	
Conifer	White-winged Crossbill	*Loxia leucoptera*	
Conifer/Upl. Forest	Boreal Owl	*Aegolius funereus*	S. Wilson, pers. comm.
Forest	Broad-winged Hawk	*Buteo platypterus*	Observed by MCBS near Site and probably occurs within it
Forest	Ruby-throated Hummingbird	*Archilochus colubris*	Observed by MCBS near Site and probably occurs within it
Forest	Pileated Woodpecker	*Drycocopus pileatus*	Observed by MCBS near Site and probably occurs within it
Forest	Yellow-bellied Sapsucker	*Sphyrapicus varius*	
Forest	Hairy Woodpecker	*Picoides villosus*	Observed by MCBS near Site and probably occurs within it
Forest	Eastern Wood-pewee	*Contopus virens*	Observed by MCBS near Site and probably occurs within it
Forest	Least Flycatcher	*Empidonax minimus*	
Forest	Red-eyed Vireo	*Vireo olivaceus*	
Forest	Red-breasted Nuthatch	*Sitta canadensis*	Observed by MCBS near Site and probably occurs within it
Forest	Brown Creeper	*Certhia americana*	
Forest	Winter Wren	*Troglodytes troglodytes*	
Forest	Hermit Thrush	*Catharus guttatus*	
Forest	Veery	*Catharus fuscescens*	Observed by MCBS near Site and probably occurs within it
Forest	Canada Warbler	*Wilsonia canadensis*	Observed by MCBS near Site and probably occurs within it
Forest	Chestnut-sided Warbler	*Dendroica pensylvanica*	
Forest	Black-throated Green Warbler	*Dendroica virens*	
Forest	Blackburnian Warbler	*Dendroica fusca*	Observed by MCBS near Site and probably occurs within it
Forest	American Redstart	*Setophaga ruticilla*	Observed by MCBS near Site and probably occurs within it
Forest	Black-and-white Warbler	*Mniotilta varia*	
Forest	Ovenbird	*Seiurus aurocapilla*	
Forest	Mourning Warbler	*Oporornis philadelphicus*	
Forest	Rose-breasted Grosbeak	*Pheucticus ludovicianus*	
Forest	Baltimore Oriole	*Icterus galbula*	
Forest	Purple Finch	*Carpodacus purpureus*	
Forest/Shrub	Nashville Warbler	*Vermivora ruficapilla*	

Table 4. Breeding Birds Observed in or near the Headwaters Site continued

Habitat	Common Name	Scientific Name	Remarks
Forest/Edge	Ruffed Grouse	*Bonasa umbellus*	Observed by MCBS near Site and probably occurs within it
Forest/Edge	Northern Flicker	*Colaptes auraptus*	Observed by MCBS near Site and probably occurs within it
Forest/Edge	White-throated Sparrow	*Zonotrichia albicollis*	
Swamp/Shrub	Northern Waterthush	*Seiurus noveboracensis*	
Shrub	Alder Flycatcher	*Empidonax alnorum*	
Shrub	Common Yellowthroat	*Geothlypis trichas*	
Shrub/Edge	Yellow Warbler	*Dendroica petechia*	
Shrub/Edge	Wilson's Warbler	*Wilsonia pusilla*	South of main breeding range
Shrub/Open Wetland	Eastern Kingbird	*Tyrannus tyrannus*	
Open Wetland	Northern Harrier	*Circus cyaneus*	
Open Wetland	American Bittern	*Botaurus lentiginosus*	Observed 2005
Open Wetland	Sandhill Crane	*Grus canadensis*	
Open Wetland	Wilson's Snipe	*Gallinago delicata*	
Open Wetland	Sedge Wren	*Cistothorus platensis*	
Open Wetland	Savannah Sparrow	*Passerculus sand-wichensis*	
Open Wetland	Le Conte's Sparrow	*Ammodramus leconteii*	
Open Wetland	Swamp Sparrow	*Melospiza georgiana*	
Open Wetland	Red-winged Blackbird	*Agelaius phoeniceus*	
Open Wetland	Brewer's Blackbird	*Euphagus cyanocep-halus*	Colony observed near Ridge-pole Lake 1988 (S. Wilson, pers. comm.)
Edge	American Kestrel	*Falco sparverius*	
Edge	Tree Swallow	*Tachycineta bicolor*	
Edge	Eastern Bluebird	*Sialia sialis*	Observed in 1988 (S. Wilson, pers. comm.)
Edge	Cedar Waxwing	*Bombycilla cedrorum*	
Edge	Song Sparrow	*Melospiza melodia*	
General	Downy Woodpecker	*Picoides pubescens*	
General	Blue Jay	*Cyanocitta cristata*	
General	American Crow	*Corvus brachyrhyn-chos*	
General	Common Raven	*Corvus corax*	
General	Black-capped Chickadee	*Poecile atricapillus*	
General	American Robin	*Turdus migratorius*	
General	Chipping Sparrow	*Spizella passerina*	

Although not state or federally listed, the boreal owl is an uncommon species in Minnesota. Its breeding range is restricted to the far northeastern counties and it has been observed in the Headwaters Site. Boreal owls forage in lowland conifers and nest in abandoned holes excavated by pileated woodpeckers in mature aspen trees. The Headwaters Site has both uplands with mature aspen and adjacent lowland conifer forests and likely provides some of the best habitat in the state for this species.

A breeding pair of adult sandhill cranes (also tracked, but not state or federally listed) and one sub-adult plumaged bird were observed in July 2002, and breeding season pairs were observed during fieldwork in both 2003 and 2005. This species rarely breeds in northeastern Minnesota.

Mammals

Among the earliest written documentation of mammals from the Headwaters Site is from the 1891 Public Land Survey General Description for T59N R11W, in which the surveyor wrote, “Great numbers of Caribou (American Reindeer) live in these swamps on the mosses that grow in great abundance. If these animals are to be preserved, a fork of 10 sq. miles should be fenced and guarded as they are fast disappearing before the Winchester rifles of the hunters.” Although the caribou did not survive landscape changes and hunting pressures in the Headwaters region, a wide variety of mammals still inhabit the landscape, and have been observed or are likely to occur in the Site. No site-specific mammal surveys have been conducted in the Headwaters Site. However, MCBS ecologists noted evidence and observations of wolf, moose, red squirrel, white-tailed deer, beaver, and black bear in 2005. Survey work and observation in habitats in Minnesota of similar type and quality also provide some indication of the species likely to be present and the habitats they are likely to use. Mammals potentially found in the Headwaters Site are listed in Table 5.

Table 5. Mammals Potentially Found in the Headwaters Site (Wright et al. 1992, G. Nordquist, pers. comm. 2006).

Common Name	Scientific Name
Arctic Shrew	*Sorex arcticus*
Masked Shrew	*Sorex cinereus*
Pygmy Shrew	*Sorex hoyi*
Water Shrew	*Sorex palustris*
Northern Short-tailed Shrew	*Blarina brevicauda*
Star-nosed Mole	*Condylura cristata*
Little Brown Myotis	*Myotis lucifugus*
Northern Myotis	*Myotis septentrionalis*
Eastern Red Bat	*Lasiurus borealis*
Hoary Bat	*Lasiurus cinereus*
Silver-haired Bat	*Lasionycteris noctivagans*
Big Brown Bat	*Eptisicus fuscus*
Snowshoe Hare	*Lepus americanus*
Least Chipmunk	*Tamias minimus*
Eastern Chipmunk	*Tamias striatus*
Woodchuck	*Marmota monax*

Table 5. Mammals Potentially Found in the Headwaters Site continued

Common Name	Scientific Name
Franklin's Ground Squirrel	*Spermophilus franklinii*
Red Squirrel	*Tamiasciurus hudsonicus*
Northern Flying Squirrel	*Glaucomys sabrinus*
American Beaver	*Castor canadensis*
White-footed Mouse	*Peromyscus leucopus*
Woodland Deer Mouse	*Peromyscus maniculatus gracilis*
Southern Red-backed Vole	*Clethrionomys gapperi*
Meadow Vole	*Microtus pennsylvanicus*
Southern Bog Lemming	*Synamptomys cooperi*
Meadow Jumping Mouse	*Zapus hudsonius*
Woodland Jumping Mouse	*Napaeozapus insignis*
Common Porcupine	*Erethizon dorsatum*
Red Fox	*Vulpes vulpes*
Coyote	*Canis latrans*
Gray Wolf	*Canis lupus*
Black Bear	*Ursus americanus*
Common Raccoon	*Procyon lotor*
American Marten	*Martes americana*
Fisher	*Martes pennanti*
Ermine	*Mustela erminea*
Mink	*Mustela vison*
Northern River Otter	*Lontra canadensis*
Striped Skunk	*Mephitis mephitis*
Lynx	*Lynx canadensis*
Bobcat	*Lynx rufus*
White-tailed Deer	*Odocoileus virginianus*
Moose	*Alces alces*

Reptiles and Amphibians

No herpetofaunal surveys have been conducted specific to the Headwaters Site. However, survey work in wetland and forest habitats of similar type and quality in northern Minnesota provides some indication of the species likely to be present and the habitats they are likely to use. Research suggests amphibians are extremely important in the ecological dynamics of both aquatic and terrestrial environments (Burton and Likens 1975; Stockwell 1985; Wright et al. 1992; DeMaynadier and Hunter 1995). Evidence of amphibian biomass and number of individuals suggests there is probably more biomass of amphibians in Minnesota's large patterned peatlands than all other vertebrates combined (Wright et al. 1992). While research has also shown a similar significance in some forest habitats, the fire-dependent communities typical of the Headwaters have not specifically been studied. The Headwaters Site, with its wide variety of wetland types, both within the uplands and the peatland complex, provides a stable base of unfragmented breeding and over-wintering habitat that can support robust amphibian and reptile populations, which are limited in their ability to disperse in response to unfavorable annual or cyclic environmental conditions such as drought.

While there is relatively low herpetofaunal species richness in large peatlands, especially in nutrient-poor bogs, amphibians and reptiles are nevertheless an abundant and conspicuous faunal component whose individual presence and abundance is influenced by a complex combination of physical, biotic, and historical factors (Wright et al. 1992). Seasonal ponds and semi-permanent wetlands in upland forests provide important breeding habitat for a variety of woodland amphibians. Wood frogs *(Rana sylvatica)*, spring peepers *(Hyla c. crucifer)*, gray treefrogs *(Hyla versicolor),* and blue-spotted salamanders *(Ambystoma laterale)* are likely to occur in the Site, utilizing temporary wetlands and surrounding upland forest habitat. Eastern red-backed salamanders *(Plethodon c. cinereus)* may occur in forests with sufficient duff layers and coarse woody debris, where eggs are laid. Eastern newts *(Notophthalmus v. viridescens),* northern leopard frogs *(Rana pipiens),* green frogs *(Rana clamitans melanota),* and mink frogs *(Rana septentrionalis)* likely occupy permanent water bodies and creeks. Other species likely using the Site's habitats include American toads *(Bufo a. americanus)*, boreal chorus frogs *(Pseudacris maculata),* snapping turtles *(Chelydra s. serpentine),* painted turtles *(Chrysemys picta belli),* common gartersnakes *(Thamnophis s. sirtalis),* and red-bellied snakes *(Storeria o. occipitomaculata)*. The most limited herpetofaunal habitat in the Headwaters Site may be turtle nesting sites (C. Hall, pers. comm. 2006).

Fish

Significant fisheries in the Headwaters Site are limited to Big Lake. Surveys there have recorded burbot, northern pike, rock bass, walleye, white sucker, and yellow perch. Fisheries data for the upper North River include three species: white sucker *(Catostomus commersoni),* walleye *(Stizostedion vitreum),* and shorthead redhorse *(Moxostoma macrolepidotum)*. According to a hydrological report by Fedora (2005), aquatic organisms in the North River likely include species in the families Cyprinidae (minnow), Gasterosteidae (stickleback), Percidae (perch), and Umbridae (mudminnow). A fisheries survey of nearby Cougar Lake turned up only fathead minnows *(Pimephales promelas)* and brook sticklebacks *(Culaea inconstans).*

Invertebrates

Although there are some nearby records, no invertebrate surveys have been conducted specific to the Headwaters Site. However, limited invertebrate survey work in wetland and upland habitats of similar type and quality in northeastern Minnesota provides some indication of the species likely to be present.

Butterflies

In the Headwaters area, as elsewhere in Minnesota, more is known about butterflies than other invertebrate fauna. There are several distinctive butterflies of the northeastern part of Minnesota that either have been documented from the area or could occur in the Site's habitats. Three of these species are listed in Minnesota as Special Concern. Mancinus alpine *(Erebia mancinus,* formerly *E. disa mancinus*), which is listed as Special Concern, has been documented from the area and is associated with shady, black spruce-dominated habitats. Other peatland butterflies documented from the area during 2005 include the bog fritillary *(Boloria eunomia)*, Freija fritillary *(Boloria freija)*, Jutta arctic *(Oeneis jutta)*, arctic fritillary *(Boloria chariclea)*, and Frigga fritillary *(Boloria frigga)* (R. Dana, pers. comm. 2006).

The red-disked alpine *(Erebia discoidalis)* occurs in the area. Although not a true peatland insect, it seems to occur in damp meadow areas on the margins. The arctic fritillary *(Boloria chariclea)* is often associated with habitats near peatlands (R. Dana, pers. comm. 2006).

Macoun's arctic *(Oeneis macounii)*, about which little is known with respect to abundance, has been encountered in jack pine woodlands in the general area. Minnesota may be the only state in the contiguous United States where this species occurs. Its habitat preferences are uncertain, but it has most often been encountered in upland jack pine woodland or jack pine forest with openings. Nabokov's blue *(Lycaeides idas nabokovi)*, listed as Special Concern, is also a possibility in openings in upland settings of jack pine and in black spruce forest if its host plant, dwarf bilberry *(Vaccinium cespitosum)*, is present (R. Dana, pers. comm. 2006).

Another more remote possibility is the extremely elusive grizzled skipper *(Pyrgus centaureae freija)*, a species listed as Special Concern. Within its main range, its habitat is described as "forest edges and openings as well as mixed scrub/heath tundra … in the taiga zone, adjacent to or in boggy areas, or in scrubby willow thickets on the tundra." The species is also known to occur well into the boreal forest of Canada; for instance, it is known from a number of locations in southern Manitoba (Klassen et al. 1989, Layberry et al. 1998). It is known in Minnesota only from the McNair Site, 13 miles south of the Headwaters Site (R. Dana, pers. comm. 2006). Table 6 below summarizes the localized and common butterflies from the Headwaters and surrounding area.

Table 6. Butterflies of Headwaters and Surrounding Area (R. Dana, pers. comm. 2006)

Peatland associates:	
Grizzled skipper *Pyrgus centaureae freija* (remote possibility) SPC	Bog fritillary *Boloria eunomia*
Frigga fritillary *Boloria frigga*	Freija fritillary *Boloria freija*
Arctic fritillary *Boloria chariclea*	Taiga alpine *Erebia mancinus*
Red-disked alpine *Erebia discoidalis* SPC	Macoun's arctic *Oeneis macounii*
Jutta arctic *Oeneis jutta*	Dorcas copper *Lycaena dorcas*
Cranberry copper *Lycaena epixanthe*	
Northern species, somewhat localized:	
Pine elfin *Callophrys niphon*	Hoary elfin *Callophrys polia*
Tawny crescent *Phyciodes batesii*	Western tailed blue *Everes amyntula*
Satyr anglewing *Polygonia faunus*	Harris's checkerspot *Chlosyne harrisii*
Harvester *Feniseca tarquinius*	
Northern species, common:	
Mustard white *Pieris oleracea*	Canadian tiger swallowtail *Papilio canadensis*
Brown elfin *Callophrys augustinus*	Pink-edged sulphur *Colias interior*
Atlantis fritillary *Speyeria atlantis*	Spring azure *Celastrina ladon**
Compton's tortoiseshell *Nymphalis vau-album*	Green comma *Polygonia faunus*

Table 6. Butterflies of Headwaters and Surrounding Area continued

Common roadside skipper *Amblyscirtes vialis*	Pepper-and-salt skipper *Amblyscirtes hegon*
Widespread species, common:	
Dreamy dusky wing *Erynnis icelus*	Tawny-edged skipper *Polites themistocles*
Hobomok skipper *Poanes hobomok*	Dun skipper *Euphyes vestris*
Clouded sulphur *Colias philodice*	Acadian hairstreak *Satyrium acadicum*
Eastern tailed blue *Everes comyntas*	Summer azure *Celastrina neglecta**
Aphrodite fritillary *Speyeria aphrodite*	Great spangled fritillary *Speyeria cybele*
Silver-bordered fritillary *Boloria selene*	Meadow fritillary *Boloria bellona*
Silvery checkerspot *Chlosyne nycteis*	Northern crescent *Phyciodes cocyta* (=*selenis*)
Comma *Polygonia comma*	Gray comma *Polygonia progne*
Mourning cloak *Nymphalis antiopa*	Milbert's tortoiseshell *Nymphalis milberti*
Virginia lady *Vanessa virginiensis*	White admiral *Limenitis arthemis arthemis*
Viceroy *Limenitis archippus*	Northern pearly-eye *Enodia anthedon*
Little wood-satyr *Megisto cymela*	Common wood-nymph *Cercyonis pegala*

*Follows Layberry et al., who recognize two species of this genus in our area. Others recognize three species.

Other invertebrates

Quite a few moth species that are more wide-ranging father north, are restricted to peatland habitats at the southern limits of their ranges, such as those at the Headwaters Site, but little is known about them in Minnesota. Some species of leafhoppers are also likely to fit this pattern, and perhaps species of many other invertebrate groups such as beetles, caddisflies, flies, and wasps (R. Dana, pers. comm. 2006).

HUMAN DISTURBANCE AND USE

The primary human use of the general Headwaters area has been for timber harvest, starting in the early 1900s. This early cutting was probably high-grading for white pine and other high-value trees. The Skibo Sawmill was located on the north side of the St. Louis River, downstream from Seven Beavers Lake. A tug company operated on Seven Beavers Lake to move logs, and a couple of rafting booms are still lying in mud on the lower North River. Log transport on the St. Louis River to the Skibo Sawmill likely involved the use of a splash dam at the outlet of Seven Beavers Lake (Fedora 2005). This may have increased water levels in the lake and its tributaries, as is evident for the North River in a 1934 aerial photo. Old dead stumps along the treeless bank of the North River may be a result of this fluctuation.

Historical aerial photos demonstrate extensive cutting of peatland (and some upland) forests in the North River area in the 1930s and 1940s. Most of the rich spruce swamps in the area were clearcut, but bogs and poor conifer swamps were not cut. In the extensive upland forests around Big Lake, 1948 aerial photos show a network of narrow forest roads through a predominately deciduous forest about 20–30 years old. The tree canopy usually obscures the roads, but they are clear whenever they cross small peatlands. Because such extensive clearcutting was unlikely in this remote area at such an early date, this forest probably regenerated after a fire around 1920. The roads visible in the 1948 photos probably date from pre-fire high-grading. Harvesting continues today at a much smaller scale, particularly in the northwest corner of the Site. There has also been a recent timber sale on islands within the peatland near Ridgepole Lake. Winter roads associated with this and the earlier swamp forest harvests are still evident in narrow tracks in the open peatlands and narrow, linear canopy openings in the forests.

Despite the history of extensive logging activities and the sensitivity of stream channels to changes in hydrologic processes and sediment inputs, Fedora (2005) found no evidence of changes to stream channels in the upper St. Louis River watershed. Stream banks have been stable over decades, and no changes in stream channel erosion, deposition, or channel migration were observed. In fact, the Headwaters Site as a whole has recovered remarkably from past logging, and ecological processes continue to function at a large scale.

MCBS survey work in 2005 found large upland and lowland areas in the Headwaters Site to be free of non-native species, including earthworms. Typically, non-native species within the Site were associated with roads and upland trails, and with forest stands that have been managed since the 1960s. No comprehensive earthworm surveys were conducted, but the forest in much of the Site is probably worm-free due to the lack of human traffic, recent disturbance, and likely introduction sites. In mesic hardwood forests, European earthworms can change soil profiles and negatively impact some understory ferns and other herbaceous species (Hale 2004, Hale and Host 2005). Although preliminary results do not show similar effects on vegetation in fire-dependent forests, the full impact is unknown, and the ecological change could be significant (Hale and Host 2005). The only likely places for the introduction of earthworms in the Site are at Big Lake and the cabin near Swamp Lake (via discarded bait) or the area along the Dunka River Road in the northwest (via transport and deposition by vehicle tire treads). MCBS field surveys in these areas found no obvious signs of earthworm presence, but surveys did not specifically target earthworms.

Timber harvest at the Site has resulted in changes in the age-class distribution of the forests. The predominance of forests in the range of 60–80 years old, which is a result of past logging and probably also the huge early-century fires that often started in logging slash, mirrors the skew in age class in northeastern Minnesota as a whole and the under-representation of older multi-aged conifers (MFRC 2003). In at least some parts of the Headwaters Site there appear to be fewer of the older residual patches than would be expected in forests that burned naturally (such as the pattern of residuals documented in naturally burned forests by Carlson [2001]). Nevertheless, the Site may represent the best opportunity in the Section to restore the multi-aged conifer stage in patch sizes approximating natural patterns.

Human activities may also have directly and indirectly changed tree species composition in some forests in the Headwaters Site. According to one study of northeastern Minnesota, white pine and tamarack each currently make up 0.5% of the trees in aspen-birch-spruce-balsam fir forests, compared to 8% and 7% in presettlement times (White 2001). The same study showed an increase in aspen from 7.5 % to 26.5%, closely matching the present composition in the Headwaters Site. Although some of the mixed aspen-birch-spruce-balsam fir forest [FDn43b] in the Site has a significant conifer component (predominantly balsam fir and black spruce), this forest type has fewer of some long-lived conifers than it did historically. Many Public Land Survey bearing trees south of Big Lake, for example, were white pines, but few pines grow in that area today. Pines still grow in parts of the upland forest to the north of Big Lake, possibly as a result of less intensive high-grade logging.

Roads and Trails
There are no all-season roads in the Headwaters Site, but there are trails and logging roads (including old logging roads in the peatlands) that have persisted for decades. Along many of these roads in the peatlands, road construction removed the porous peat layer that raises the surface above the water table (or the layer was compacted, even in winter, by heavy use), and the layer of *Sphagnum* moss has been replaced by sedge-dominated vegetation. Compacted peat can also block the flow of water through a peatland, but Fedora (2005) found no evidence of altered hydrology as a result of winter roads. He stressed, however, that further investigation would be required for a thorough evaluation. Some old peatland logging roads have become overgrown (often with alder) and are no longer passable, including some that are visible on current aerial photos. Even trails still used by snowmobiles do not generally receive heavy use at present. Most roads and trails were designed only for winter use because of the extensive wetlands, but there are some upland ATV trails south of Big Lake. Additionally, there has been some non-winter ATV use of the winter roads, causing localized damage.

Railroads
Railroad grades present at the Headwaters Site may be disrupting water flow through the peatlands. Fedora (2005) makes particular note of the railroad crossing on the North River. The two culverts present at the crossing are evidently insufficient during high water flow, causing build-up on the upstream side and a scour pool on the downstream side. In addition, a tributary stream was diverted to this crossing, adding more water volume. The increased flooding has altered wetlands covering about 18.8 acres upstream. This same railroad grade has also blocked water flowing toward Cougar Lake, flooding part of the rich fen to the south.

Recreation
Recreational use of the area is relatively low, due to difficult access. A little-used hiking trail follows an esker southwest from Big Lake toward Stone Lake. There is a boat landing at the southern tip of Big Lake, where several boats are stored; the landing is accessed by an ATV trail across the railroad tracks. ATV trails also lead to another spot on the eastern shore of Big Lake and to a private cabin. The U.S. Forest Service maintains a campsite on the western shore. A county cabin leaseholder keeps a single boat at Swamp Lake. A rotten boat by the edge of Lobo Lake indicates some past use. Dispersed recreation such as camping, and ATV use of minimum maintenance roads, logging roads, and trails is common, particularly during the fall hunting season.

LAND OWNERSHIP PATTERN
The U.S. Forest Service and the MN DNR manage most of the Headwaters Site (see Table 7 below and Figure 2, page 81). The DNR manages the majority of the extensive peatland, while the Forest Service manages the majority of the uplands around Big Lake and in the northwestern corner of the Site. About half the state-owned peatland is within the Sand Lake Peatlands SNA, and most of the federal peatlands are within the Big Lake – Seven Beavers candidate Research Natural Area, which extends west to the shore of Big Lake. There are scattered parcels of St. Louis County and Lake County land, and The Nature Conservancy owns several parcels in the southeastern part of the Site. Some land along railroad tracks is owned by mining or railroad companies, and there are a few private non-industrial parcels, particularly around Big Lake.

Table 7. Ownership in the Headwaters Site

Ownership	Acres	Percent	Combined Percent
U.S. Forest Service (non-cRNA)	14,248	38	53
U.S. Forest Service (cRNA)	5,469	15	
Minnesota State Forest	9,855	26	37
Minnesota Scientific and Natural Area	4,103	11	
St. Louis County	1,145	3	3
Lake County	393	1	1
The Nature Conservancy	824	2	2
Other Private Land	1,409	4	4
TOTAL UPLAND	37,446	100	100
Lakes	1,267		
TOTAL AREA	38,713		

THREATS

The primary threats to the ecological and biological integrity of the Headwaters Site are: 1) fragmentation, decreased patch size, and edge effects associated with roads, timber harvesting, and recreational developments such as campgrounds or dispersed sites, boat landings, and some types of trails; 2) silvicultural methods that do not mimic the spatial and temporal scale and intensity of natural disturbances relevant to the native plant community being managed; 3) introduction and establishment of exotic species as a result of all the above mentioned activities and via all non-winter uses of roads, logging access routes, winter roads, trails, and water access; and 4) fire suppression in fire-dependent native plant communities.

MANAGEMENT RECOMMENDATIONS

Overview

The Headwaters Site is a large, natural area with features of widely recognized statewide ecological and biological significance. These include:

- one of the 15 most significant peatlands in the state (MN DNR 1984, Wright et al. 1992);
- the largest SNA in the Northern Superior Uplands Section;
- one of the largest, unfragmented, predominantly upland forest patches in the Laurentian Uplands, Toimi Uplands, and North Shore Highlands subsections;
- an ecologically functional mosaic of high quality native plant and animal communities;
- a concentration of excellent occurrences of rare species populations;
- support of species with large home ranges;
- six state-designated old-growth stands;
- remote, undeveloped lakes.

The Site's Outstanding Statewide Biodiversity Significance rank and recommendation by MCBS as an area for ecologically based management reflect these features, and its importance from a statewide and regional perspective. The Headwaters Site's natural features merit protection and management intended to sustain the Site's biological and ecological features and value. This is particularly crucial in the face of increasing pressures on public and private lands in northeastern Minnesota ranging from increasing demand for wood products and recreational access to the subdivision, sale, and development of large blocks of commercial forest and other private lands.

The Headwaters Site is part of the Sand Lake/Seven Beavers Project Area that has been identified as a priority conservation area by The Nature Conservancy (The Nature Conservancy 2000; The Nature Conservancy and Nature Conservancy Canada 2002). In part, recognition of this unique and high-quality landscape prompted the formation of the Sand Lake/Seven Beavers (SL7B) collaborative, which provides a forum for informed, coordinated land management among the large landowners of a four-township area (Figure 1, page 79). The collaborative was formally organized in December 2002 via a Memorandum of Understanding (MOU) agreement, signed by Lake County Land Department, MN DNR, TNC, and U.S. Forest Service Superior National Forest. The MOU states that the agreement "provides the framework for cooperation and coordination between the parties within the Sand Lake/Seven Beavers Area, in order to serve the public interest in the conservation and management of this Area." The St Louis County Land Department was not a signatory, but also participates in the collaborative.

To date, the collaborative has supported a watershed assessment and a forested communities assessment for the area. It also formed a data management group to compile biodiversity and forest management related survey, inventory, and project-planning data. The collaborative has also agreed to develop mutually agreed upon landscape objectives for units/zones within the SL7B area.

Management options appropriate to the exceptional qualities and opportunities present in the Site include: 1) protection using RNA and SNA designation of additional public lands; and 2) similar protection strategies on private and county lands, or acquisition if necessary. Wherever these protection strategies are not pursued, MCBS recommends that any other management use a selected set of approaches in a manner designed and coordinated by the landowners to meet carefully crafted ecological goals at the landscape, LTA, and native plant community scale.

The two sections below contain more detailed recommendations for protection and management. Table 8 summarizes these recommendations.

Table 8. Summary of MCBS Recommendations for the Headwaters Site

Actions
• Protect Ecologically Important Lowland Conifers as designated Old-Growth, if appropriate, or as Scientific and Natural Area (DNR)
• Establish Big Lake – Seven Beavers Research Natural Area (U.S. Forest Service)
• Maintain large patch sizes of mature upland and peatland forests, particularly the forest around Big Lake
• Allow natural processes to predominate
Research Needs
• Investigate natural disturbance ecology of Site (landforms, native plant communities, applicable natural disturbances) to inform management
Management Considerations
• Maintain biodiversity significance factors that contribute to MCBS rank of Outstanding, including hydrological and ecological connections between uplands and peatlands, large patch sizes, minimal fragmentation, intact ecological function at multiple scales, and support of regional scale organisms
• Be consistent with the Minnesota Forest Resources Council Landscape Committee vision, Superior National Forest Plan, and MN DNR NTL Subsection Forest Resource Management Plan

Table 8. Summary of MCBS Recommendations for the Headwaters Site continued

Management Considerations continued
• Use techniques to mimic full range of natural disturbances, particularly fire
• Use ecologically compatible management practices previously applied and evaluated outside the Site
• Effect an increase in multi-aged forest growth stages
• Effect an increase in long-lived conifers
• Avoid abrupt forest edges
• Minimize all roads and trails; no new permanent roads; restore duplicate roads and trails to native vegetation
• Prevent exotic species encroachment (including earthworms) via roads and road-building, harvest equipment, and recreational activities

Protection Recommendations

A study of potential natural areas to represent ecosystems in the Superior National Forest (SNF) resulted in the identification of three areas within the Headwaters Site: Dunka, Sand Lake Peatlands SNA Addition, and Big Lake – Seven Beavers (Vora 1997). As part of the SNF Plan revision there was further evaluation of the SNF for potential Research Natural Areas. The Big Lake – Seven Beavers potential Research Natural Area (approximately 6,750 acres), including both peatlands and upland forests, was identified as a priority (Wagner et al. 2000). Most of this area (5,469 acres) was included in the final SNF Plan in 2004 as a Candidate Research Natural Area (Figure 2, page 83). The Headwaters Site also includes the Sand lake Peatlands SNA, and six state-designated old-growth stands.

Peatlands

Roughly two-thirds of the Headwaters Site's peatlands are owned by the MN DNR and one-third by the U.S. Forest Service. About half of the Site's peatlands, including the majority of the patterned peatlands, is currently protected in the Sand Lake Peatland SNA.

The NTL Subsection Forest Resource Management Plan identifies almost all of the remaining peatlands on state land in the Site as Ecologically Important Lowland Conifers (EILC), including the lands identified by the MN DNR in its 1984 report (MN DNR 1984) as the Sand Lake Peatland Watershed Protection Area (WPA) (Figure 7, page 91). The delineation of the WPA was intended to highlight the importance of peatlands bordering the SNA to the protected features in the SNA, alerting managers to the need to consider the higher hydrologic sensitivity of these lands in management decisions. The WPA was limited to peatlands, and did not address the hydrologic connections between uplands and peatlands in the SNA (N. Aaseng, pers. comm. 2006). The EILC designation provides temporary protection until a State of Minnesota old-growth policy is developed for lowland conifers. MCBS recommends that lands designated as EILC in the Extensive Peatlands area of the Headwaters Site be permanently protected, either by SNA designation or as old-growth (if appropriate). This peatland area is unique in the Northern Superior Uplands Section, warranting its protection as a whole. In addition, the EILC lands in the Extensive Peatlands are ecologically linked to the Sand Lake Peatland SNA so activity on the EILC lands has the potential to impact protected lands in the SNA.

Most of the peatlands owned by the U.S. Forest Service, including most of the North River peatland, is within the Big Lake – Seven Beavers Candidate Research Natural Area (cRNA). The Forest Service should establish this area as an RNA. The RNA, together with the SNA, a long-term protection commitment by the MN DNR for the EILC, and the parcels owned by The Nature Conservancy, would protect most of the Extensive Peatlands, stretching from Seven Beavers Lake to Bonga Lake. The RNA would also protect some adjacent uplands ecologically linked to the peatlands, as well as a portion of the shoreline of Big Lake.

Uplands

Existing protected areas, combined with the peatland protections recommended above, cover roughly half the Headwaters Site. The largest area not covered is the fire-dependent upland forest intermixed with small peatlands around Big Lake. At roughly 7,000 acres, this forest is one of the largest unfragmented upland forests in the Laurentian Uplands, Toimi Uplands, and North Shore Highlands subsections. This mature forest has some significant development of structural and compositional diversity, such as older patches and older individual trees. In addition, an unfragmented mosaic of forested upland and lowland communities projects from this large patch into the patterned peatland complex in the north-central part of the Site. During the Superior National Forest Plan revision of 2004, the U.S. Forest Service identified the federally owned portion of the upland forest in the Big Lake Area as one of the few large, mature/old upland patches greater than 1,000 acres on the SNF. Implementation of the SNF Plan goals for large, mature/old upland patches on the landscape should maintain this area as a large mature upland patch during the term of the Plan (D. Ryan, pers. comm. 2006).

The lack of disturbance in these areas since forest stand initiation, dating from the late 1800s through the 1930s, has allowed the development of mature to old forest communities in which natural disturbance patterns have been operating at multiple scales over a large area. With a high proportion of long-lived conifers and a high degree of compositional and structural diversity, these upland communities are an integral part of landscape connectivity within the Site, functioning as transitional connections between the peatland LTA and the two adjacent morainal LTAs.

In light of intensifying land use of all kinds and its impacts (such as parcelization, fragmentation, and spread of exotic species) as well as the potential impacts of climate change on forests and their biota in northeastern Minnesota, there is a clear need for some fire-dependent upland forest landscapes in the Laurentian Uplands, Toimi Uplands, and North Shore Highlands subsections to be kept in reference condition. In these Subsections most of the upland forest communities that have received permanent protection are mesic hardwood forests or small patches of old-growth conifer forest. The large area of high-quality fire-dependent forest in the Big Lake Area of the Headwaters Site is a prime candidate to be managed through coordinated protection. MCBS recommends that lands lying within the natural boundaries of the large mature/old upland patch in the Big Lake Area and projecting into the peatland complex, be given high priority for protection; it is recommended that the patch be maintained and the native plant communities throughout allowed to continue to grow and develop in their current and older growth stages.

Uplands throughout the Site are ecologically linked to the peatlands, including through transitional communities immediately adjacent to the peatlands. In particular, MCBS recommends no harvest in the upland-peatland transition forests where black spruce is a significant component of the canopy, subcanopy, or understory.

Management Considerations

MCBS recommends that any forest management in the Headwaters resemble the natural disturbance regimes and natural stand development processes relevant to this heterogeneous landscape and its native plant communities. It is recommended that any harvest undertaken in the Headwaters Site be: 1) informed by site-specific understanding of natural disturbance ecology and native plant community ecology; 2) guided by and consistent with recent landscape planning efforts; 3) meet carefully crafted ecological goals and objectives at the landscape, LTA, and native plant community scales; and 4) include only those silvicultural approaches that have been tried in similar conditions outside the Site and proved to be successful in achieving the desired ecological goals and objectives.

Research Needs

Silviculture that does not mimic the spatial and temporal scale and intensity of natural disturbances relevant to the native plant communities being managed threatens the Site's ecological integrity. An understanding of the natural disturbance ecology of the Site is necessary to inform any management intended to mimic natural disturbance regimes and sustain ecological function and biological features.

Further investigation into the natural disturbance ecology of the Site is recommended to inform patch planning and design (including the size, native plant community composition, and age class of patches in the landscape mosaic) and goals for structural and compositional variation within patches. For instance, patterns in the conifer swamp native plant communities in the Extensive Peatlands reflect patch size and within-patch variation (or lack thereof) resulting from past management, and not necessarily from natural disturbance regimes. In upland patches, past management ranging from selective harvest to fire suppression may have altered patch landscape patterns and patterns within patches.

Ecologically compatible forest management practices have not been widely used in the landscape of northeastern Minnesota, nor have outcomes been monitored and evaluated. The statewide and regional ecological and biological importance of the Headwater Site make it valuable as a reference area for studies involving evaluation of ecologically compatible management practices. In such studies, any experimentation with specific management practices should be done on adjacent lands or similar native plant communities elsewhere, with outcomes evaluated against conditions at the Headwaters Site. Only if proven successful in ecological management on other sites should such practices be used in the Headwaters Site.

Landscape Guidance

The Northeast Regional Landscape Committee of the Minnesota Forest Resources Council in 2003 reported on the desired future condition of forests in the region (MFRC 2003). Elements of the Council's report that are especially applicable to the Headwaters Site are summarized in table 9.

According to the Superior National Forest Plan of 2004, the Headwaters Site is part of Management Areas 10.2 – Longer Rotation Emphasis, 8.6 – Riparian Emphasis, and 6.1 – Semi-primitive Motorized Recreation, in addition to the candidate RNA (Management Area 8.2a) mentioned above.

Table 9. Summary of Minnesota Forest Resources Council Report on Desired Forest Condition

• Forests should approximate/move toward the range of variability (the spectrum of conditions possible in ecosystem composition, structure, and function considering both temporal and spatial factors) for plant communities naturally living and reproducing in northeastern Minnesota.
• Forests should have spatial patterns (size and location of openings) that are consistent with the ecology of northeastern Minnesota.

Based on the features and quality described in this ecological evaluation, the Headwaters Site is ranked by MCBS as having Outstanding Statewide Biodiversity Significance. The MN DNR's North Shore, Toimi Uplands, and Laurentian Uplands Subsection Forest Management Plan (General Direction Statement-1E) directs management of MCBS Sites of Statewide Biodiversity Significance "to sustain or minimize the loss to the biodiversity significance factors that contribute to the ranking" (MN DNR 2004b). Strategies presented in the plan that are relevant to management of biodiversity at the Headwaters Site are listed in Table 10.

Table 10. Summary of Strategies for Management of MCBS Sites of Statewide Biodiversity Significance in North Shore, Toimi Uplands, and Laurentian Uplands Subsection Forest Management Plan.

• Consider the broader context and significance of the MCBS site as a whole when assigning management objectives and selecting stands for treatment.
• Determine location and composition of stand conversions based on native plant community (NPC) class.
• Have forest mangers determine the NPC Class for stands planned for site preparation and tree planting
• Plan forest development activities using the Field Guide to the Native Plant Communities of Minnesota: The Laurentian Mixed Forest Province.
• Allow some stands to succeed naturally to long-lived conifer communities.
• Strive to emulate the within-stand composition, structure, and function of older vegetative growth stages (VGSs) when managing some stands.
• Apply variable density techniques during harvest or reforestation.
• Apply variable retention techniques during harvest.
• Designate some stands as ERF (extended rotation forests) to provide old forest conditions.
• Maintain or increase within-stand species, age, and structural composition that is moving toward the mix and proportion of species found in the native plant community appropriate to that site.
• Whenever possible and practical, manage stand cover type conversions with less intensive site preparation or plantations with less intensive timber stand improvement.
• Increase the use of prescribed fire as a silvicultural technique in managing fire-dependent NPCs.
• Locate roads to minimize fragmentation of MCBS site.
• Emulate natural disturbance conditions in large patch management.
• Apply special management recommendations for known rare features.
• Defer management of some stands for further assessment (e.g., Ecologically Important Lowland Conifers and nominated natural areas).

Patch Recommendations
MCBS recommends the large patch sizes and minimal habitat fragmentation of the Site be maintained, which will require active coordination of management activities across ownerships. MCBS recommends patch planning and implementation in any part of the Site be consistent with the above landscape planning direction and with investigation specific to the Site.

Restoration Recommendations
To move the forest age-class distribution toward the range of natural variation, the mature and pole-mature growth stages, if managed, require an approach that allows them to move into the old multi-aged growth stage (see MFRC 2003). This will happen naturally as forests age if rotations are lengthened and seed sources for older growth stage species are present. However, in places where seed trees from older stage species are absent, active restoration via management and forest development activities may speed up this process. If natural gaps do not exist, planting or seeding these species may require some timber harvest to open up the canopy. Given the existing overall ecological and biological integrity of the communities, MCBS recommends that all planting be accomplished without the use of intensive mechanical site preparation or herbicides. MCBS also recommends the use of prescribed fire for site preparation to, for instance, establish pines to restore or sustain heterogeneity, or to maintain mid-successional communities such as mesic pine forests.

Native Plant Community/Stand Composition and Structure Recommendations
In general, MCBS recommends natural processes be allowed to predominate in the Headwaters Site. It is recommended that any harvest in the Headwaters Site resemble the natural disturbance regimes and natural stand development processes relevant to this heterogeneous landscape and its native plant communities. For example, in upland communities within the Extensive Peatlands and the greater Big Lake Area patch, MCBS recommends that harvest prescriptions result in much greater cover of post-harvest residual trees than traditional clearcuts with residuals.

MCBS recommends that the intent of forest management be stand continuation not stand initiation. The Voluntary Site-level Forest Management Guidelines (MFRC 2005) suggest 5% canopy cover of residuals, but wildfires usually leave much more than this (Carlson 2001), as does windthrow. Retention at harvest, informed by an understanding of the applicable natural disturbance regimes and in conjunction with complimentary rotations, is recommended to achieve specific structural and, by association, compositional goals. For example, rare native plant communities such as mesic pine [FDn43a] and upland cedar [FDn43c] communities should be reserved, and their dominant species (red pine, white pine, and white cedar) retained in mixed forests to sustain elements of older growth stages and provide a local seed source for natural regeneration. Variable retention harvest and variable density thinning prescriptions (Franklin et al. 1997) in aspen-dominated stands should promote retention and establishment of long-lived conifers (white pine, white spruce, white cedar, and tamarack) to move the forest toward more natural species composition ratios (see Human Disturbance and Use above).

If cutting occurs, edges between treated and untreated areas should not be 'hard'. Hard edges are abrupt, with little or no transition between closed-canopy forest and harvest openings, and increase subsequent windthrow and change the environment (in terms of light, moisture, etc.) in the adjacent forest. Instead, the tree canopy in treated areas should be gradually reduced with increasing distance from the closed-canopy forest.

In areas where dwarf mistletoe is identified as a concern, it is recommended that any effort to reduce the severity and extent of mistletoe infection recognize that dwarf mistletoe is an integral part of the ecosystem and complete eradication is not the objective. The following is recommended regarding treatment decisions:

- Dwarf mistletoe develops and spreads slowly; therefore there is time to implement management actions to slow or halt the spread of mistletoe infection. Mistletoe spreads more slowly in even-aged than uneven-aged forests, and more slowly in mixed forests comprised of host and non-host species.
- Conduct on-site evaluation of the severity and incidence of the mistletoe infection using a broadly accepted approach such as the Hawksworth six-class rating system. (Severity is defined as the average rating of all infected trees. Incidence is the proportion of susceptible trees infected within the stand).
- In areas where timber production is the priority, slowing or halting the spread of dwarf mistletoe infection into these stands should be the objective, as opposed to complete eradication within the infected stand.
- If it is determined that management of dwarf mistletoe in a stand at the Headwaters Site is imperative, use minimum host-free buffer distances recognized in the literature (50–65 feet). Incorporate natural barriers—such as lakes, rivers, and forests types other than black spruce (which serve as host-free buffers)—and other barriers such as existing roads, railroad and power line ROWs, and so on, into the management area design.
- Pruning (using specified methodology) combined with monitoring may be an acceptable approach for managing mistletoe infection in environmentally sensitive areas (e.g., adjacent to lakes, in riparian areas, in areas of hydrologic concern, or in areas with operability concerns).
- Prescribed burning should be seriously considered when treating areas rated with heavy mistletoe infection adjacent to or within the Headwaters Site.

Slash

MCBS recommends that slash from logging activities be evenly distributed over harvested areas of the patch, and the amount of large coarse woody debris (CWD) be maintained or increased. Decaying CWD contributes significantly to nutrient cycling in the forest ecosystem, helps in maintaining productivity, and provides habitat for species that form the base of the food web, including lichens, mosses, insects, amphibians, small mammals, and microorganisms.

Roads and Trails

Roads, both temporary and permanent, are among the few incontrovertible threats to the Site's integrity. Roads create additional forest edges that alter the environment of the forest, often disrupt water flow in wetlands, can be a barrier to the movements of some small vertebrate and invertebrate species, and facilitate the invasion of exotic plant and animal species (Trombulak and Frissell 2000). Exotic species are one of the greatest threats to native species, and to human-disturbed ecosystems worldwide (Reid and Miller 1989). Road building and use facilitate invasion by exotic species by providing a seedbed and regularly introducing seeds or other propagules (via fill materials, mulch, and equipment, and via users and their vehicles) into a conducive environment for establishment and growth (Westbrook 1998). MCBS survey work in 2005 found large upland and lowland areas in the Headwaters Site to be free of non-native species. Other portions not visited, but with similar absence of recent disturbance can be reasonably assumed to also be free of exotic species. Typically, non-native species within the Site were associated with roads and upland trails, and with forest stands that have been managed since 1960s.

Much of the forest in the Headwaters Site is probably free of exotic earthworm species. A major vector for earthworm establishment is road building, especially because of the fill brought in from off-site. In forest types, earthworms have been found to change soil profiles and negatively impact some understory fern and wildflower species (Hale 2004, Hale and Host 2005). Currently, there are no known control methods; once established, earthworms cannot be removed.

MCBS recommends roads, both temporary and permanent, be kept to an absolute minimum through careful planning and coordination among landowners. Given the extent of existing roads and trails and increasing off-highway vehicle use on these trails, we recommend no construction of new permanent roads or access for any purpose; that duplicate roads be eliminated through restoration of corridors to native vegetation; and closure of temporary roads or access be immediate and effective both when a management project has been completed and between work periods if multiple years of activity are necessary. Although trails normally cause less damage than roads, both motorized and non-motorized wheeled vehicles can act as vectors, carrying and dispersing earthworm eggs, exotic insect larvae, and propagules of exotic plant species on their tires along trails.

The peatlands complex and wetland areas within uplands are inappropriate for non-winter trails. It is possible that snowmobile trails may cross wetlands without extensive negative impacts. However, repeated, abnormally deep freezing on heavily used and compacted trails can alter vegetative composition. Given the extent of existing winter roads and trails and increasing off-highway vehicle use on these trails, MCBS recommends no new winter access roads be established in the Extensive Peatlands, that winter road access be limited to a few existing winter roads, and duplicate winter access be eliminated and corridors be restored to native vegetation where necessary.

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AFS SPECIAL REPORT

Headwater Streams and Wetlands are Critical for Sustaining Fish, Fisheries, and Ecosystem Services

Photo credit: Peter Turcik

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Att. 4 to MCEA/Friends, et al. June 6, 2022 Comment

Headwater streams and wetlands are integral components of watersheds that are critical for biodiversity, fisheries, ecosystem functions, natural resource-based economies, and human society and culture. These and other ecosystem services provided by intact and clean headwater streams and wetlands are critical for a sustainable future. Loss of legal protections for these vulnerable ecosystems would create a cascade of consequences, including reduced water quality, impaired ecosystem functioning, and loss of fish habitat for commercial and recreational fish species. Many fish species currently listed as threatened or endangered would face increased risks, and other taxa would become more vulnerable. In most regions of the USA, increased pollution and other impacts to headwaters would have negative economic consequences. Headwaters and the fishes they sustain have major cultural importance for many segments of U.S. society. Native peoples, in particular, have intimate relationships with fish and the streams that support them. Headwaters ecosystems and the natural, socio-cultural, and economic services they provide are already severely threatened, and would face even more loss under the Waters of the United States (WOTUS) rule recently proposed by the Trump administration.

INTRODUCTION

Headwaters are broadly defined as portions of a river basin that contribute to the development and maintenance of downstream navigable waters including rivers, lakes, and oceans (FEMAT 1993). Headwaters include wetlands outside of floodplains, small stream tributaries with permanent flow, tributaries with intermittent flow (e.g., periodic or seasonal flows supported by groundwater or precipitation), or tributaries or areas of the landscape with ephemeral flows (e.g., short-term flows that occur as a direct result of a rainfall event; USEPA 2013; USGS 2013). Headwater streams comprise the majority of river networks globally (Datry et al. 2014a); in the conterminous United States, headwater streams comprise 79% of river length, and they directly drain just over 70% of the land area (Figure 1). Along with wetlands, these ecosystems are essential for sustaining fish and fisheries in the USA (Nadeau and Rains 2007; Larned et al. 2010; Datry et al. 2014b). When headwaters are polluted, or headwater habitats are destroyed, fish, fisheries, and ecosystem services (i.e., benefits that humans gain from the natural environment and from normally functioning ecosystems) are compromised or completely lost.

With the U.S. Clean Water Act of 1972 (Federal Water Pollution Control Act), Congress recognized the importance of aquatic habitat and ecosystem connectivity in the stated objective of the Act "to restore and maintain the chemical, physical, and biological integrity of the nation's waters." Biological integrity has been defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region" (Frey 1977; Karr and Dudley 1981). The Act provides authority for the federal government to protect navigable waterways from channelization, pollution, and other forms of impairment by making it unlawful to discharge dredged or fill material into "navigable waters" without a permit, 33 U. S. C. §§1311(a), 1342(a). This authority extends to wetlands that are not navigable but adjacent to navigable-in-fact waterways (*United States v. Riverside Bayview Homes, Inc.*, 474 U.S. 121, 1985). The authority does not extend to waters that lack a "significant nexus" to navigable waters (*Solid Waste Agency of Northern Cook County [SWANCC] v. Army Corps of Engineers*, 531 U. S. 159, 2001). However, federal jurisdiction over non-navigable and their adjacent waters remained unclear.

The 2006 Supreme Court decision *Rapanos v. United States* (547 U.S. 715, 2006) did little to resolve the confusion, with a split decision from the Court regarding the extent of federal jurisdiction. In writing for four justices, Justice Scalia defined "waters of the United States" as only those waters and wetlands that contain "a relatively permanent flow" or that possess "a continuous surface connection" to waters with relatively permanent flow. Scalia's definition excluded intermittent and ephemeral streams, and wetlands that lack a continuous surface connection to other jurisdictional waters (i.e., wetlands outside of floodplains). This definition differs from that posited by Justice Kennedy in an opinion concurring with the plurality judgment to remand the case for further proceedings but not agreeing with the reasoning of the four justices represented by Scalia. In contrast, Kennedy gave deference to Congressional intent to allow the agencies to regulate pollution (dredge and fill) of waters of the United States. Justice Kennedy ruled that wetlands outside of floodplains, and intermittent and ephemeral streams should be included as waters of the United States if they "significantly affect the physical, chemical, and biological integrity" of downstream navigable waters. Therefore, Kennedy's definition of waters of the United States includes headwaters that are not necessarily navigable but are nevertheless connected to some degree with navigable waters downstream.

Following an extensive scientific review of the literature on waterbody connectivity (USEPA 2015), which included a detailed review by a U.S. Environmental Protection Agency

Headwaters in a Nutshell

- Headwater streams comprise 79% of our nation's stream networks; wetlands outside of floodplains comprise 6.59 million ha in the conterminous USA.
- Headwater streams and wetlands strongly influence ecological functions and fisheries not only within headwater regions, but also in downstream rivers, lakes, and coastal areas.
- Headwater ecosystems provide habitat for many endemic and threatened fish species as well as species supporting economically important fisheries.
- Headwaters provide native fish species with refuge from invasive aquatic species and can provide threatened species with critical refuge habitat.
- Commercial and recreational fisheries, which are dependent on headwaters, are vital economic components of local and regional economies.
- Headwater streams and wetlands are culturally important for many segments of U.S. society, with particularly high significance for many native peoples.
- Estimates of headwaters at risk under a narrower rule are likely low, because many of the 33% of streams in the conterminous western USA mapped as perennial were found to be intermittent or ephemeral.
- Headwater ecosystem impairment, loss, or destruction is assured under the revised WOTUS rule proposed, and would have severe and long-lasting negative consequences for fisheries and environmental conditions throughout the USA.

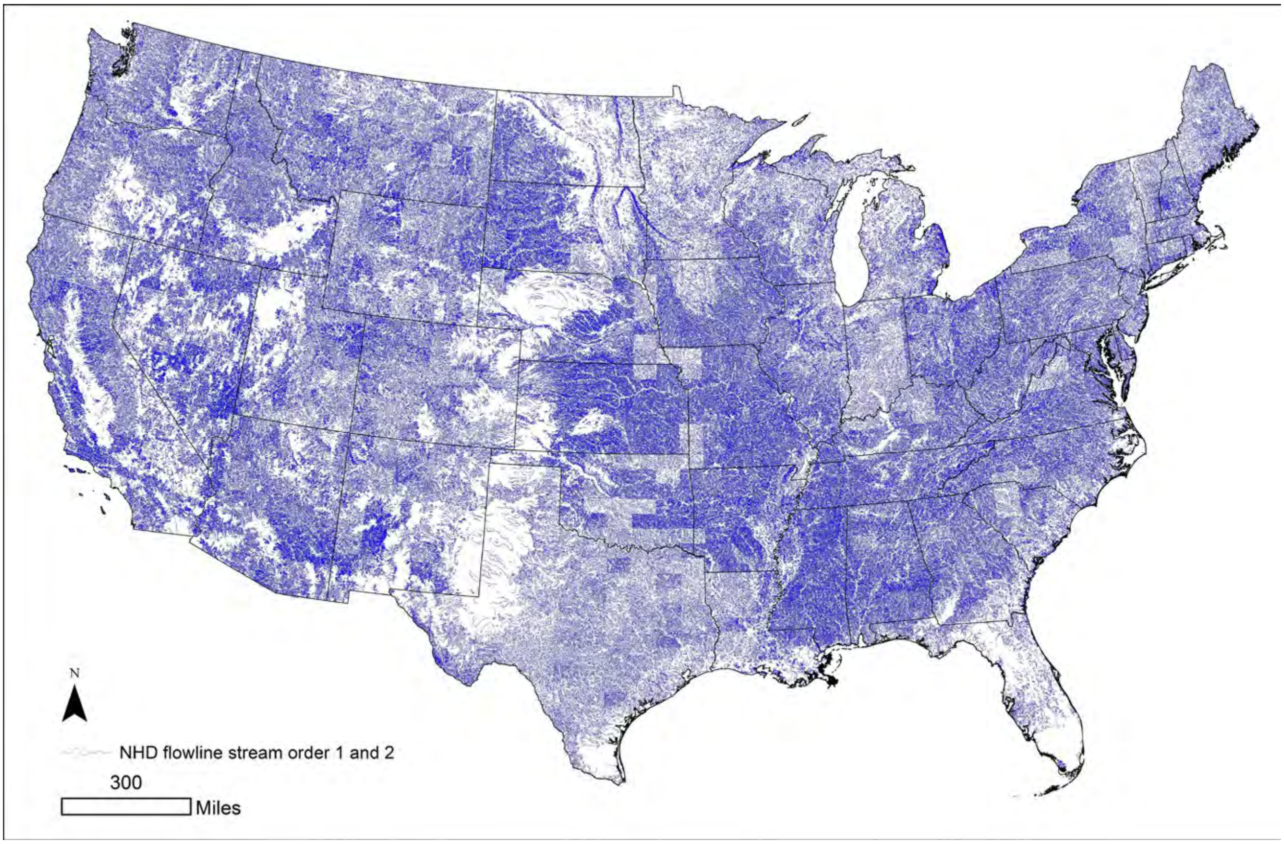

Figure 1. Map of 1st- and 2nd-order tributaries (a stream lacking a tributary and a stream with only first-order tributaries, respectively) comprising river networks of the conterminous United States as characterized by the 1:100,000 scale National Hydrography Dataset Plus Version 2 (NHDPlusV2; USEPA & USGS 2012). However, this is not a full accounting of all 1st- and 2nd-order headwater streams. Currently, it is not possible to comprehensively map all headwater streams because of the sheer number of headwater tributaries that comprise river networks, variability in tributary flow permanence, and the resolution and accuracy of available spatial data necessary to accurately map or model streams and other overland flows (Hughes and Omernik 1981). For example, note the differing stream densities that occur within different regions of the USA (e.g., Indiana versus the Central Plains) or even within states (e.g., varied densities throughout Oklahoma). The differences in density result from state-by-state differences in how streams are mapped or modeled. Despite these limitations, the NHDPlusV2 represents the most comprehensive coverage of tributaries and catchments available for the U.S., allowing us to assess their general prominence of headwaters in U.S. river networks.

(EPA) Science Advisory Board (SAB) of technical experts from the public ("SAB Review;" SAB, 2014 Letter to Gina McCarthy, Review of the Draft EPA Report Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of Scientific Evidence), the Obama administration issued the Waters of the Unites States (WOTUS) Rule in 2015 that clarified the jurisdiction of the Clean Water Act to include protections for intermittent and ephemeral headwater streams and hydrologically connected wetlands (i.e., with a permanent surface inflow or outflow and directly adjacent to navigable waters), with wetlands outside of the floodplains to be evaluated on a case-by-case basis. The American Fisheries Society (AFS) supports that rule and the science underpinning its development, as documented by review of more than 1,200 peer-reviewed scientific studies by technical experts to determine degrees of connectivity and their ecological consequences between navigable waters, wetlands, and headwater streams (USEPA 2015). On February 28, 2017, the Trump administration issued an executive order directing the EPA and the Department of the Army to review and rescind or revise the 2015 rule. The proposed "Recodification of Pre-Existing Rules" (U.S. Army Corps of Engineers, Department of Defense, USEPA 2018 Revised Definition of "Waters of the United States") establishes a narrower legal definition, implementing the pre-Obama era regulations that provided fewer protections for thousands of miles of headwater streams and millions of acres of wetlands outside of floodplains. Those wetlands are distributed across 6.59 million ha in the conterminous USA as, for example, playa lakes, prairie potholes, Carolina and Delmarva bays, pocosins, and vernal pools; they provide valuable habitat for fish and other organisms and are particularly vulnerable ecosystems (Tiner 2003; Lane and D'Amico 2016; Creed et al. 2017; Figure 2). We refer to headwater streams and wetlands outside of floodplains collectively as "headwaters." However, we also emphasize the inherent complexity of natural systems, and recognize and provide examples of waterbody types that provide similar functions as headwaters such as floodplain wetlands that lack a continuous hydrologic surface connection to a river, low-gradient streams that flow through floodplains, and sloughs and side-channels of navigable rivers.

Headwaters provide numerous services that are essential to ecosystems (Peterson et al. 2001; Meyer et al. 2003), including sustaining aquifers and supplying clean water for more than

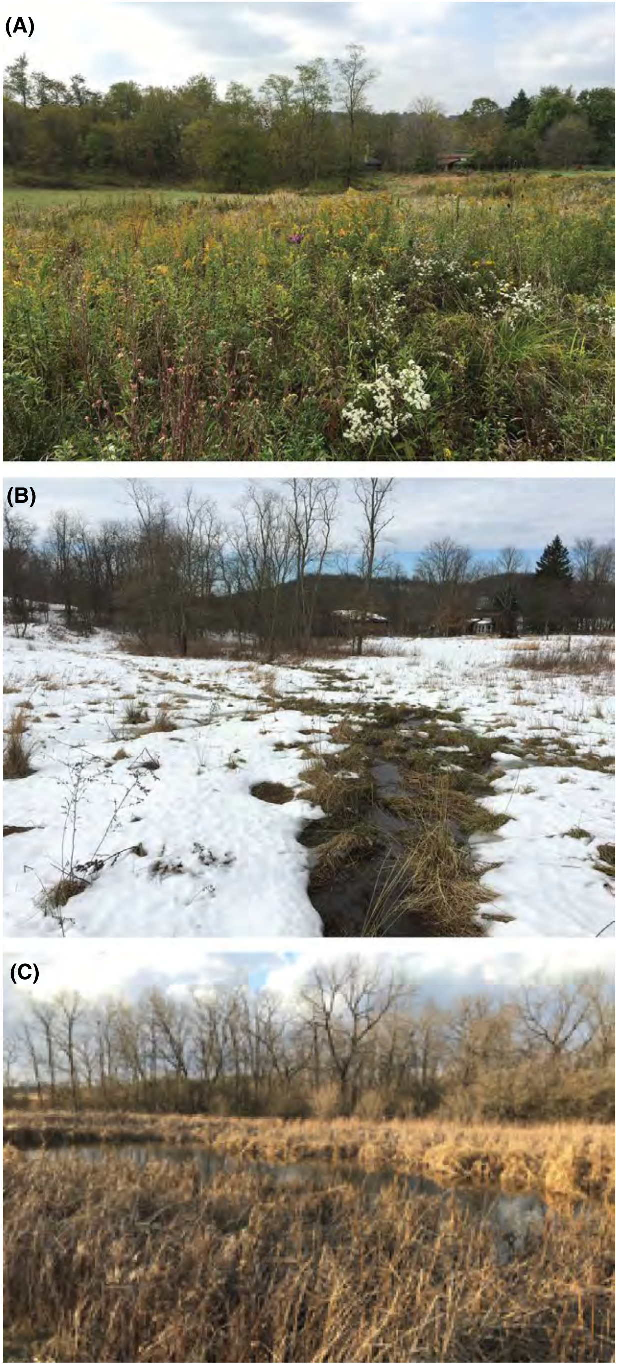

Figure 2. Wetlands outside of floodplains—such as the headwater/source wetland (**A**) in summer and (**B**) winter in Pennsylvania and the (**C**) prairie wetland in Ohio—would be particularly vulnerable to loss of protections. Photo credits: P. D. Shirey: A, B; S. M. P. Sullivan: C.

one-third of the U.S. population (USEPA 2009). At regional scales, headwaters are critical for sustaining aquatic biodiversity (Meyer et al. 2007; Clarke et al. 2008) and for providing vital spawning and rearing habitat for migratory fishes, including commercially fished species (Quinn 2005; Schindler et al. 2010; McClenachan et al. 2015). Headwaters provide dispersal corridors and habitat for fishes and other aquatic and semiaquatic organisms (e.g., invertebrates, amphibians, and birds), including many endemic and rare species (Steward et al. 2012; Jaeger et al. 2014; Sullivan et al. 2015). Ephemeral headwater streams can support levels of aquatic invertebrate diversity and abundance comparable to, or greater than, those estimated for perennial headwaters, as well as taxa found nowhere else in the watershed (Dieterich and Anderson 2000; Progar and Moldenke 2002; Price et al. 2003).

Headwaters and their ecosystem services are tightly intertwined with the nation's cultural landscape (Boraas and Knott 2018) and are highly vulnerable to a host of human impacts (Creed et al. 2017). Climate change, channel modification, water diversion, and land development (e.g., urbanization, agriculture, mining, deforestation) impair and destroy headwaters by, for example, increasing erosion, sedimentation, and desiccation in both headwaters and downstream reaches of river networks (Walsh et al. 2005; Freeman et al. 2007; Perkin et al. 2017). Pollution of headwaters, including runoff of excess nutrients and other pollutants, degrades water quality affecting downstream ecosystems. Two striking U.S. examples are discharge effluent from mining (Woody et al. 2010; Daniel et al. 2015; Giam et al. 2018) and nutrient loading in the Mississippi River causing the Gulf of Mexico's "dead zone," a vast area of hypoxia that reduces biodiversity and commercial fisheries, with major economic and social costs (Rabalais et al. 1995; Rabotyagov et al. 2014). Similarly, polluted headwaters contribute to harmful algal blooms that result in toxic water, fish kills, domestic animal and human morbidity, and economic damage (Tango 2008; Zimmer 2014; Staletovich 2018). For wetlands outside of floodplains, global estimates indicate continued loss of >30% since 1970 (Dixon et al. 2016).

Discrepancies between actual and estimated stream length and type have long been recognized as problematic and may lead to increased ambiguity in applying a narrower WOTUS rule, especially over time. Headwater stream losses in many regions of the USA are underestimated because drainage networks have not been mapped at sufficiently fine spatial scales (Hughes and Omernik 1981; Meyer and Wallace 2001; Colson et al. 2008), thus posing serious risk to ecological and societal benefits (Creed et al. 2017). Stream type is also often misattributed or changes over time, for example, 207,770 km (33%) of the total length of stream networks in the conterminous western USA mapped as perennial was determined to be non-perennial or not a stream. The map error varied from 55% of stream length in the Southwest to 33% in the western Great Plains to 24% in the western mountains (Stoddard et al. 2005). Changes in estimates from perennial to intermittent or ephemeral streams is a result of mapping errors, climate change, and water withdrawals. Similarly, Perkin et al. (2017) determined a loss of 558 km (21%) of stream length from 1950 to 1980 in the Upper Kansas River Basin, presumably as a result of ground-water pumping accentuated by climate change. These investigators projected a cumulative loss of 844 km (32%) by 2060. In other words, highly vulnerable intermittent and ephemeral streams and rivers are increasingly replacing perennial streams and rivers.

Non-perennial streams and non-floodplain wetlands are integral components of aquatic ecosystems, especially when considered in the aggregate. As supported by the SAB Review (SAB, 2014 Letter to Gina McCarthy, Review of the Draft EPA Report Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of Scientific Evidence), connectivity between headwaters and downstream waterbodies reflects a gradient in the variability of the frequency, duration, magnitude, predictability, and consequences of physical, chemical, and biological connections. The SAB Review notes

BOX 1. LONGNOSE SUCKERS LINK TRIBUTARY STREAMS AND LAKES

Several fish species migrate from the Laurentian Great Lakes into headwater tributaries to spawn. During spring, Longnose Suckers *Catostomus catostomus* undergo massive spawning runs from Lake Michigan into tributary streams (Figure 3). Egg and larval survival to outmigration appears to be strongly influenced by spring flow and temperature, and this variability can influence stock dynamics (Childress et al. 2016). Egg mortality and excretion by migrating adult suckers contributes significant amounts of nitrogen and phosphorus to stream ecosystems. The millions of larval suckers that may be exported from a single stream to the lake provide a significant nutritional subsidy for a host of recreational fishes that include Walleye *Sander vitreus*, bass, and salmon (Childress and McIntyre 2015). Stream network connectivity has been reduced over large portions of Great Lakes drainage basins, with negative effects on Longnose Suckers, the ecosystem functions they support, and stocks of other fishes that migrate into tributaries for spawning.

that even low levels of connectivity can be important relative to impacts on the chemical, physical, and biological integrity of downstream waters. The SAB Review also highlights the importance of the cumulative effects of streams and wetlands on downstream waters. These relationships also vary spatially and temporally as in some areas, such as arid regions, ephemeral streams comprise the majority of the stream network. Although they flow infrequently during an annual cycle, they are integral to the ecological function of their watersheds, which have evolved with this type of flow network (Meyer et al. 2003). In these and other systems, ephemeral streams and wetlands provide unique and essential habitat for species for which there is no known perennial equivalency (Falke et al. 2010, 2012; Medley and Shirey 2013; Hutson et al. 2018).

Because of the importance of headwaters, any rule that excludes their protection will have far reaching implications for fish, wildlife, and their habitats, as well as economies dependent on those ecosystems. Headwaters are key to the sustainability of fish stocks in both upstream and downstream waters. Threatened and endangered species will be harder to recover, and more species will be at risk of becoming imperiled. Simply put, loss of protections for headwaters would have grave consequences for fish and fisheries. Ultimately, communities across the USA would lose the economic, social, and cultural benefits derived from headwaters. In the following sections, we provide a brief overview of scientific evidence supporting the ecological, social, economic, and cultural importance of headwaters, and highlight some implications of returning to reduced federal protections.

HEADWATERS SUPPORT ECOSYSTEMS

Headwaters perform ecological functions (i.e., biological, geochemical, and physical processes that occur within an ecosystem) that are critical for ecosystem services throughout their drainage basins. Headwaters deliver water, sediments, and organic material to downstream waters; contribute to nutrient cycling and water quality; enhance flood protection and mitigation; and provide recreational opportunities (Gomi et al. 2002; Richardson and Danehy 2007; Hill et al. 2014; Cohen et al. 2016). Headwater ecosystems provide both habitat and food resources for fish and other aquatic and riparian organisms; in turn, fish in headwaters affect food-web dynamics and contribute to the functioning of headwater ecosystems (Richardson and Danehy 2007; Sullivan 2012; Hill et al. 2014). Ecosystem functions in headwaters also maintain aquatic and riparian biodiversity and the sustainability of fish stocks not only in headwater reaches, but also in larger downstream habitats. These and other functions of headwater streams make them economically vital, with recent estimates at $US15.7 trillion/year in ecosystem services for the conterminous USA and Hawai'i (Nadeau and Rains 2007). For wetlands outside of floodplains, ecosystem service estimates are $673 billion/year for the conterminous USA (Lane and D'Amico 2016).

Headwaters receive runoff and groundwater from watersheds and discharge to larger waterbodies downstream. In doing so, they transport sediment and organic material, including large wood from adjacent and upstream riparian systems that are essential for the ecological condition of downstream ecosystems (Gregory et al. 1991; Benda and Dunne 1997). Drifting organic matter (organisms and particulate organic matter) from headwaters provides food for fishes and invertebrates in downstream reaches (Gomi et al. 2002; Wipfli and Gregovich 2002; Wipfli and Baxter 2010). The provisioning of

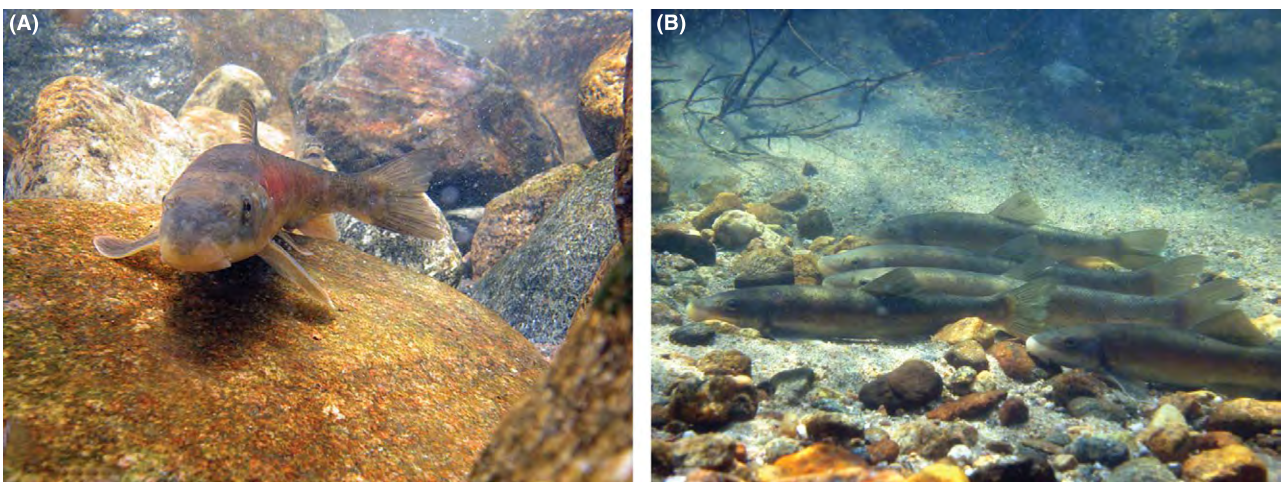

Figure 3. An individual Longnose Sucker (A), and an aggregation (B) similar to those that spawn en masse in tributaries of Lake Michigan. Photo credit: Jeremy Monroe, Freshwaters Illustrated.

Att. 4 to MCEA/Friends, et al. June 6, 2022 Comment

large wood for habitat development is crucial for aquatic biota, including juvenile salmon and trout (Bilby and Ward 1991; Bilby et al. 2003; Herdrich et al. 2018). Changes in the large-wood recruitment regime resulting from timber harvests have depleted complexity in many mountain streams (Fausch and Young 2004) as well as in streams in other areas of the country (e.g., upper Midwest; Richards 1976; Wohl 2014). Removing wood from streams can also result in reduction of pools and overall habitat complexity as well as fewer and smaller individuals of both coldwater and warmwater fishes (Fausch and Northcote 1992; Dolloff and Warren 2003). Unpolluted headwaters are essential for maintenance of coldwater fish stocks, including Chinook Salmon *Oncorhynchus tshawytscha*, Coho Salmon *O. kisutch*, Steelhead *O. mykiss*, Cutthroat Trout *O. clarkii*, Bull Trout *Salvelinus confluentus*, Apache Trout *O. apache*, Gila Trout *O. gilae*, Golden Trout *O. aguabonita*, Redband Trout *O. mykiss*, Brook Trout *S. fontinalis*, Brown Trout *Salmo trutta*, and Atlantic Salmon *S. salar*.

When the natural flow regimes of headwater streams are altered, downstream water quality often is impaired. Headwaters mediate the intensity and frequency of downstream floods, and play a significant role in global carbon and nitrogen cycling (Gomi et al. 2002; Bernhardt et al. 2005; Lowe and Likens 2005; Marx et al. 2017). Discharge from headwaters also influences downstream fluxes of dissolved and particulate organic matter and nutrients (Alexander et al. 2007; Lassaletta et al. 2010). The cycling of nutrients—including rates of nitrogen uptake, storage, regeneration, and export—is a critical function of headwaters. For instance, Peterson et al. (2001) reported that the most rapid uptake and transformation of inorganic nitrogen can occur in the smallest streams of a catchment, particularly temporary streams, where tightly coupled water-streambed interactions facilitate in-stream retention of nitrogen. Most nitrogen flowing through a drainage network is estimated to come from headwater streams; in the northeastern USA, headwater tributaries can deliver up to 45% of the nitrogen load flowing downstream (Alexander et al. 2007). Additionally, transfer of nitrogen to the atmosphere occurs in headwater systems through denitrification (Mulholland et al. 2009). Hotspots of nutrient transformations are typically linked to physical and microbial processes in headwaters (e.g., McClain et al. 2003). Channel alterations, excess nutrients and sediments, and losses of flows in headwater streams deteriorate water quality (e.g., eutrophication and hypoxia) in downstream systems throughout the USA (Alexander et al. 2007; USEPA 2016a, 2016b; USEPA 2009). Further loss of headwater systems is expected to have major negative consequences for biogeochemical cycles at local to continental and global scales.

Important ecological functions and ecosystem services are provided even by ephemeral and intermittent headwaters (Steward et al. 2012). In arid and semi-arid regions, dry streambeds are “seed and egg banks” for aquatic biota, and when flowing, function as dispersal corridors and temporal ecotones linking wet and dry phases. During dry phases, ephemeral streams store organic material; when flowing, these streams are hotspots for nutrient cycling and other biogeochemical processes (Fisher et al. 1982; McClain et al. 2003). In some arid regions, up to 96% of streams contain little or no flow during much of the year; however, during monsoons they are critical for conveying runoff (Meyer et al. 2003). Permeable surficial geology and low slopes can reduce flood peaks in headwaters and extend the flow of cool water to downstream reaches, thereby expanding thermal refuges (Gomi et al. 2002). Cool headwaters provide important thermal refuges in regions especially susceptible to climate change, including the desert Southwest and intermountain western United States.

Although fish abundance and diversity generally are lower in headwater systems compared to downstream reaches (Schlosser 1987), species composition can be distinct from the rest of the network (Paller 1994). Further, headwaters often support ecological specialist as well as threatened taxa not found elsewhere within the river network (DeRolph et al. 2015; Liang et al. 2013; Lowe and Likens 2005; also see *The importance of headwaters for imperiled species*). Fish inhabiting wetlands located outside of floodplains may benefit from greater availability of food resources compared to habitats in other aquatic ecosystems (Snodgrass et al. 2001; Baber et al. 2002).

Fish contribute both directly and indirectly to headwater ecosystem processes (e.g., Hanson et al. 2005) that, in turn, affect biodiversity and productivity in the receiving river network (Meyer et al. 2007). Through their spawning and foraging activities, fish influence local biotic communities by modifying substrates (e.g., spawning salmonid redds; Montgomery et al. 1996; Moore et al. 2004) and resuspending detritus and other particulate organic matter into the water column (e.g., benthic feeding by the Ozark Minnow *Notropis nubilis*; Gelwick et al. 1997) where it drifts downstream to support populations of aquatic invertebrates. Furthermore, fish feeding and excretion increase availability of inorganic nutrients and stimulate aquatic primary productivity (McIntyre et al. 2008).

Fish are often the top predators in headwater food webs, and thereby exert top-down control of invertebrate assemblages and indirectly affect ecosystem functions such as aquatic primary and secondary production, the latter including emergent aquatic insects that export biomass from streams to terrestrial food webs (Nakano et al. 1999; Baxter et al. 2004). Fish also link aquatic and terrestrial ecosystems in other, more direct ways. During annual leaf-out periods, insectivorous fishes feed on arthropods that fall from riparian vegetation into streams (Wipfli 1997; Baxter et al. 2005). Fish also provide important nutritional subsidies for terrestrial consumers, such as the American dipper *Cinclus mexicanus*, North America’s only aquatic songbird (e.g., Sullivan et al. 2015), and grizzly bear *Ursus arctos* (e.g., Matt and Suring 2018).

Many fish species occupy both headwater and downstream habitats during their life cycles (Fausch et al. 2002). For instance, most anadromous salmonids return to their natal streams after spending most of their lives in the ocean. In doing so, fish transport marine-derived nutrients to headwater streams (Zhang et al. 2003). Marine-derived nutrients from salmon carcasses have been shown to increase production of aquatic basal resources, macroinvertebrates, and resident fish stocks (Zhang et al. 2003; Janetski et al. 2009). Marine-derived nutrients are especially important for oligotrophic streams, which are predominant in the Pacific Northwest and Alaska where even small inputs of certain nutrients and sources of organic matter can significantly augment ecosystem productivity (Bilby et al. 1996). Moreover, fish in headwater streams are an important food source for terrestrial consumers, thereby transferring nutrients and energy from aquatic to terrestrial ecosystems. By linking nutrients, energy, and gene pools across space and time, fish migration has been characterized as a type of ecological “memory” of an ecosystem (Holling and Sanderson 1996). Headwaters, their receiving waters, and their functions already have been severely degraded by multiple human activities, including channel alteration, water diversion, and land modification by agriculture, livestock grazing, mining, and urbanization (e.g., Hughes et al. 2010, 2014, 2016; Beschta et al. 2013). These land uses and others have eliminated countless headwater streams and wetlands that once served as natural primary, secondary, and tertiary nutrient, sediment, and contaminant treatment systems, thereby leading to untreated runoff from diffuse pollution sources (Karr and Schlosser 1978; Karr 1991; Gammon 2005; Woody et al. 2010; Hughes et al. 2014; Daniel et al. 2015). These stressors have caused biological and environmental degradation to over 70% of stream and river length in the conterminous USA (USEPA 2009; Crawford et al. 2016; USEPA 2016a, 2016b). Wetland loss—including but not limited to wetlands outside of floodplains—across the USA is staggering, with some Midwestern states (e.g., Illinois, Indiana, Ohio, Missouri) having lost >85% of wetland area since the 1780s (Dahl 1990). Given the vulnerability and many important ecosystem functions provided by headwaters, policies that would reduce protections are a serious concern.

HEADWATERS SUPPORT IMPERILED SPECIES

Habitat loss and pollution are the primary causes of extinction of aquatic biota (Miller et al. 1989; Dudgeon et al. 2006; Arthington et al. 2016), and emerging threats exacerbate population decline of rare or range-restricted species (Minckley and Deacon 1991; Reid and Mandrak 2008; Shirey et al. 2018). Many threatened desert fishes, such as pupfishes *Cyprinodon* spp., have geographic distributions limited entirely to one or more isolated spring-fed headwaters (Rogowski et al. 2006; Dzul et al. 2013; Figure 4) but many such isolated waters would likely not be protected under a narrower rule. In the 1950s and 1960s, groundwater pumping in Nevada destroyed springs and associated spring-fed wetlands, resulting in the extinction of Las Vegas Dace *Rhinichthys deaconi* and Ash Meadows Poolfish *Empetrichthys merriami*, and put other species at risk of extinction, including the Devils Hole Pupfish *Cyprinodon diabolis*. By highlighting the plight of the remaining imperiled desert fishes, fisheries professionals increased public awareness of the nexus between groundwater and surface water habitat (Deacon and Williams 1991). This awareness stimulated support for halting groundwater pumping in order to protect the remaining habitat and avert further extinctions, although new threats continue to emerge (Deacon et al. 2007). For instance, up to 31 rare and endangered fish species or subspecies that inhabit headwater streams or springs of Nevada, Utah, and California are threatened by proposed groundwater withdrawals in southern Nevada.

Figure 4. **(A)** Death Valley Pupfish *Cyprinodon salinus* spawn during spring flows in **(B)** Salt Creek, Death Valley National Park, California. **(C)** a boardwalk provides access to view the Death Valley Pupfish during winter and spring flows. **(D)** Salt Creek ceases to flow during the remainder of the year and Death Valley Pupfish take refuge in headwater pools. Photo Credit: A–C, National Park Service; D, Jessica Wilson, Creative Commons.

Again, the primary objective of the Clean Water Act (1972) is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. That objective includes species that have become imperiled and are listed as threatened or endangered federally under the Endangered Species Act or protected by states and other entities (Angermeier and Karr 1994). If headwater impairment threatens a federally listed species residing in navigable waters downstream, then that headwater clearly would merit protection under the Clean Water Act because it meets the "significant nexus" test (after SWANCC 2001), and this would be true whether flows are intermittent or ephemeral.

Cavefish habitat demonstrates the importance of the significant nexus perspective, because ephemeral or intermittent headwaters support habitat for imperiled species living in habitat farther downstream (Figure 5). Aquatic habitats of federally listed Ozark Cavefish *Amblyopsis rosae* (threatened) in Cave Springs Cave, Arkansas (Graening et al. 2010), and Alabama Cavefish *Speoplatyrhinus poulsoni* (endangered) in Key Cave, Alabama (USFWS 2017), are supplied water from streams that flow intermittently above and below the surface at intervals as well as seeps, sink holes, and fractures in karst formations. Headwater streams in this region are not navigable, but they are essential for cavefish habitat, and their discharge contributes to flows in the Illinois (Arkansas; Brown et al. 1998) and Tennessee (USFWS 2017) rivers. Therefore, pollution of a sinkhole impacts both cave habitat and navigable waters downstream. A narrower rule defining waters of the United States that excludes headwaters in karst terrain would allow cavefish habitat to be polluted or destroyed such as by filling of or discharging to sinkholes.

Whereas cavefish are restricted to habitats fed by headwaters, other fishes use headwater streams and wetlands that are intermittent or ephemeral during specific stages of

Figure 5. **(A)** Fed by headwaters in karst topography, Cave Springs Cave discharges groundwater to Osage Creek, a tributary to the navigable Illinois River. The Cave Springs Cave headwater (Photo Credit: Arkansas Natural Heritage Commission) provides habitat for **(B)** the federally threatened Ozark Cavefish *Amblyopsis rosae* (Photo Credit: Jim Rathert, Missouri Department of Conservation). **(C)** The Calapooia River's lowland tributaries provide habitat to several species including the first fish species to be delisted under the Endangered Species Act (Photo Credit: Randall Colvin), **(D)** the Oregon Chub *Oregonichthys crameri* (Photo Credit: USFWS). **(E)** The Arikaree River (Photo Credit: Jeff Falke) is an intermittent plains streams in eastern Colorado that supported 16 native fish species adapted to this harsh habitat, including **(F)** the Orangethroat Darter *Etheostoma spectabile* (Photo Credit: Jeremy Monroe, Freshwaters Illustrated) that is imperiled in Colorado.

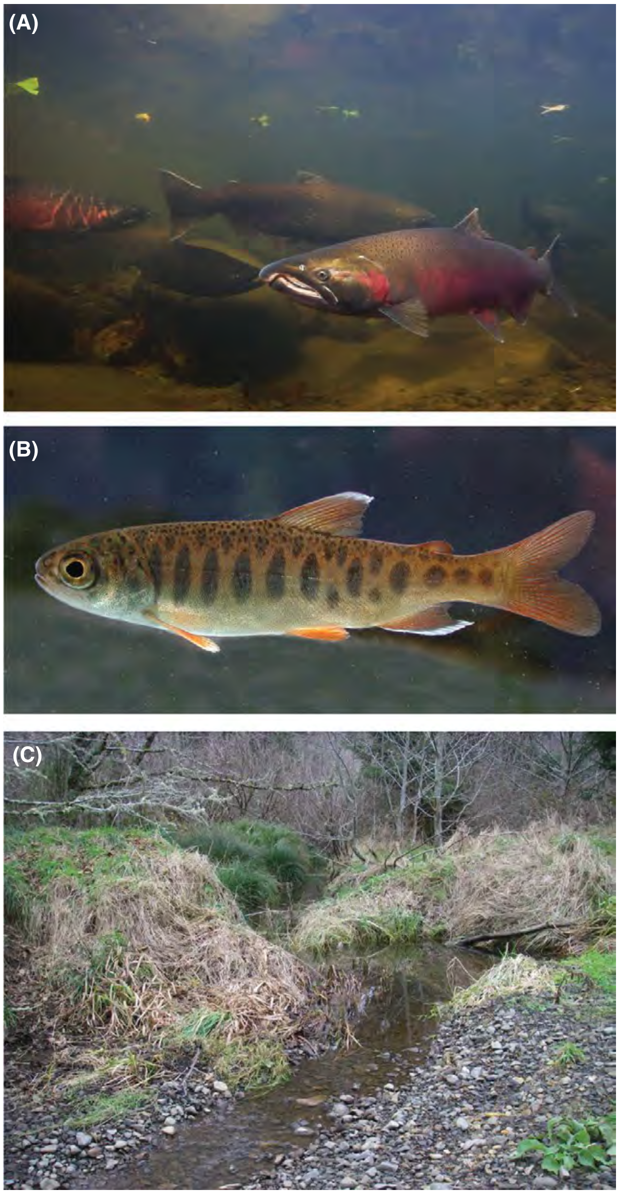

Figure 6. The Oregon Coast Coho Salmon (**A**; Jeremy Monroe, Freshwaters Illustrated) is an evolutionarily significant unit listed as threatened under the Endangered Species Act. Juvenile coho (**B**; Lance Campbell); of several life history types of this species use very small headwater habitats in coastal streams that are wet only in winter, including side-channels and backwaters that are dry during summer like Crowley Creek, Oregon in the Salmon River watershed (**C**; Trevan Cornwell).

their life cycles. Because they may be dry for much of the year, these headwaters might seem unimportant for fishes, and yet they can be essential for the persistence of certain stocks. Intermittent streams are important spawning and refuge habitats for imperiled salmon, trout, darters, minnows, suckers, and other fishes (Figures 5 and 6). Examples include federally listed Coho Salmon and Chinook Salmon, species with juveniles that occupy headwater tributaries and seasonal floodplain wetlands during winter. During the rest of the year, these habitats are either dry or so small that they are not considered suitable salmon habitat (Brown and Hartman 1988; Sommer et al. 2001; Jones et al. 2014; Katz et al. 2017; Woelfle-Erskine et al. 2017). Nonetheless, these intermittent habitats can play a critical role in recruitment. Coho Salmon smolts that inhabit pools in intermittent headwater streams in Oregon are larger than smolts from perennial streams in the same river basin (Wigington et al. 2006). Because larger smolts have higher ocean survival rates, the loss of these intermittent streams could be detrimental to salmon populations in coastal drainages.

Historically, western Oregon's upper Willamette River was bordered by a floodplain forest 2–9 km wide with multiple shaded waterways; winter floods markedly increased its floodplain stream network (Hughes et al. in press). During the past century, agriculture and channelization have altered or eliminated most intermittent water bodies in the valley. However, the remaining temporary streams and ditches still provide critical habitat for a wide diversity of native fish species, such as Cutthroat Trout, Rainbow Trout *O. mykiss*, endangered Chinook Salmon, and the endemic Oregon Chub *Oregonichthyes crameri*. These seasonal habitats provide flood refuge, rearing habitats, and separation from invasive alien fish species, all of which are essential for recovering and maintaining valuable sport and commercial fisheries and endangered species (Colvin et al. 2009; Hughes et al. in press; Figure 5). Collaborations with Willamette Valley landowners have been instrumental in improving Oregon Chub habitat and its delisting, and farmers are pleased to know that their winter-wet waterways offer important habitats for valued salmonids.

Headwater streams also are important for salmon in the eastern USA. In Maine, federally endangered Atlantic Salmon migrate up rivers and streams in early summer to take residence in deep pools with cool, well-oxygenated water prior to their ascent into tributaries for spawning during fall (Baum 1997; NMFS 2009). Atlantic Salmon eggs, larvae, and juveniles require clean gravel and cool, oxygenated water to ensure adequate growth and survival in headwaters until returning to marine habitat to mature (Danie et al. 1984; NMFS 2009). Recovery of Atlantic Salmon stocks may also require reestablishing populations of other diadromous species, such as Alewives *Alosa pseudoharengus*, that also depend on headwaters and that were important prey (Saunders et al. 2006). A narrower rule that excludes intermittent headwaters in the Pacific Northwest and New England would allow pollution and destruction of significant salmon habitat and further risk the extirpation of salmon.

Non-anadromous trout and charr also use headwaters as critical habitats, including for spawning and refuge from harsh conditions. Nearly half of the population of Rainbow Trout in a Sierra Nevada mountain stream spawned in an intermittent tributary that provided refuge from flood disturbance and nonnative Brook Trout (Erman and Hawthorne 1976). In their native range, Brook Trout are highly reliant on cool headwaters (Figure 7) and face declines in much of their native distribution due to impacts from dams, water diversion, channelization, and sedimentation (Curry et al. 1997; Etnier 1997; Hudy et al. 2008). Throughout the western United States, the many subspecies of native Cutthroat Trout persist primarily in small headwater streams above natural or created barriers that create refuges from nonnative species (Shepard et al. 2005; Roberts et al. 2013).

Many headwaters of the western Great Plains and dry valleys of the intermountain western United States are ephemeral, and yet are important habitats for fish during months when they have water (Figures 5 and 8). Several imperiled minnow species use ephemeral or intermittent backwaters in floodplain wetlands adjacent to stream channels for spawning and rearing (e.g., *Hybognathus* spp.; Falke et al. 2010, 2012; Medley

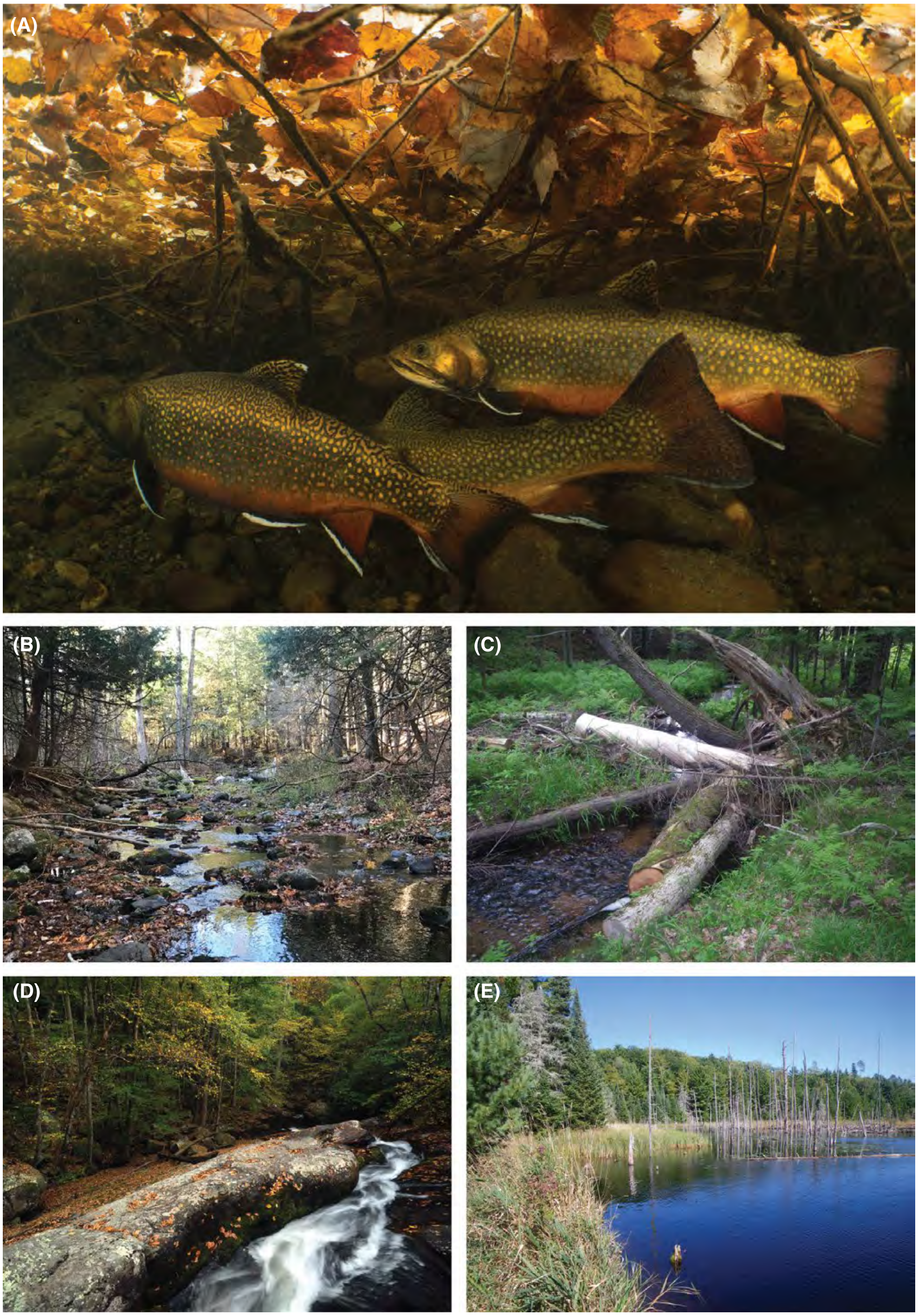

Figure 7. **(A)** Brook Trout *Salvelinus fontinalis* require cold, clear, and well-oxygenated water often found in headwater habitats. Examples of headwater streams inhabited by Brook Trout are shown for **(B)** a stream which becomes intermittent and composed of isolated pools in dry years in Maine (Photo Credit: Susan A.R. Colvin), **(C)** Michigan (Photo Credit: Patrick D. Shirey), and **(D)** an Appalachian headwater stream (Photo Credit: David Herasimtschuk, Freshwaters Illustrated). **(E)** an intermittent stream in Wisconsin impounded by beaver *Castor canadensis* creates diverse headwater habitat and provides ecosystem services of nutrient cycling and floodwater storage (Photo Credit: Patrick D. Shirey).

and Shirey 2013; Hutson et al. 2018). Many minnows, suckers, sunfishes, and darters in arid-land streams disperse between deep pools that retain water by exploiting ephemeral channels when flowing (Fausch and Bramblett 1991; Labbe and Fausch 2000). Though adjacent floodplain wetlands of navigable waters that are defined as wetlands are currently regulated under the Clean Water Act (*United States v. Riverside Bayview 1985*), if the protection of temporary headwaters were to be rescinded, significant amounts of this essential fish habitat would be at risk from changes in headwater source flows or pollution resulting from fill and contaminated discharges.

Headwaters sometimes provide the last refuge for species threatened by loss of habitat elsewhere in the watershed. Examples include the federally endangered Yellowcheek

Figure 8. **(A)** Cottonwood Creek is an intermittent tributary of the Gunnison River (Colorado River basin) in western Colorado that hosts large numbers of **(B)** Bluehead Sucker *Catostomus discobolus*, **(C)** Flannelmouth Sucker *C. latipinnis*, and **(D)** Roundtail Chub *Gila robusta* during spring spawning. Stream discharge varies widely based on snowfall, but these three imperiled species show considerable behavioral plasticity in timing their entry from the main river to this headwater tributary to take advantage of the seasonally available spawning habitat it provides. Fish enter the stream as soon as water depths permit, often in consecutive years. Spawning suckers of both species displayed tributary residency of more than 25 days in years when March or early April flows were adequate **(E** and **F)**, and more than 10,000 individuals used the stream annually (Hooley-Underwood et al., in press). Adults and just-hatched larvae subsequently moved out of the stream **(G)**, and by mid-June **(H)** flow ceased and the streambed dried completely. Intermittent tributaries like these are critical for sustaining populations of these three species, which are the subject of rangewide conservation efforts to prevent listing under the Endangered Species Act.

Darter *Etheostoma moorei* (endemic to the Boston Mountains of Arkansas; Robison and Buchanan 1988; Magoulick and Lynch 2015) and the federally threatened Leopard Darter *Percina pantherina* (endemic to a few headwater streams in the Ouachita Mountains of southeastern Oklahoma and southwestern Arkansas; Zale et al. 1994). The endangered Shortnose Sucker *Chasmistes brevirostris* and Lost River Sucker *Deltistes luxatus* depend on clean gravel in headwater tributaries or springs for spawning as well as adjacent wetlands and nearshore vegetation for juvenile rearing (USFWS 2012b). Wetlands that were replaced by pasture and cropland have contributed to the continued listing of these species. Thermal habitats unique to mountain headwater streams throughout the western Unites States are expected to provide important refuges for native species in the face of climate change, including many of conservation concern, such as Bull Trout and many subspecies of Cutthroat Trout (Wenger et al. 2011; Isaak et al. 2016). For the highly endemic Miller Lake Lamprey *Lampetra minima* and southeastern pygmy sunfishes *Elassoma* spp., headwaters provide refuge from thermal stress, extreme hydrological conditions, and exposure to invasive species (Hayes et al. 1998; Meyer et al. 2007).

Protecting headwater habitats is critical for the recovery and delisting of several endangered fishes. For instance, the recently delisted Modoc Sucker *Catostomus microps* is abundant in intermittent and low-flow headwater streams in northeastern California and southern Oregon (Moyle and Marciochi 1975). Delisting resulted from protecting headwater tributaries and wetlands on public and private lands from threats that included livestock grazing and stream channelization that eliminated refuge pools (Moyle and Marciochi 1975; USFWS 2015). By protecting headwaters, the United States can not only reduce the uncertainty and economic costs that come with an imperiled species being listed under the ESA, but also provide the foundation for successful recovery and delisting of species.

HEADWATERS SUPPORT RECREATIONAL AND COMMERCIAL FISHERIES

Inland and coastal fisheries resources have tremendous economic and social importance. In the USA, commercial and recreational fisheries contributed over $208 billion in economic impact and 1.62 million jobs in 2015 (NMFS 2015). Fishing is a major recreational activity in the USA, with nearly 12 million participants in 2011 and creating 439 thousand jobs and generating more than $63 billion across the United States in 2015 (USFWS 2012a, NMFS 2015). For instance, headwater tributaries in the western USA are visited annually by thousands of anglers for both catch-and-release as well as harvest fishing. Nationally, trout anglers spent $3.5 billion on their pursuits, supported over 100 thousand jobs, and had a $10 billion economic impact, including $1.3 billion in federal and state tax revenues in 2006 (USFWS 2014).

An important consideration for the protection of headwaters is to safeguard recreational and commercial fisheries from point and non-point sources of pollution. Removing those protections will perpetuate current sources of pollution and worsen future impacts to downstream fisheries. In many regions of the USA, past and current pollution continues to degrade fisheries. For example, in the western USA, legacy metal and acid-mine drainage into headwater systems continue to threaten recreational trout fisheries (Woody et al. 2010). In 2015, the Gold King Mine spilled approximately 3 million gallons of untreated acid mine drainage into a headwater stream, instantly changing the color and turbidity of the stream for 2 days, and closing a valuable trout fishery for the entire summer (Rodriguez-Freire et al. 2016). Climate change and the increased frequency of warmer and drier years is predicted to extirpate trout from nearly half their habitat throughout the interior western United States by the 2080s (Wenger et al. 2011), as well as fragment the remaining habitats and reduce trout population sizes and their connectivity (Williams et al. 2015; Isaak et al. 2016). Further erosion of protections for headwaters may reduce or end opportunities to catch trout in these waters and have huge impacts on recreational angling tourism.

Recreational fisheries and headwaters are tightly interconnected. Depending on the state and location, the daily economic value of trout angling was $50–157 per person (USFWS 2012a). For example, blue-ribbon trout streams in two Idaho and Wyoming river basins yielded $12 million and $29 million in county income and 341 and 851 jobs in 2004, respectively (Hughes 2015). The trout fishery in Colorado alone was valued at $1.3 billion in 2011 (Williams et al. 2015). Brook Trout fishing in northern Maine generated over $150 million in 2013 and anglers spent $200 per day on fishing logistics (Fleming 2016). In Pennsylvania, trout anglers spent $45 per day and generated $2 million annually for rural economies (MDNR 2018). North Carolina trout anglers generated $174 million in economic output (NCWRC 2013). Based on travel cost modeling, Georgian trout anglers spent $60–160 per trip, generating $70–200 million annually (Dorison 2012). Recent estimates of freshwater fishing contributions to U.S. Gross Domestic Product total $41.9 billion while providing 526.6 thousand jobs nationwide (Allen et al. 2018). Economic contributions from freshwater fishing is also increasing, growing 11% since 2011 (Allen et al. 2018). It is also critical economic growth when compared to other sectors, collectively the outdoor recreation economy grew 3.8% in 2016 while the overall economy grew 2.8% during the same time period (Allen et al. 2018).

The headwater systems that support these recreational fisheries are typically found at higher elevations, with critical physical habitat requirements (e.g., temperature, flow, and dissolved oxygen) for prized trout species. Species-specific habitat requirements are uniquely provided by these streams and driven by annual snow accumulation (and snowmelt). Recreational anglers avidly pursue several target fishes (Cutthroat Trout, Rainbow Trout, Bull Trout, Brook Trout, Brown Trout, and Arctic Grayling *Thymallus arcticus*) found in these higher-elevation streams. Although they represent a small proportion of recreational angling nationally, these stocks sustain a huge market for fly-fishing anglers from throughout the USA and other nations.

Trout are not the only prized fishery that depends on headwaters. The Alligator Gar *Atractosteus spatula*, one of the largest and most primitive fishes in North America, is a popular target for anglers and archers in the southeastern USA. This fishery has created a booming market for gar-fishing guides that charge $750 per day (Benning 2009). Alligator Gar stocks have declined throughout their native ranges, including apparent extirpations in many regions. During late spring and summer high flows, adult gar move from rivers into small floodplain tributaries (and ditches) to spawn in flooded ephemeral wetlands and fields containing submerged vegetation (Solomon et al. 2013; Kluender et al. 2016). Recruitment success of juvenile gar is correlated with large, long-duration summer floods and spawning habitat availability (Buckmeier et al. 2017; Robertson et al. 2018). This connectivity allows for gar dispersal between rivers and ephemeral floodplain headwaters, which is critical for sustaining this species (Robertson et al. 2018).

Commercial fisheries are affected by headwaters both directly and indirectly. Among the most valuable commercial fisheries dependent on headwaters are the salmon fisheries of Alaska and the Pacific Northwest. From 2012 to 2015, salmon commercial and recreational fisheries were valued at $3.4 million in economic output and produced $1.2 million in wages and 27 thousand full-time jobs annually (Gislason et al. 2017). The world's most valuable wild salmon fishery in Bristol Bay, Alaska, where headwaters remain relatively pristine, generates $1.5 billion in annual economic activity and 20 thousand full-time jobs (BBNC 2017). As mentioned previously, spawning Pacific Salmon *Oncorhynchus* spp. import marine-derived nutrients into nutrient-poor headwaters, thereby augmenting production of basal resources in aquatic food webs. In the northeastern United States, a burgeoning commercial fishery has developed for juvenile American Eel *Anguilla rostrata* to supply Asian markets. American Eel catches in Maine were valued at more than $10 million annually from 2015 to 2017 (ASMFC 2017b), and the fishery provided well over $20 million in 2018 (Whittle 2018). Some estimates suggest American Eel stocks along the eastern coast of North America have declined dramatically in the last several decades (Busch et al. 1998). However, conclusions from recent assessments on stock status are variable, ranging from "threatened" and "endangered" to "not threatened or endangered" (Jessop and Lee 2016). More clearly, headwaters are important rearing habitats for American Eel, and stream restoration has been recommended as an important strategy for recovery where depleted (Machut et al. 2007).

Protections currently afforded to headwaters through the 2015 WOTUS rule help maintain and contribute to the stability of commercial and recreational fisheries and the rural economies that they support. In rural areas, nature tourism also contributes to sustainable economic growth where visitors spend recreational dollars to see rare fish up close (Figure 4). For example, the Ash Meadows National Wildlife Refuge is home to the highest concentration of endemic species in the USA and draws nearly 70 thousand visitors annually that contribute over $3 million to the local economy (unpublished data from Ash Meadows National Wildlife Refuge, Visitor Service Staff).

HEADWATERS ARE CULTURALLY SIGNIFICANT

Cultural values of headwaters and the downstream rivers they support are diverse, and clearly expressed in nature-based tourism, aesthetic values, recreational fishing, and other activities (Beier et al. 2017). Human–natural resource relationships have evolved in the context of intricate interactions among cultures, communities, and water (e.g., its quality, access, use, and associated resources) for both native and other peoples (Johnston 2013). Wild salmon, for example, hold central roles in the creation and migration narratives of native peoples, and continue to be present in prayers and visions in addition to diets (Stumpff 2001). Fly fishing for trout can be a religious, transformative experience for many. This pursuit strengthens ties with nature, shapes local-to-regional economies, and has a complex history with environmental stewardship (Hemingway 1973; Maclean 1976; Brown 2012, 2015). However, impairment of headwaters has strongly altered the interactions between people and nature, with the ecosystem services provided by rivers to society declining over time (Gilvear et al. 2013; Lynn et al. 2013; Marttila et al. 2016).

The spiritual and socio-cultural values of fish and healthy ecosystems—which are dependent on clean, free-flowing headwaters—are intangible and extend well beyond any economic measures (Boraas and Knott 2018). Pacific Salmon fisheries are a major source of subsistence and income for many native peoples in Alaska and the western USA (e.g., Boraas and Knott 2018). Salmon are also a traditional "first food," honored in many tribal traditions and strongly linked to cultural identities (e.g., CRITFC 2018; NPT 2018). For example, the Nimiipuu (Nez Perce) view salmon as economic and spiritual keystones, with the survival of the tribe and the salmon being interdependent (Colombi 2012).

Similar to Pacific Salmon, Bull Trout inhabiting western streams are culturally important to many groups, including the Confederated Salish and Kootenai Tribes. Bull Trout are part of the history, oral traditions, culture, and identity that are passed down among generations (CSKT 2011). The Confederated Tribes of western Montana credit the abundance of Bull Trout for preventing starvation during harsh winters (Laughlin and Gibson 2011). Even though Bull Trout are not currently harvested for subsistence and economic purposes, Rich Janssen, the natural resource manager for the Confederated Salish and Kootenai Tribes, highlights their interrelationship as follows: "It's part of who you are. It's part of your culture. It's part of your history. You don't want to lose who you are. You don't want to lose that connection" (Laughlin and Gibson 2011).

The importance of headwaters to indigenous cultures extends beyond the well-established examples from Alaska, the Pacific Northwest, and intermountain western USA. For instance, the Ash Meadows National Wildlife Refuge is also culturally important to the Timbisha Shoshone and Southern Paiute peoples because of its life-giving pools fed by headwater springs (Shirey et al. 2018). The Rio Grande and Colorado River flow from headwaters in the Rocky Mountains through traditional lands of the largest concentrations of indigenous peoples within the conterminous USA (Navajo, Apache, Pueblo, and others) and intersect the ranges of Apache Trout and Gila Trout. These headwater ecosystems and the services they provide are central to traditional place-based lifestyles of indigenous tribes (Johnston 2013). Eastern North Carolina Cherokee highly value headwater streams for their cultural significance (extending back thousands of years) as well as for fishery-based tourism (Balster 2018). For the Passamoquoddy of present-day Maine, water and fish are sacred and inextricably linked to their history, culture, traditional beliefs, lore, and spirituality (Bassett 2015). Caloric-rich Alewife and Blueback Herring *A. aestivalis* migrate from the ocean to spawn in the headwaters of the St. Croix River, Maine, where they were a key resource with cultural importance for the Passamoquoddy for thousands of years before European colonization and habitat impairment from pollution, dams, overfishing, and stocking of alien species. In 2013, in cooperation with the Bureau of Indian Affairs, U.S. Fish and Wildlife Service, NOAA and others, the Passamoquoddy began restoring the St. Croix Watershed and returning these species to the ecosystem and the Passamoquoddy people. Traditional ecological knowledge provides an important line of evidence supporting protection and restoration of headwaters. For example, Maine Sea Grant and the National Marine Fisheries Service (NMFS) collaborated to document and disseminate harvesters' knowledge of

BOX 2. ALEWIVES IN MAINE

Alewives *Alosa pseudoharengus*, ascend freshwater rivers and tributaries in early summer to access lakes and headwater ponds where they spawn; in the fall, juvenile Alewives migrate from headwaters to the marine environment (Saunders et al. 2006; Figure 9). Alewife recovery resulting from dam removals and improved access has provided an additional food resource for endangered Atlantic Salmon and terrestrial piscivores, such as the bald eagle *Haliaeetus leucocephalus*. Restored Alewife stocks also have enhanced local economies by diversifiying fisheries, including creation of a major fishery for bait to supply the lobster fishery (Saunders et al. 2006; McClenachan et al. 2015). Lakes with restored alewife populations also have shown improvements in water quality and clarity because out-migrating juveniles remove phosphorus from these systems (McClenachan et al. 2015). Despite some recent population recoveries of Alewife in Maine, coastwide populations of river herring, including both Alewives and Blueback Herring *A. aestivalis,* are depleted and near historic lows (ASMFC 2017a).

Alewife, Blueback Herring, and American Eel, all of which are returning to headwater streams following recent dam removals (Hitt et al. 2012; Hogg et al. 2015). Similarly, the Yurok and Karuk people of the Klamath region in northern California, who have deep cultural and subsistence ties with Pacific Lamprey *L. tridentata*, provided important information that improved understanding of lamprey population crashes in the Klamath Basin (Lewis 2009).

The strong interrelationships between native peoples, fish, and fluvial systems also implicate environmental justice issues, particularly as related to chemical contaminants and traditional food systems that include fish (Kuhnlein and Chan 2000). Contaminants affect not only human health, but also broader issues of food security and social and cultural wellbeing (Jewett and Duffy 2007). Impairment of headwaters and water quality extends to many other groups as well, and can lead to greater environmental inequality (e.g., Elkind 2006). Moving forward, heightened respect for and recognition of the rights and values of culturally diverse peoples in the use of river systems, including headwaters and associated resources, warrants additional and thoughtful consideration when legislating and implementing protections (Johnston 2013).

Figure 9. Juvenile Alewife *Alosa pseudoharengus* from Unity Pond, Maine. Photo Credit: Susan A. R. Colvin.

HEADWATERS NEED CONTINUED PROTECTION

The repeal and replacement of the 2015 Clean Water Rule would roll back Clean Water Act protections for a majority of the nation's streams and wetlands, including thousands of miles of headwater streams and millions of acres of wetlands that provide invaluable ecosystem services and habitat for many species of fish. The recently proposed rule, which excludes wetlands outside of floodplains (or those that lack a continuous surface connection to other jurisdictional waters), ephemeral streams, and likely some intermittent streams, would threaten fish and the headwater ecosystems on which they rely, result in severe economic losses, and cause irreparable cultural and social damage. To recap, some examples of headwaters that would not meet Scalia's definition and could lose protection under the new rule include the karst features, critically important to threatened and endangered cavefish (Figure 5); intermittent streams used by imperiled fish for spawning and early rearing (Figure 8); and intermittent side channels and floodplains that provide critical habitat for juvenile salmon (Figure 6). Justice Scalia's definition, which largely aligns with the proposed rule, ignored the intent of Congress in passing and updating the Clean Water Act, failed to give deference to the agencies that implement the law, and issued a decision not grounded in science. In contrast, Justice Kennedy's definition deferred to Congressional intent and federal agency experts and relied on the available scientific evidence. The science of waterbody connectivity has advanced markedly in the time since the *Rapanos* case, and the 2015 Clean Water Rule was based on the demonstrated importance of physical, chemical, and biological connections of headwaters to the ecological condition of navigable waters and their biota (Leibowitz et al. 2018).

Headwaters are critically important for many ecosystem functions, including sustaining fish stocks, with influences extending from small tributary streams and wetlands to navigable waterbodies downstream. The recently proposed rule offers protection only to a narrower subset of headwaters and will have far-reaching implications for fish, wildlife, and humans that depend on freshwater ecosystems. Species already at risk of extinction would be more difficult to recover, and it is highly likely that many fishes and other aquatic taxa would face greater imperilment. It is clear that communities across the USA would lose significant economic, spiritual, and socio-cultural benefits that are derived from headwaters under the proposed rule. Therefore, we recommend that the EPA follow the approach in its National Aquatic Resource Surveys and conduct a formal ecological and economic risk assessment to quantify the potential effects of changing the current WOTUS rule.

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AUTHORS' CONTRIBUTIONS

S.A.R.C. and S.M.P.S. conceived the original structure of the manuscript. S.A.R.C. served as overall lead author and led the writing of the Introduction. S.M.P.S led the Ecosystem Function and Cultural Significance sections. P.D.S. led the Endangered Species section, with contributions from K.D.F. R.W.C. led the section on Commercial and Recreational Fishing. These authors wrote the manuscript with contributions from all authors. R.M.H., K.O.W., and K.D.F. provided important editorial suggestions.

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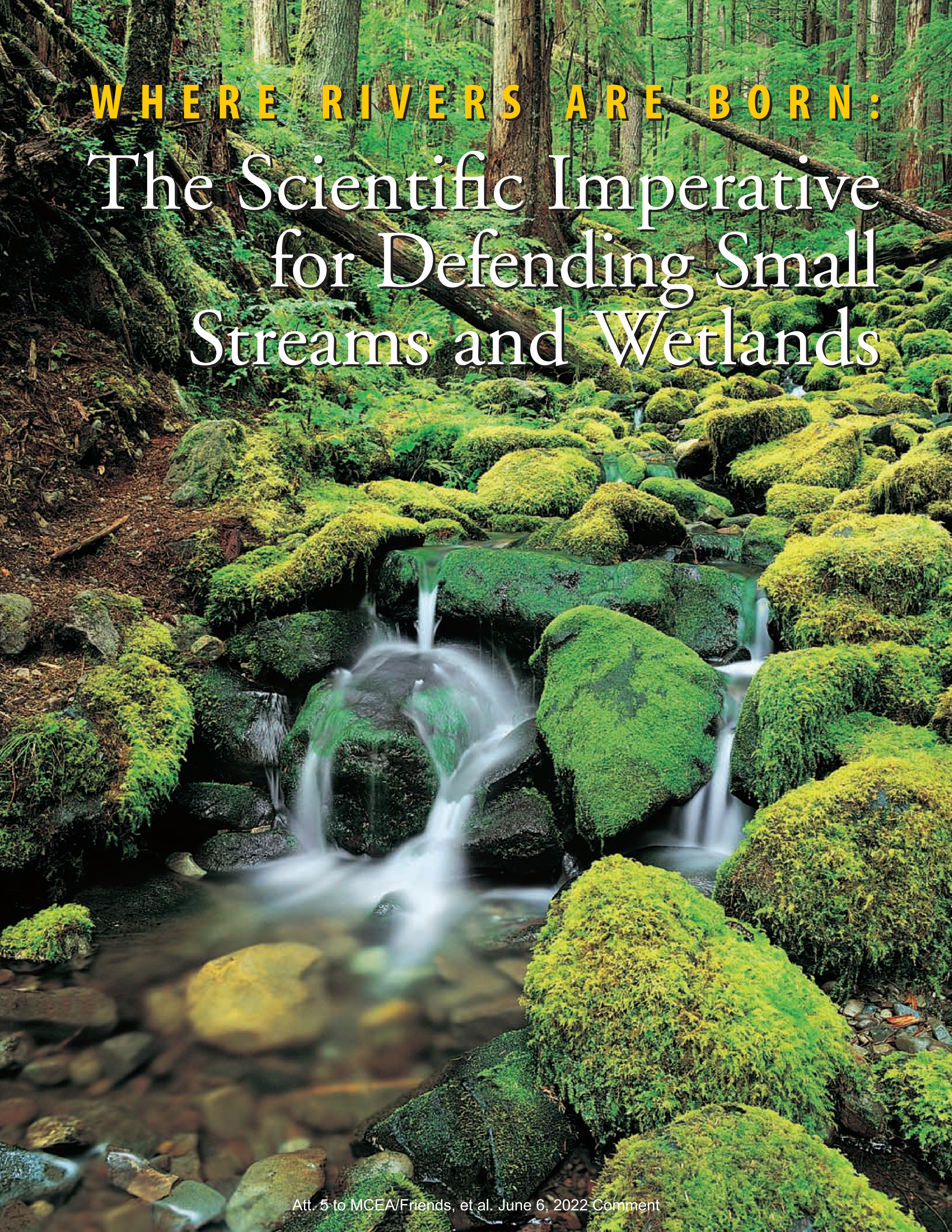
Att. 4 to MCEA/Friends, et al. June 6, 2022 Comment

WHERE RIVERS ARE BORN:

The Scientific Imperative for Defending Small Streams and Wetlands



WHERE RIVERS ARE BORN:

The Scientific Imperative for Defending Small Streams and Wetlands

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WHERE RIVERS ARE BORN:

The Scientific Imperative for Defending Small Streams and Wetlands

EXECUTIVE SUMMARY

Our nation's network of rivers, lakes and streams originates from a myriad of small streams and wetlands, many so small they do not appear on any map. Yet these headwater streams and wetlands exert critical influences on the character and quality of downstream waters. The natural processes that occur in such headwater systems benefit humans by mitigating flooding, maintaining water quality and quantity, recycling nutrients, and providing habitat for plants and animals. This paper summarizes the scientific basis for understanding that the health and productivity of rivers and lakes depends upon intact small streams and wetlands.

Historically, federal agencies have interpreted the protections of the Clean Water Act to cover all the waters of the United States, including small streams and wetlands. Despite this, many of these ecosystems have been destroyed by agriculture, mining, development and other human activities. The extent to which small streams and wetlands should remain under the protection of the Clean Water Act is currently (2003) under consideration in federal agencies and Congress. Extensive scientific studies document the significance of these small systems and form the basis for this paper. Further references are provided at the end of the document.

We know from local/regional studies that small, or headwater, streams make up at least 80 percent of the nation's stream network. However, scientists' abilities to extend these local and regional studies to provide a national perspective is hindered by the absence of a comprehensive database that catalogs the full extent of streams in the United States. The topographic maps most commonly used to trace stream networks do not show most of the nation's headwater

streams and wetlands. Thus, such maps do not provide detailed enough information to serve as a basis for stream protection and management.

Scientists often refer to the benefits humans receive from the natural functioning of ecosystems as ecosystem services. The special physical and biological characteristics of intact small streams and wetlands provide natural flood control, recharge groundwater, trap sediments and pollution from fertilizers, recycle nutrients, create and maintain biological diversity, and sustain the biological productivity of downstream rivers, lakes and estuaries. These ecosystem services are provided by seasonal as well as perennial streams and wetlands. Even when such systems have no visible overland connections to the stream network, small streams and wetlands are usually linked to the larger network through groundwater.

Small streams and wetlands offer an enormous array of habitats for plant, animal and microbial life. Such small freshwater systems provide shelter,

food, protection from predators, spawning sites and nursery areas, and travel corridors through the landscape. Many species depend on small streams and wetlands at some point in their life history. For example, headwater streams are vital for maintaining many of America's fish species, including trout and salmon. Both perennial and seasonal streams and wetlands provide valuable habitat. Headwater streams and wetlands also provide a rich resource base that contributes to the productivity of both local food webs and those farther downstream. However, the unique and diverse biota of headwater systems is increasingly imperiled. Human-induced changes to such waters, including filling streams and wetlands, water pollution, and the introduction of exotic species, can diminish the biological diversity of such small freshwater systems, thereby also affecting downstream rivers and streams.

Because small streams and wetlands are the source of the nation's fresh waters, changes that degrade these headwater systems affect streams, lakes, and rivers downstream. Land-use changes in the vicinity of small streams and wetlands can impair the natural functions of such headwater systems. Changes in surrounding vegetation, development that paves and hardens soil surfaces, and the total elimination of some small streams reduces the amount of rainwater, runoff and snowmelt the stream network can absorb before flooding. The increased volume of water in small streams scours stream channels, changing them in a way that promotes further flooding. Such altered channels have bigger and more frequent floods. The altered channels are also less effective at recharging groundwater, trapping sediment, and recycling nutrients. As a result, downstream lakes and rivers have poorer water quality, less reliable water flows, and less diverse aquatic life. Algal blooms and fish kills can become more common, causing problems for commercial and sport fisheries. Recreational uses may be compromised. In addition, the excess sediment can be costly, requiring additional dredging to clear navigational channels and harbors and increasing water filtration costs for municipalities and industry.

The natural processes that occur in small streams and wetlands provide Americans with a host of benefits, including flood control, adequate high-quality water, and habitat for a variety of plants and animals. Scientific research shows that healthy headwater systems are critical to the healthy functioning of downstream streams, rivers, lakes and estuaries. To provide the ecosystem services that sustain the health of our nation's waters, the hydrological, geological, and biological characteristics of small streams and wetlands require protection.

Introduction

Our nation's rivers, from the Shenandoah to the Sacramento, owe their very existence to the seemingly insignificant rivulets and seeps that scientists call headwater streams. Although 19th century explorers often searched for the headwaters of rivers, the birthplace of most rivers cannot be pinpointed. The origins of rivers are many anonymous tiny rills that can be straddled by a 10-year-old child, and no one trickle can reasonably be said to be "the" start of that river. Rather, rivers arise from a network of streamlets and wetlands whose waters join together above and below ground as they flow downstream. As other tributaries join them, creeks grow larger, eventually earning the title "river." The character of any river is shaped by the quality and type of the numerous tributaries that flow into it. Each of the tributaries is, in turn, the creation of the upstream waters that joined to form it.

The ultimate sources of a river often appear insignificant. They could be a drizzle of snowmelt that runs down a mountainside crease, a small spring-fed pond, or a depression in the ground that fills with water after every rain and overflows into the creek below. Such water sources, which scientists refer to as headwater streams and wetlands, are often unnamed and rarely appear on maps. Yet the health of these small streams and wetlands is critical to the health of the entire river network. The rivers and lakes downstream from degraded headwater streams and wetlands may have less consistent flow, nuisance algal growth, more frequent and/or higher floods, poorer water quality, and less diverse flora and fauna.

Historically, federal agencies have interpreted the protections of the Clean Water Act to cover all the waters of the United States, including small streams and wetlands. The current administration is examining whether such streams and wetlands merit protection. In January 2003, the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers announced an "advance notice of proposed rulemaking" to solicit public comments on whether and how to exclude "isolated," intrastate, and non-navigable waters from the scope of the Clean Water Act. Many small streams and wetlands, including headwater streams, could fall into one or more of those categories. At the same time, the agencies instructed their field staff not to enforce the law to protect such waters or, depending on the situation, to seek case-by-case guidance from headquarters before enforcing the Act.

Small streams and wetlands provide crucial linkages between aquatic and terrestrial ecosystems and also between upstream watersheds and tributaries and the downstream rivers and lakes. This paper summarizes the scientific basis for understanding how small streams and wetlands mitigate flooding, maintain water quality and quantity, recycle nutrients, create habitat for plants and animals, and provide other benefits.

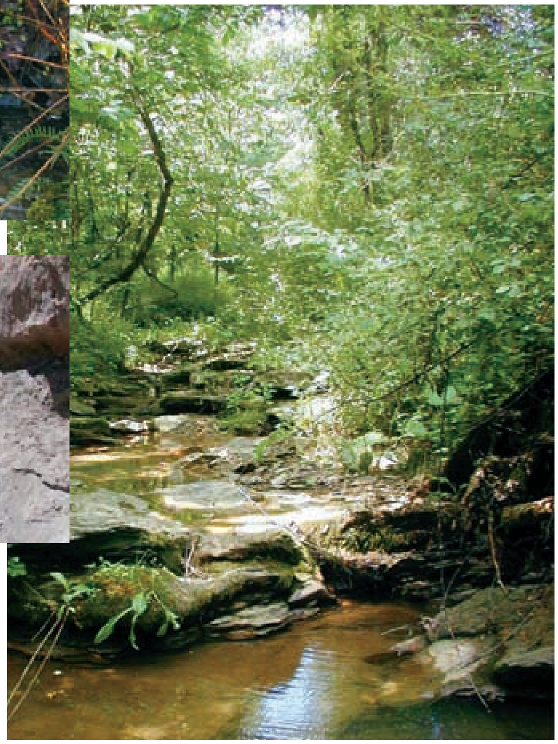
"THE RIVER ITSELF HAS NO BEGINNING OR END. IN ITS BEGINNING, IT IS NOT YET THE RIVER; IN ITS END, IT IS NO LONGER THE RIVER. WHAT WE CALL THE HEADWATERS IS ONLY A SELECTION FROM AMONG THE INNUMERABLE SOURCES WHICH FLOW TOGETHER TO COMPOSE IT. AT WHAT POINT IN ITS COURSE DOES THE MISSISSIPPI BECOME WHAT THE MISSISSIPPI MEANS?"

–T.S. Eliot

Human Beings Depend on Functioning Headwater Stream Systems

Human civilizations and economies are ultimately based on the products and processes of the natural world. While frequently hidden from view, some of the processes integral to the functioning of ecosystems-such as the purification of water and the processing of waste-are crucial to human well-being. Scientists often refer to the benefits humans receive from the functioning of natural ecosystems as *ecosystem services.*

The natural processes that occur in intact headwater streams and wetlands affect the quantity and quality of water and the timing of water availability in rivers, lakes, estuaries and groundwater. For example, the upper reaches of stream networks are important for storing water, recharging groundwater, and reducing the intensity and frequency of



Top: Lake Joy Creek is an intermittent zero- and first-order tributary stream to the Snoqualmie River in the Puget Sound area of Washington. Photo courtesy of Washington Trout

Center: A primary headwater stream in arid Cienega Creek Preserve, Pima County. Photo courtesy of Arizona Game and Fish Division

Right: A primary headwater stream in Athens County, Ohio. Photo courtesy of Ohio EPA

Bottom: Diagram of stream orders within a stream system. Image created by Sierra Club, based on EPA graphic.

floods. Stream and wetland ecosystems also process natural and human sources of nutrients, such as those found in leaves that fall into streams and those that may flow into creeks from agricultural fields. Some of this processing turns the nutrients into more biologically useful forms. Other aspects of the processing store nutrients, thereby allowing their slow and steady release and preventing the kind of short-term glut of nutrients that can cause algal blooms in downstream rivers or lakes.

The Extent of U.S. Headwater Streams is Underestimated

For many people, *headwater stream* brings to mind a small, clear, icy-cold, heavily-shaded stream that tumbles down a steep, boulder-filled channel. Indeed, there are thousands of miles of such shaded, mountainous headwater streams in the United States. But the term "headwater" encompasses many other types of small streams. Headwaters can be intermittent streams that flow briefly when snow melts or after rain, but shrink in dry times to become individual pools filled with water. Desert headwater streams can arise from a spring and run above ground only a few hundred yards before disappearing into the sand. Other spring-fed headwaters contain clear water with steady temperature and flow. Yet other headwaters originate in marshy meadows filled with sluggish tea-colored water.

No comprehensive study has been conducted to catalog the full extent of streams in the United States. However, on the basis of available maps, scientists have estimated that these smallest streams, called first- and second-order streams, represent about three-quarters of the total length of stream and river channels in the United States. The actual proportion may be much higher because this estimate is based on the stream networks shown on the current U.S. Geological Survey (USGS) topographic maps,

TYPES OF STREAMS

Any one river typically has several different types of sources: *perennial* streams that flow year-round; *intermittent* streams that flow several months during the year, such as streams that come from snowmelt; and *ephemeral* streams that flow at the surface only periodically, usually in response to a specific rainstorm. All these types of streams can be the *headwaters* of a river.

One way scientists classify streams is the *stream order* system, which assigns streams a number depending upon their location in the network's branching pattern. The term *zero-order stream* refers to swales: hollows that lack distinct stream banks but still serve as important conduits of water, sediment, nutrients, and other materials during rainstorms and snowmelt. Such zero-order streams are integral parts of stream networks. *First-order streams* are the smallest distinct channels.

The rivulet of water that flows from a hillside spring and forms a channel is a *first-order stream. Second-order streams* are formed when two first-order channels combine, *third-order streams* are formed by the combination of two second-order streams, and so on.

The term *headwaters* refers to the smallest streams in the network. Scientists often use the term headwaters to refer to zero-, first- and second-order streams. Easily half of the total length of the channels in a stream network can be first-order streams. Such small headwater streams can join a river system at any point along the network. So, a fourth-order stream resulting from the upstream merger of many first-, second-, and third-order streams may flow through a forest and be joined by another first-order stream that meanders out of a nearby marshy meadow.

which do not show all headwater streams. The absence of a comprehensive survey of U.S. streams hinders our ability to estimate the nationwide importance of these systems; it also indicates our need to better understand them.

Studies including field surveys of stream channel networks have found far more headwater streams than are indicated on USGS topographic maps. For example, an on-the-ground survey of streams in the Chattooga River watershed in the southern Appalachian Mountains found thousands of streams not shown on USGS topographic maps. Approximately one-fifth or less of the actual stream network was shown on the USGS map. The missing streams were the smaller ones-the headwaters and other small streams and wetlands. Similar discrepancies have been found at the state level. For example, Ohio's Environmental Protection Agency found that the state's primary headwater streams, although generally absent from USGS topographic maps, comprise more than 80 percent of the total length of the state's streams. Even when small streams are on the map, they are sometimes misclassified: a large number of Ohio streams shown as intermittent on topographic maps are actually perennial.

Intact stream networks contain streams that flow year-round and others that flow only part of the time. Compared with the humid-region examples above, stream and river networks in arid regions have a higher proportion of channels that flow intermittently. For example, in Arizona, most of the stream networks-96 percent by length-are classified as ephemeral or intermittent.

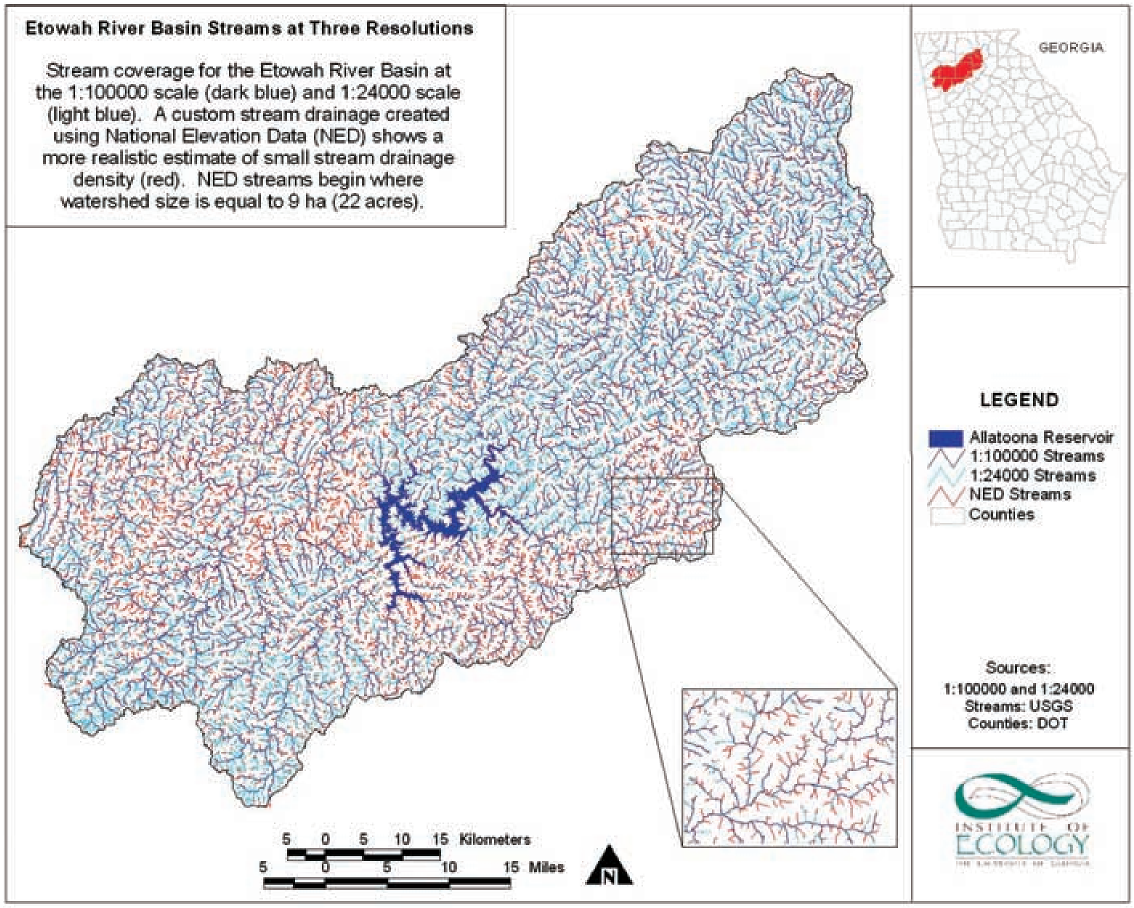
Top: Sycamore Creek in Arizona, an arid stream during a dry period. Photo Courtesy of Nancy Grimm

Center: Sycamore Creek (the same stream) after a winter storm. Photo Courtesy of Nancy Grimm

Thus, regional calculations on the extent of small streams grounded in solid evidence show these streams to be underestimated by existing inventories and maps. But actual measurements are not available for the whole nation. Moreover, the topographic maps commonly used as catalogues of stream networks are not detailed enough to serve as a basis for stream management and protection. The very foundation of our nation's great rivers is a vast network of unknown, unnamed, and underappreciated headwater streams.

Sometimes resource managers define a stream based on the size of its watershed, the land area that drains into the stream. For example, Ohio's EPA defines headwater streams as those that drain an area 20 square miles or smaller. Such a definition includes first-, second-, and often third-order streams. Other managers suggest that headwater systems can be defined as those having watersheds of less than one square kilometer, a definition that would generally include only first- and second-order streams. For the purposes of this paper, we consider zero-, first- and second-order streams as headwaters.

Existing tools for cataloging U.S. waters generally omit a large proportion of the headwaters. In this illustration of Georgia's Etowah River Basin, National Elevation Data details, in red, the approximately 40 percent and 60 percent of headwaters not captured by standard cataloging methods. Diagram courtesy of B.J. Freeman, University of Georgia.



Small Streams Provide Greatest Connection Between Water and Land

Within any intact stream and river network, headwater streams make up most of the total channel length. Therefore, such small streams offer the greatest opportunity for exchange between the water and the terrestrial environment. Small streams link land and water in several ways. As a stream flows, it links upstream and downstream portions of the network. In addition, water flows out of and into a channel during events such as floods and runoff from rainstorms. Floodwaters and runoff carry various materials, ranging from insects and bits of soil to downed trees, between land and a channel. Much exchange between land and water occurs in the transition zone along edges of stream channels, called the *riparian zone.*

Water and land also meet in saturated sediments beneath and beside a river channel, a region which scientists call the *hyporheic zone.* Stream water flows within the stream channel and the hyporheic zone. It is in this zone, where stream water makes its most intimate contact with the channel bed and banks, that much of a stream's cleansing action and nutrient processing occurs. This zone is also where groundwater and surface water come into contact.

Ecological processes that occur in hyporheic zones have strong effects on stream water quality. Rivers with extensive hyporheic zones retain and process nutrients efficiently, which has a positive effect on water quality and on the ecology of the riparian zone. Scientific research is illuminating the importance of maintaining connectivity between the channel, hyporheic, and riparian components of river ecosystems. When human actions, such as encasing streams in pipes, sever those connections, the result is poorer water quality and degraded fish habitat downstream.

Wetlands Have Hidden Connections to Streams

Like headwater streams, wetlands are also key components of the nation's network of rivers and streams. Many wetlands, such as marshes that border lakes or streams, have obvious connections to surface waters. Other wetlands, however, seem cut off from stream networks - but that appearance is deceiving. Wetlands are almost always linked to stream networks and other wetlands through groundwater. There are biological connections also; many aquatic and semi-aquatic animals, ranging in size from aquatic insects to raccoons, routinely move between land-locked wetlands, streamside wetlands, and stream channels. Animals often use different parts of the aquatic environment at different points in their life cycle, so groundwater connections and food webs link many wetlands to larger waterways.

Wetlands without obvious surface connections to streams are diverse. Scientists generally distinguish between wetlands that have permanent water and others, called ephemeral wetlands, that are only seasonally wet. At least one out of five wetlands does not have a visible connection to a waterway, and, in some areas, more than half of the wetlands fall into that category. Despite the abundance of such wetlands, the United States has no national inventory of their numbers or locations.

A U.S. Fish and Wildlife Service study of wetlands in 72 areas within the United States found that wetlands without obvious surface connections to waterways are generally small in area, but numerous. All such wetlands are depressions in the ground that hold water, whether from rainwater, snowmelt, or groundwater welling up to the surface. Each region of the United States has unique types of depressional wetlands. Ephemeral wetlands called vernal pools occur in California and the Northeast; the prairie potholes used by ducks and other waterfowl dot the Upper Midwest; and Carolina bays, cypress ponds, and grass-sedge marshes occur in the Southeast.

Top: A vernal pool in Massachusett's Ipswich River Basin during the dry phase in summer. Photo courtesy of Vernal Pool Association

Bottom: The same Ipswich River Basin vernal pool inundated by fall precipitation. Photo courtesy of Vernal Pool Association

Small Streams and Wetlands Provide Beneficial Ecosystem Services

A headwater stream channel near Toledo, OH relocated to accommodate development. Photo courtesy of Marshal A. Moser

Natural processes that occur in small streams and wetlands provide humans with a host of benefits, including flood control, maintenance of water quantity and quality, and habitat for a variety of plants and animals. For headwater streams and wetlands to provide ecosystem services that sustain the health of our nation's waters, the hydrological, geological and biological components of stream networks must be intact.

Small Streams and Wetlands Provide Natural Flood Control

Floods are a natural part of every river. In times past, waters of the Mississippi River routinely overtopped its banks. Floodwaters carried the sediment and nutrients that made the Mississippi Delta's soil particularly suitable for agriculture. But floods can also destroy farms, houses, roads and bridges.

When small streams and wetlands are in their natural state, they absorb significant amounts of rainwater, runoff and snowmelt before flooding. However, when a landscape is altered, such as by a landslide or large forest fire or a housing development, the runoff can exceed the absorption capacity of small streams. Moreover, the power of additional water coursing through a channel can change the channel itself. Humans often alter both landscape and stream channels in ways that result in larger and more frequent floods downstream.

A key feature of streams and rivers is their shape. Unlike a concrete drainage ditch, a natural streambed does not present a smooth surface for water flow. Natural streambeds are rough and bumpy in ways that slow the passage of water. Particularly in small narrow streams, friction produced by a stream's gravel bed, rocks, and dams of leaf litter and twigs slows water as it moves downstream. Slower moving water is more likely to seep into a stream's natural water storage system-its bed and banks-and to recharge groundwater. Slower moving water also has less power to erode stream banks and carry sediment and debris downstream.

In watersheds that are not carefully protected against impacts of land development, stream channels often become enlarged and incised from increased runoff. Changed channels send water downstream more quickly, resulting in more flooding. For example, after forests and prairies in Wisconsin watersheds were converted to agricultural fields, the size of floods increased. This change in land use had altered two parts of the river systems' equation: the amount of runoff and shape of the stream channel. Cultivation destroyed the soil's natural air spaces that came from worm burrows and plant roots. The resulting collapse of the soil caused more rainfall to run off into streams instead of soaking into the ground. Additional surface runoff then altered the stream channels, thereby increasing their capacity to carry large volumes of water quickly downstream. These larger volumes flow downstream at much higher velocity, rather than soaking into the streambed.

Urbanization has similar effects; paving previously-vegetated areas leads to greater storm runoff, which changes urban stream channels and ultimately sends water more quickly downstream. Covering the land with impermeable surfaces, such as roofs, roads, and parking lots, can increase by several times the amount of runoff from a rainstorm. If land uses change near headwater streams, effects are felt throughout the stream network. In an urban setting, runoff is channeled into storm sewers, which then rapidly discharge large volumes of water into nearby streams. The additional water causes the stream to pick up speed, because deeper water has less friction with the streambed. The faster the water moves, the less it can soak into the streambed and banks. Faster water also erodes channel banks and beds, changing the shape of a channel. The effect is magnified downstream, because larger rivers receive water from tens, sometimes hundreds, of small headwater basins. When such changes are made near headwater streams, downstream portions of the stream network experience bigger and more frequent flooding.

As regions become more urbanized, humans intentionally alter many natural stream channels by replacing them with storm sewers and other artificial conduits. When larger, smoother conduits are substituted for narrow, rough-bottomed natural stream channels, flood frequency increases downstream. For example, three decades of growth in storm sewers and paved surfaces around Watts Branch Creek, Maryland more than tripled the number of floods and increased average annual flood size by 23 percent.

"Alteration of small streams and wetlands disrupts the quantity and availability of water in a stream and river system."

Small Streams and Wetlands Maintain Water Supplies

Headwater systems play a crucial role in ensuring a continual flow of water to downstream freshwater ecosystems. Water in streams and rivers comes from several sources: water held in the soil, runoff from precipitation, and groundwater. Water moves between the soil, streams and groundwater. Wetlands, even those without any obvious surface connection to streams, are also involved in such exchanges by storing and slowly releasing water into streams and groundwater, where it later resurfaces at springs. Because of these interactions, groundwater can contribute a significant portion of surface flow in streams and rivers; conversely, surface waters can also recharge groundwater. If connections between soil, water, surface waters, and groundwater are disrupted, streams, rivers, and wells can run dry. Two-thirds of Americans obtain their drinking water from a water system that uses surface water. The remaining one-third of the population relies on groundwater sources. The quality and amount of water in both of these sources respond to changes in headwater streams.

USGS estimates that, on average, from 40 to 50 percent of water in streams and larger rivers comes from groundwater. In drier regions or during dry seasons, as much as 95 percent of a stream's flow may come from groundwater. Thus, the recharge process that occurs in unaltered headwater streams and wetlands both moderates downstream flooding in times of high water and maintains stream flow during dry seasons.

Headwater streams and wetlands have a particularly important role to play in recharge. These smallest upstream components of a river network have the largest surface area of soil in contact with available water, thereby providing the greatest opportunity for recharge of groundwater. Moreover, water level in headwater streams is often higher than the water table, allowing water to flow through the channel bed and banks into soil and groundwater. Such situations occur when water levels are high, such as during spring snowmelt or rainy seasons. During dry times, the situation in some reaches of the stream network, particularly those downstream, may reverse, with water flowing from the soil and groundwater through the channel banks and bed into the stream. This exchange of water from the soil and groundwater into the stream maintains stream flow. However, if land-use changes increase the amount of precipitation that runs off into a stream rather than soaking into the ground, the recharge process gets short-circuited. This increased volume of stream water flows rapidly downstream rather than infiltrating into soil and groundwater. The consequence is less overall groundwater recharge, which often results in less water in streams during drier seasons.

Therefore, alteration of small streams and wetlands disrupts the quantity and availability of water in a stream and river system. Protecting headwater streams and wetlands is important for maintaining water levels needed to support everything from fish to recreational boating to commercial ship traffic.

Small Streams and Wetlands Trap Excess Sediment

Headwater systems retain sediment. Like the flow of water, movement of sediment occurs throughout a river network. Thus, how a watershed is managed and what kinds of land uses occur there have substantial impact on the amount of sediment delivered to larger rivers downstream. Increased sediment raises water purification costs for municipal and industrial users, requires extensive dredging to maintain navigational channels, and degrades aquatic habitats. Intact headwater streams and wetlands can modulate the amount of sediment transported to downstream ecosystems.

Runoff from rain, snowmelt and receding floodwaters can wash soil, leaves and twigs into streams, where the various materials get broken up into smaller particles or settle out. If natural vegetation and soil cover are disturbed by events and activities such as fires, farming or construction, runoff increases, washing more materials into streams. At the same time, the increased velocity and volume of water in a stream cause erosion within the streambed and banks themselves, contributing additional sediment to the stream system. Moreover, the faster, fuller stream can carry more and larger chunks of sediment further downstream.

"Intact headwater streams and wetlands can modulate the amount of sediment transported to downstream ecosystems."

One study found that land disturbances such as urban construction can, at minimum, double the amount of sediment entering headwater streams from a watershed. A Pennsylvania study showed how, as a 160-acre headwater watershed became more urbanized, channel erosion of a quarter-mile stretch of stream generated 50,000 additional cubic feet of sediment in one year-enough to fill 25 moderate-sized living rooms. In a non-urban watershed of the same size, it would take five years to generate the same amount of sediment. Such studies demonstrate that landscape changes such as urbanization or agriculture, particularly without careful protection of headwater streams and their riparian zones, may cause many times more sediment to travel downstream.

Excess Sediment in Downstream Ecosystems Costs Money

Keeping excess sediment out of downstream rivers and lakes is one ecosystem service intact small streams and wetlands provide. Once sediment moves further downstream, it becomes an expensive problem. Too much sediment can fill up reservoirs and navigation channels, damage commercial and sport fisheries, eliminate recreation spots, harm aquatic habitats and their associated plants and animals, and increase water filtration costs.

Additional sediment damages aquatic ecosystems. Sediment suspended in the water makes it murkier; as a result, underwater plants no longer receive enough light to grow. Fish that depend on visual signals to mate may be less likely to spawn in murky water, thereby reducing fish populations. High levels of sediment suspended in water can even cause fish kills. Even as it settles to the bottom, sediment continues to cause problems because it fills the holes between gravel and stones that some animals call home, smothers small organisms that form the basis of many food webs, and can also smother fish eggs.

Getting rid of sediment is expensive. For example, keeping Baltimore Harbor navigable costs $10 to $11.5 million annually to dredge and dispose of sediment the Patapsco River deposits in the harbor.

Small Streams and Wetlands Retain Sediment

Headwater streams and wetlands typically trap and retain much of the sediment that washes into them. The faster the water travels, the larger the particles it can carry. So, natural obstructions in small streams-rocks, downed logs, or even just a bumpy stream bottom-slow water and cause sediment to settle out of the water column. Wetlands, whether or not they have a surface connection to a nearby stream, are often areas where runoff slows and stops, dropping any debris the water may be carrying. Because headwater streams represent 75 percent or more of total stream length in a stream network, such streams and their associated wetlands retain a substantial amount of sediment, preventing it from flowing into larger rivers downstream.

Even ephemeral streams can retain significant amounts of sediment. Such small headwater streams expand and contract in response to heavy rains. During expansion, a stream flows over what was a dry or damp streambed. Most of the water at the leading edge of a growing stream, called the "trickle front," soaks into the streambed and does not carry sediment downstream. In a small watershed near Corvallis, Oregon, researchers found that 60 to 80 percent of sediment generated from forest roads traveled less than 250 feet downstream before settling out in stream pools. Headwater streams can store sediment for long periods of time: research in Oregon's Rock Creek basin found that headwater streams could retain sediment for 114 years.

Natural Cleansing Ability of Small Streams and Wetlands Protects Water Quality

Materials that wash into streams include everything from soil, leaves and dead insects to runoff from agricultural fields and animal pastures. One of the key ecosystem services that stream networks provide is the filtering and processing of such materials. Healthy aquatic ecosystems can transform natural materials like animal dung and chemicals such as fertilizers into less harmful substances. Small streams and their associated wetlands play a key role in both storing and modifying potential pollutants, ranging from chemical fertilizers to rotting salmon carcasses, in ways that maintain downstream water quality.

Excess Nutrients Cause Problems in Rivers and Lakes

Inorganic nitrogen and phosphorus, the main chemicals in agricultural fertilizers, are essential nutrients not just for plants, but for all living organisms. However, in excess or in the wrong proportions, these chemicals can harm natural systems and humans.

In freshwater ecosystems, eutrophication, the enriching of waters by excess nitrogen and phosphorus, reduces water quality in streams, lakes, estuaries and other downstream waterbodies. One obvious result is the excessive growth of algae. More algae clouds previously clear streams, such as those favored by trout. In addition to reducing visibility, algal blooms reduce the amount of oxygen dissolved in the water, sometimes to a degree that causes fish kills. Fish are not the only organisms harmed: some of the algae species that grow in eutrophic waters generate tastes and odors or are toxic, a clear problem for stream systems that supply drinking water for municipalities. In addition, increased nitrogen can injure people and animals. Excess nitrogen in the form called nitrate in drinking water has been linked to "blue baby disease" (methemoglobinemia) in infants and also has toxic effects on livestock.

Stream networks filter and process everything from leaves and dead insects to runoff from agricultural fields and animal pastures. Without such processing, algal blooms can ruin living conditions for fish and the quality of drinking water. Here, algae overtakes a lake in Iowa. Photo courtesy of Lynn Betts, USDA NRCS

Headwater Streams Transform and Store Excess Nutrients

Headwater streams and associated wetlands both retain and transform excess nutrients, thereby preventing them from traveling downstream. Physical, chemical and biological processes in headwater streams interact to provide this ecosystem service.

Compared with larger streams and rivers, small streams, especially shallow ones, have more water in physical contact with a stream channel. Therefore, the average distance traveled by a particle before it is removed from the water column is shorter in headwater streams than in larger ones. A study of headwater streams in the southern Appalachian Mountains found that both phosphorus and the nitrogen-containing compound ammonium traveled less than 65 feet downstream before being removed from the water.

In headwater streams and wetlands, more water is in direct contact with the streambed, where most processing takes place. Bacteria, fungi and other microorganisms living on the bottom of a stream consume inorganic nitrogen and phosphorus and convert them into less harmful, more biologically beneficial compounds. A mathematical model based on research in 14 headwater streams throughout the U.S. shows that 64 percent of inorganic nitrogen entering a small stream is retained or transformed within 1,000 yards.

Channel shape also plays a role in transforming excess nutrients. Studies in Pennsylvania have shown that when the forest surrounding headwaters is replaced by meadows or lawns, increased sunlight promotes growth of grasses along stream banks. The grasses trap sediments, create sod, and narrow the stream channel to one-third of the original width. Such narrowing reduces the amount of streambed available for microorganisms that process nutrients. As a result, nitrogen and phosphorus travel downstream five to ten times farther, increasing risks of eutrophication.

Streams do not have to flow year-round to make significant contributions to water quality. Fertilizers and other pollutants enter stream systems during storms and other times of high runoff, the same times that ephemeral and intermittent streams are most likely to have water and process nutrients. Federal, state and local programs spend considerable sums of money to reduce non-point source inputs of nutrients because they are a major threat to water quality. One principal federal program, the EPA's 319 cost-share program, awarded more than $1.3 billion between 1990 and 2001 to states and territories for projects to control non-point pollution. Failure to maintain nutrient removal capacity of ephemeral and intermittent streams and wetlands would undermine these efforts.

Wetlands also remove nutrients from surface waters. Several studies of riparian wetlands have found that those associated with the smallest streams to be most effective in removing nutrients from surface waters. For example, headwater wetlands comprise 45 percent of all wetlands able to improve water quality in four Vermont watersheds. Another study found that wetlands associated with first-order streams are responsible for 90 percent of wetland phosphorus removal in eight northeastern watersheds. Such studies demonstrate that riparian wetlands, especially those associated with small streams, protect water quality.

As land is developed, headwater streams are often filled or channeled into pipes or paved waterways, resulting in fewer and shorter streams. For example, as the Rock Creek watershed in Maryland was urbanized, more than half of the stream channel network was eliminated. In even more dramatic fashion, mining operations in the mountains of central Appalachia have removed mountain tops and filled valleys, wiping out entire headwater stream networks. From 1986 to 1998, more than 900 miles of streams in central Appalachia were buried, more than half of them in West Virginia.

"If headwater streams and wetlands are degraded or filled, more fertilizer applied to farm fields or lawns reaches larger downstream rivers."

If headwater streams and wetlands are degraded or filled, more fertilizer applied to farm fields or lawns reaches larger downstream rivers. These larger rivers process excess nutrients from fertilizer much more slowly than smaller streams. Losing the nutrient retention capacity of headwater streams would cause downstream waterbodies to contain higher concentrations of nitrogen and phosphorus. A likely consequence of additional nutrients would be the further contamination and eutrophication of downstream rivers, lakes, estuaries and such waters as the Gulf of Mexico.

Natural Recycling in Headwater Systems Sustains Downstream Ecosystems

Recycling organic carbon contained in the bodies of dead plants and animals is a crucial ecosystem service. Ecological processes that transform inorganic carbon into organic carbon and recycle organic carbon are the basis for every food web on the planet. In freshwater ecosystems, much of the recycling happens in small streams and wetlands, where microorganisms transform everything from leaf litter and downed logs to dead salamanders into food for other organisms in the aquatic food web, including mayflies, frogs and salmon.

Like nitrogen and phosphorus, carbon is essential to life but can be harmful to freshwater ecosystems if it is present in excess or in the wrong chemical form. If all organic material received by headwater streams and wetlands went directly downstream, the glut of decomposing material could deplete oxygen in downstream rivers, thereby damaging and even killing fish and other aquatic life. The ability of headwater streams to transform organic matter into more usable forms helps maintain healthy downstream ecosystems.

Headwater Stream Systems Store and Transform Excess Organic Matter

Intact headwater systems both store and process organic matter in ways that modulate the release of carbon to downstream lakes and rivers. Headwater systems receive large amounts of organic matter, which can be retained and transformed into more palatable forms through decomposition processes. This organic matter is anything of biological origin that falls into, washes into or dies in a stream. Plant parts, such as leaves, twigs, stems and larger bits of woody debris, are the most common of these items. Another source of organic material is dead stream organisms, such as bits of dead algae and bacteria or bodies of insects and even larger animals. Waste products of plants and animals also add organic carbon to water. Water leaches dissolved organic carbon from organic materials in a stream and watershed like tea from a tea bag.

"The ability of headwater streams to transform organic matter into more usable forms helps maintain healthy downstream ecosystems."

Much of the organic matter that enters headwater systems remains there instead of continuing downstream. One reason is that the material often enters headwater streams as large pieces, such as leaves and woody debris, that are not easily carried downstream. In addition, debris dams that accumulate in headwater streams block the passage of materials. One study found four times more organic matter on the bottoms of headwater streams in forested watersheds than on the bottoms of larger streams.

Another reason material stays in headwater streams is that food webs in small streams and wetlands process organic matter efficiently. Several studies have found that headwater streams are far more efficient at transforming organic matter than larger streams. For example, one study showed that, for a given length of stream, a headwater stream had an eight-fold higher processing efficiency than a fourth-order channel downstream. Microorganisms in headwater stream systems use material such as leaf litter and other decomposing material for food and, in turn, become food for other organisms. For example, fungi that grow on leaf litter become nutritious food for invertebrates that make their homes on the bottom of a stream, including mayflies, stoneflies and caddis flies. These animals provide food for larger animals, including birds such as flycatchers and fish such as trout.

Headwater Systems Supply Food for Downstream Ecosystems

The organic carbon released by headwater streams provides key food resources for downstream ecosystems. Headwater ecosystems control the form, quality and timing of carbon supply downstream. Although organic matter often enters headwaters in large amounts, such as when leaves fall in autumn or storm runoff carries debris into the stream, those leaves and debris are processed more slowly. As a result, carbon is supplied to downstream food webs more evenly over a longer period of time. Forms of carbon delivered range from dissolved organic carbon that feeds microorganisms to the drifting insects such as mayflies and midges that make ideal fish food. Such insects are the preferred food of fish such as trout, char and salmon. One study estimated that fishless headwater streams in Alaska export enough drifting insects and other invertebrates to support approximately half of the fish production in downstream waters.

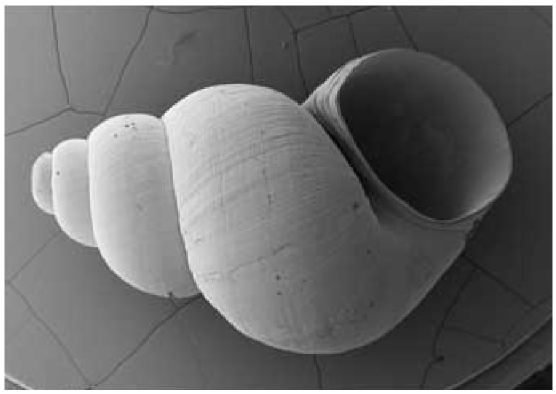
Processed organic matter from headwater streams fuels aquatic food webs from the smallest streams to the ocean. Only about half of all first-order streams drain into second-order streams; the other half feed directly into larger streams or directly into estuaries and oceans, thus delivering their carbon directly to these larger ecosystems. The health and productivity of downstream ecosystems depends on processed organic carbon-ranging from dissolved organic carbon to particles of fungus, and leaf litter to mayflies and stoneflies-delivered by upstream headwater systems.

Headwater Streams Maintain Biological Diversity

Headwater Habitats are Diverse

Headwater streams are probably the most varied of all running-water habitats; they range from icy-cold brooks tumbling down steep, boulder-filled channels to outflows from desert springs that trickle along a wash for a short distance before disappearing into sand. As such, headwater systems offer an enormous array of habitats for plant, animal and microbial life.

Top left: Populations of the ellipse mussel (Venustaconcha ellipsiformis) have disappeared from many of its native Midwestern headwaters. Photo courtesy of Kevin Cummings, Illinois Natural History Survey



Top right: A hydrobiid snail [Pyrgulopsis robusta] found in the headwaters of the Snake River in Wyoming. Photo courtesy of Dr. Robert Hershler

Center: Caddis flies and other aquatic insects spend their larval stage in streams, feeding on the algae, vegetation and decaying plant matter. The Brachycentris, a caddis fly found in headwater streams of eastern North America, constructs a protective case out of twigs, leaves and other debris. Photo courtesy of David H. Funk

Bottom: American dippers rely on headwater streams for sustenance, walking along stream bottoms and feeding on insect larvae and crustaceans among the rocks of the streambed. This American dipper was photographed at Tanner's Flat, just east of Salt Lake City. Photo courtesy of Pomera M. France

This variation is due to regional differences in climate, geology, land use and biology. For example, streams in limestone or sandy regions have very steady flow regimes compared with those located in impermeable shale or clay soils. Plants or animals found only in certain regions can also lend a distinctive character to headwater streams. Regionally important riparian plants, such as alder and tamarisk, exercise a strong influence on headwater streams. Headwater streams in regions with beavers are vastly different from those in regions without beavers.

Environmental conditions change throughout a stream network. In wet regions, streams grow larger and have wider channels, deeper pools for shelter, and more permanent flow as they move downstream. In arid regions and even humid regions during dry periods, headwater streams may become smaller downstream as water evaporates or soaks into a streambed. Because marked changes in environmental conditions can occur over very short distances, conditions required by a headwater species may exist for as little as 100 yards of stream. Consequently, local populations of a species may extend over just a short distance, particularly in spring-fed headwaters with sharp changes in environmental conditions along the length of a stream.

With this variety of influences, headwater streams present a rich mosaic of habitats, each with its own characteristic community of plants, animals, and microorganisms.

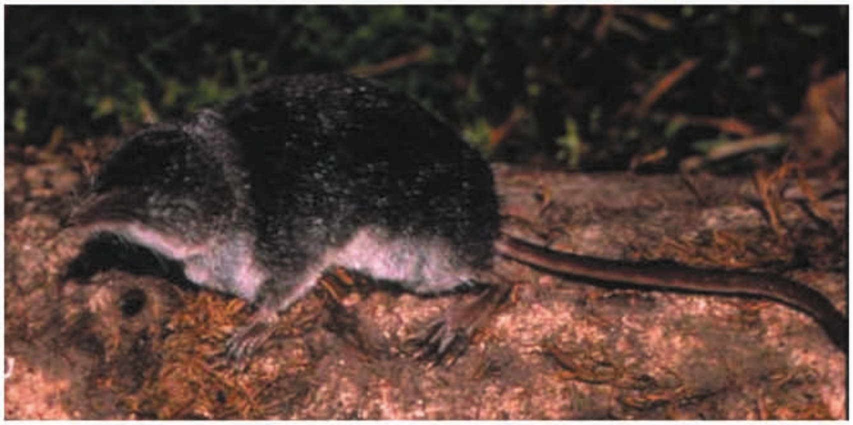
Headwater Systems Support a Diverse Array of Animals and Plants

There has never been a complete inventory of the inhabitants in even a single headwater stream, much less surveys across many types of headwaters that would permit a thorough understanding of biodiversity in headwater streams. Nevertheless, it is clear that individual headwater streams support hundreds to thousands of species, ranging from bacteria to bats.

The species in a typical headwater stream include bacteria, fungi, algae, higher plants, invertebrates, fish, amphibians, birds and mammals. Headwater streams are rich feeding grounds. Large amounts of leaves and other organic matter that fall or blow into streams, the retention of organic matter in a channel or debris dams, and the high rates of plant and algal growth in unshaded headwaters all supply food sources for animals such as caddis flies, snails and crustaceans. These animals become food for predators such as fish, salamanders, crayfish, birds and mammals, which, in turn, become prey for larger animals, including herons, raccoons and otters. Many widespread species also use headwaters for spawning sites, nursery areas, feeding areas, and travel corridors. Thus, headwater habitats are important to species like otters, flycatchers, and trout, even though these species are not restricted to headwaters. The rich resource base that headwaters provide causes the biotic diversity of headwater streams to contribute to the productivity of both local food webs and those farther downstream.

Diversity of headwater systems results in diverse headwater plants and animals. Many of these species are headwater specialists and are most abundant in or restricted to headwaters. For example, water shrews live along small, cool streams, feed on aquatic invertebrates, and spend their entire lives connected to headwater streams. Because different headwaters harbor different species, the number of headwater-dependent species across North America is far greater than the number of species in any one headwater.

Headwater specialists often have small geographic ranges. These species, many of which are imperiled, include: species of minnows, darters, and topminnows in southeastern springs and brooks; aquatic snails in spring-fed headwaters in the Great Basin, the Southeast, Florida, and the Pacific Northwest; crayfish in small streams from Illinois and Oklahoma to Florida; and salamanders and tailed frogs in small streams, springs, and seeps in the Southeast and Pacific Northwest. Two factors contribute to specialists small ranges: their limited ability to move between headwaters and high diversity of headwater habitats. Unlike mobile animals, such as mammals and birds, fully aquatic animals like fish and most mollusks cannot move from one headwater stream to another. As a result, local evolution may produce different species in adjacent headwater systems. Moreover, environmental conditions often differ greatly between adjacent headwater streams and even within the course of a single stream. For example, in a spring-fed headwater stream in western Pennsylvania, one species of caddis fly inhabits headwaters starting at the spring and going downstream about 200 yards. A different species of caddis fly inhabits the stream after that point.



A water shrew (Sorex palustris) in the water s of Oregon s Mt. Hood. Photo courtesy of RB Forbes, Mammal Images Library

Animals may use headwater streams for all or part of their lives. Although many fish species live exclusively in headwater systems, others use headwaters only for key parts of their life cycle. For example, headwaters are crucial for the diversity of salmon stocks in the Pacific Northwest because salmon spawn and rear in headwater streams. In other parts of the country, trispot darters, brook trout and rainbow trout spawn in small streams. Young cutthroat trout use shelter formed by streams debris dams but move onto larger portions of a stream network as they mature. Intermittent streams can offer special protection for young fish, because the small pools that remain in such streams often lack predators. Still other fish species use headwater streams as seasonal feeding areas.

A coho salmon migrating up a spring-fed tributary of the Snoqualmie River watershed in Washington s Puget Sound region. Many anadromous fish species spawn in headwater streams that are so small as to be omitted from standard USGS topographical maps. Photo courtesy of Washington Trout.

Both permanent and intermittent streams provide valuable habitat for microorganisms, plants and animals. Generally, biodiversity is higher in permanent streams than in intermittent streams, but intermittent streams often provide habitat for different species. Some species that occur in both types of streams may be more abundant in predator-free intermittent streams. For example, because of the lack of large predatory fish, salamanders and crayfish are sometimes more abundant in fishless intermittent streams rather than those with permanent flow. In contrast, for animals such as brook trout that require steady water temperatures and constant water flow, perennial streams provide better habitat.

A westslope cutthroat trout from Deep Creek, a headwater of the Kettle River. Cutthroat trout spawn in headwaters where the young trout seek shelter amid piles of debris, moving on to larger waters for their adult lives. Photo courtesy of Bill McMillan, Washington Trout

Canelo Hills ladies' tresses [Sprianthes delitescens] in a southwestern freshwater marsh known as a cienega. The cienegas of Arizona and New Mexico and Mexico, are the exclusive habitat for this member of the orchid family. Photo courtesy of Jim Rorabaugh, USFWS

Linkages between Headwater and Streamside Ecosystems Boost Biological Diversity

The movement of plants and animals between headwater and streamside ecosystems boosts biodiversity in both areas. Headwater streams are tightly linked to adjacent riparian ecosystems, the zones along a stream bank. Riparian ecosystems have high species diversity, particularly in arid environments where the stream provides a unique microclimate. Typical riparian vegetation depends upon moist streamside soils. Some plants must have "wet feet," meaning their roots have to stretch into portions of soil that are saturated with water. Seeds of some riparian plants, such as those of cottonwood trees found along rivers in the Southwest, require periodic floods to germinate and take root.

The Cleistes, a member of the orchid family, is found in pocosin wetlands of North Carolina. Photo courtesy of Vince Bellis

Another link between stream and land is often provided by insects, such as mayflies, that emerge from streams and provide a vital food resource for animals, including birds, spiders, lizards and bats. For example, insect-eating birds living by a prairie stream in Kansas consume as much as 87 percent of the adult aquatic insects that emerged from the stream each day. Such exchanges between land and water help maintain animal populations across landscapes. In many landscapes, the network of headwater streams is so dense that it offers a nearly continuous system of interconnected habitat for the movement of mobile species that rely on streams and riparian areas.

Biological Diversity of Headwater Systems is Threatened by Habitat Destruction

Because of their small size and intimate connections with surrounding landscape, headwaters and their inhabitants are easily influenced by human activities in watersheds and riparian zones. Changes to riparian vegetation or hydrology, water pollution, or the introduction of exotic species can have profound effects on biota living in headwaters.

Specialized headwater species can be particularly sensitive to habitat destruction because of their small geographic ranges, sometimes as small as a single headwater stream or spring. Thus, human activities have driven some headwater specialists, like the whiteline topminnow, to extinction, and imperiled many others. Furthermore, as the natural disjunction of headwater systems is increased by human activities such as pollution, impoundment, and destruction of riparian vegetation, more populations of headwater specialists may be extirpated.

Many headwater species, including fish, snails, crayfish, insects and salamanders, are now in danger of extinction as a result of human actions. A few dozen headwater species are already listed under the U.S. Endangered Species Act; hundreds of others are rare enough to be considered for listing. Given the diversity and sensitivity of headwater biota, it seems likely that continued degradation of headwater habitats will put more species at risk of extinction.

ing button celery, meadowfoam, wooly marbles and many others do the opposite; although they live in water, they cannot reproduce until water levels drop. Some plants and crustaceans most strongly identified with ephemeral wetlands worldwide, including quillworts, fairy shrimp, and tadpole shrimp, are ancient groups that probably originated at least 140 million years ago. The disappearance of ephemeral wetlands would mean the loss of these highly specialized and ancient groups of plants and animals.

One type of ephemeral wetland found in both California and the Northeast is known as a vernal pool because it generally fills with water in the spring. In California, blooming flowers ring the edges and fill depressions of such pools. Of the 450 species, subspecies, or varieties of plants found in California's vernal pools, 44 are vernal pool specialists. Several such plants are already on the Endangered Species list. If California's vernal pool habitats were completely destroyed, at least 44 species would disappear. Although vernal pool animals are less well known, there appear to be at least as many

Wetlands Make Key Contributions to Biological Diversity

The presence of wetlands adds another aspect of habitat diversity to headwater systems and therefore increases the variety of species a headwater system may support. Most headwater wetlands are depressions in the ground that hold water permanently or seasonally. Wetlands provide critical habitat for a variety of plants and animals. Scientists usually distinguish between ephemeral and perennial wetlands.

Biodiversity in ephemeral wetlands

Some species of plants and animals prefer or require ephemeral wetlands. Certain zooplankton, amphibians, and aquatic plants need the wet phase of an ephemeral wetland to complete all or part of their life cycles. Other species that rely on ephemeral wetlands wait out the aquatic phase, flourishing only when pools shrink or disappear. For example, although adult spotted salamanders are generally terrestrial, during the springtime they trek to vernal pools to breed and reproduce. So-called amphibious plants, includ-

Pitcher plants, such as this white top (Sarracenia leucophylla), pictured top left; and sundews, such as this Drosera brevifolia, pictured bottom right; are among the carnivorous plants found in the Carolina Bay wetlands of the Southeastern U.S. Photo courtesy of David Scott/SREL

Although spotted salamanders are generally terrestrial animals, they only breed and reproduce in vernal pools. Photo courtesy of Vernal Pool Association

specialized animals as plants. New species of specialists such as fairy shrimp and clam shrimp continue to be discovered.

Other ephemeral wetlands also make significant contributions to biodiversity. A study of wetlands in the Southeast including cypress-gum swamps, cypress savannas, and grass-sedge marshes, found that plants from one wetland are often very different from those in others nearby. Such differences in nearby habitats increase overall biodiversity in a region. In some cases, differences in periods of wetting and drying appear to be important for the persistence of many species. Different wetting and drying patterns explain some differences between Gromme Marsh and Stedman Marsh, two prairie pothole wetlands in Wisconsin. Although the two marshes are only about 450 yards apart, they have different species of dragonflies; also, Stedman Marsh has damselflies and caddis flies that Gromme Marsh lacks.

A female fairy shrimp from the Ipswich River Basin in Massachusetts. Fairy shrimp spend their entire life cycles in vernal pools. Photo courtesy of Vernal Pool Association

Amphibians are key parts of the food web in small wetlands. Some wetlands are hot spots for amphibian biodiversity; twenty-seven amphibian species, one of the highest numbers of amphibian species known from such a small area, inhabited a 1.2-acre ephemeral wetland in South Carolina. Other small wetlands in the region have been found to have similar numbers of amphibian species, demonstrating how small wetlands are especially important for maintaining the regional biodiversity of amphibians. Larger, more permanent wetlands may be less diverse because they may also be home to predators-such as crayfish and dragonfly larvae-that eat amphibian larvae.

Biodiversity in fens (a type of perennial wetland)

Plant biodiversity peaks in fens, unique perennial wetlands that occur where groundwater flows to the surface. Fens also provide clean water that supports downstream ecosystems; outflows from such wetlands are critical to the formation of the cold, low-nutrient streams that are ideal for trout. Although fens are rarely inundated, water seeps continuously into root zones.

Similar to other wetlands, the small land area covered by fens belies the high biodiversity found within them. For example, in northeastern Iowa, fens contain 18 percent of the state's plant species but cover only 0.01 percent of the land surface. Fens are probably the wetlands with the greatest numbers of plant species. Because groundwater that comes to the surface is typically low in available nutrients, fen plants are often dwarfed and the total mass of vegetation is typically low. As a result, no one species can become dominant and exclude other species.

In the Upper Midwest, more than 1,169 species of plants have been identified in fens, with more than half needing wet conditions. Fens also have a high proportion of plant species known to occur primarily in pristine sites. Often, such species are listed as rare, threatened or endangered. Of 320 vascular plant species found within fens in northeastern Iowa, 44 percent are considered rare. Fens themselves are imperiled: 160 fens that one researcher sampled in northeastern Iowa were all that remained from 2,333 historic fens.

Because diversity in fens stems from low nutrient availability, overfertilization can harm fens and, in turn, downstream ecosystems. Examining one fen in New York, researchers found the lowest diversity of plants where nitrogen and phosphorus inflows were greatest. Both nutrients came from agricultural activities: phosphorus was entering the fen primarily through surface water flows, while the nitrogen-containing compound nitrate was flowing with the groundwater. Thus, a loss of plant diversity in fens is a clear indication they are receiving excess nutrients, such as can occur when fertilizer runs off a field or urban lawn or water carries animal waste from farmyards. Allowing excess nutrients to enter fens can also damage downstream trout streams because trout prefer cold, low-nutrient streams. Therefore, the low-nutrient conditions of fens require protection from nutrient contamination.

A wood frog (Rana sylvatica) in an autumnal vernal pool in central Pennsylvania. Photo courtesy of Gene Wingert

Fens are unique perennial wetlands that occur where groundwater flows to the surface. Plant biodiversity peaks in fens: Among the 320 vascular plant species found in northeastern Iowa fens, 44% are considered rare. However, fens themselves are imperiled. Pictured is a fen wetland in Illinois. Photo courtesy of Steve Byers, Bluff Spring Fen Nature Preserve

Conclusion

Headwater streams and wetlands abound on the American landscape, providing key linkages between stream networks and surrounding land. Although often unnamed, unrecorded, and underappreciated, small headwater streams and wetlands-including those that are dry for parts of the year-are an integral part of our nation's river networks. Small wetlands, even those without visible surface connections, are joined to stream systems by groundwater, subsurface flows of water, and periodic surface flows. Current databases and maps do not adequately reflect the extent of headwater streams and associated wetlands. The resulting underestimate of the occurrence of such ecosystems hampers our ability to measure the key roles headwater systems play in maintaining quality of surface waters and diversity of life.

"THE PHYSICAL, CHEMICAL, AND BIOTIC INTEGRITY OF OUR NATION'S WATERS IS SUSTAINED BY SERVICES PROVIDED BY WETLANDS AND HEADWATER STREAMS."

Essential ecosystem services provided by headwater systems include attenuating floods, maintaining water supplies, preventing siltation of downstream streams and rivers, maintaining water quality, and supporting biodiversity. These small ecosystems also provide a steady supply of food resources to downstream ecosystems by recycling organic matter.

Photo courtesy of Raymond Eubanks.

Small streams and wetlands provide a rich diversity of habitats that supports unique, diverse, and increasingly endangered plants and animals. Headwater systems, used by many animal species at different stages in their life history, provide shelter, food, protection from predators, spawning sites and nursery areas, and travel corridors between terrestrial and aquatic habitats.

Since the 1970s, the federal Clean Water Act has played a key role in protecting streams and wetlands from destruction and pollution. We have made progress toward cleaner water, in part because the law has historically recognized the need to protect all waters of the United States. The health of downstream waters depends on continuing protection for even seemingly isolated wetlands and small streams that flow only part of the year.

These small streams and wetlands are being degraded and even eliminated by ongoing human activities. Among the earliest and most visible indicators of degradation is the loss of plant diversity in headwater wetlands. The physical, chemical, and biotic integrity of our nation's waters is sustained by services provided by wetlands and headwater streams.

Today's scientists understand the importance of small streams and wetlands even better than they did when Congress passed the Clean Water Act. If we are to continue to make progress toward clean water goals, we must continue to protect these small but crucial waters. The goal of protecting water quality, plant and animal habitat, navigable waterways, and other downstream resources is *not achievable* without careful protection of headwater stream systems.

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For additional information on topics discussed in this report, readers may consult the following websites:

http://www.nwrc.usgs.gov/

http://www.cwp.org/pubs_download.htm

http://www.epa.gov/OWOW/NPS/urbanize/report.html

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A Systems Approach to Ecosystem Adaptive Management

A USACE Technical Guide

J. Craig Fischenich, Sarah J. Miller, and Andrew J. LoSchiavo

November 2019

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A Systems Approach to Ecosystem Adaptive Management

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Abstract

Implementation guidance for Sections 2036 and 2039 of WRDA 2007 and Section 1161 of WRDA 2016 requires that ecosystem restoration projects either include appropriately scoped monitoring and adaptive management plans or provide sound justifications for why adaptive management is not warranted. Under adaptive management, decisions are based on the best available (yet often incomplete and imperfect) scientific data, information, and understanding, recognizing uncertainties that introduce risks to the achievement of goals and objectives. Revision to management actions based upon information derived from ongoing monitoring and evaluation is possible. This guide provides an overview of adaptive management practice, emphasizing underpinning principles. An approach to determine the need for and development of adaptive management plans is presented, and the implementation of ecosystem restoration projects under adaptive management is presented.

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Preface

Adaptive management is a powerful tool for managing risks on ecosystem restoration and mitigation projects. When developed with stakeholders, it can provide a framework for collaboratively moving forward with projects and watershed-scale programs in the face of uncertainty (and, potentially, disagreements). Adaptive management builds on information from incremental changes, reduces uncertainties, and facilitates risk communication in planning and operating sustainable systems. It ultimately helps ensure that objectives are met.

The concept of "learning by doing" -- as adaptive management is often described -- is intuitively simple. However, a more apt characterization would be "learning by doing, monitoring, evaluating results, making difficult decisions, adjusting if necessary, and repeating." The appealing nature of adaptive management as a theoretical construct belies the sometimes challenging and often complex realities of its implementation in practice. These realities underscore the need for guidance on adaptive management that is informed by its practice and the lessons learned in application.

Adaptive management plays an important role in the planning and implementation of U.S. Army Corps of Engineers (USACE) management actions. Its widespread application underscores the need for a competent, effective, and straightforward approach in the design and implementation of adaptive management across diverse USACE programs and projects under its ecosystem restoration authorities, and for the mitigation of fish and wildlife impacts from other business lines. This Adaptive Management Technical Guide was prepared to help agency practitioners and their partners meet this need.

This report was initially drafted by the USACE Adaptive Management Product Delivery Team. The team consisted of Mr. Ken Barr (lead and core team liaison), USACE, Rock Island District; Ms. Tomma Barnes, USACE, New Orleans District; Mr. Steve Bartell, E2 Consulting Engineers Inc.; Ms. Marci Johnson, USACE, Portland District; Mr. Craig Fischenich, USACE, Engineer Research and Development Center, Environmental Laboratory; Mr. Elmar Kurzbach, USACE, Jacksonville District (retired); Mr. Andy LoSchiavo, USACE, Jacksonville District; Mr. Richard Thomas, USACE, Great Lakes and Ohio River Division; and Mr. Bradley Thompson, USACE, Omaha District. Subsequent revision and updated content includes selected materials provided by Mr. David Marmorek, Aquatic Ecologist for ESSA Technologies, and Dr. Barry Noon, Conservation Ecologist at Colorado State University. Technical reviews and input from Dr. Dennis Murphy, University of Nevada, Reno, Mr. Graham Long, Compass, Dr. Kathryn McCain, USACE St. Louis District, and Dr. Mick Porter, USACE Albuquerque District, are gratefully acknowledged. The Chief of Engineers' Environmental Advisory Board (EAB) provided critical input based on the draft and discussions with USACE personnel engaged in adaptive management activities. Our sincere thanks for valuable contributions made by all participants in the Monitoring and Adaptive Management Workshops held in 2017 at the Albuquerque and St. Louis Districts and the USACE Institute for Water Resources, whose discussion of the Tech Guide informed approaches, organization and detail, particularly Mr. Brian Zettle, Ms. Jeanette Gallihugh, Mr. Jeff Trulick, Ms. Michelle Mattson, and Mr. Mark Matusiak. The final report addresses input from the Chief's EAB, Dr. Fred Sklar and Dr. Charles "Si" Simenstad, and HQUSACE.

The technical work was performed by the Ecological Resources Branch (CERD-EE-E) of the Ecosystem Evaluation and Engineering Division (CERD-EE), U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Dr. Jen Seiter-Moser was Chief, CEERD-EE-E, and Mr. Mark Farr was Chief, CEERD-EE. The Technical Director was Dr. Al Cofrancesco. The Deputy Director of ERDC-EL was Dr. Jack Davis and the Director was Dr. Ilker Adiguzel.

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COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
Acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
Hectares	1.0 E+04	square meters
Inches	0.0254	meters
Microns	1.0 E-06	meters
miles (U.S. statute)	1,609.347	meters
ounces (mass)	0.02834952	kilograms
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters
Slugs	14.59390	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
Yards	0.9144	meters

Abbreviations

AAMR	Annual Adaptive Management Report
AAR	After Action Report
AM	Adaptive Management
AMT	Adaptive management team
ANOVA	Analysis-of Variance
BA	Before-After
BACI	Before-After-Control-Impact
BiOp	Biological Opinion
CAP	Continuing Authorities Program
CEM	Conceptual Ecological Model
CEP	Critical Engagement Point
CEQ	Council on Environmental Quality
CERP	Comprehensive Everglades Restoration Plan
CESU	Cooperative Ecosystem Studies Unit
CI	Confidence Interval
CRCIP	Columbia River Channel Improvement Project
CWA	Clean Water Act
DOI	Department of the Interior
DQO	Data Quality Objectives
EA	Effects Analysis
EAB	Environmental Advisory Board
ECR	Environmental conflict resolution
EIS	Environmental Impact Statement
ER	Engineering Regulation
ERDC	Engineer Research and Development Center
ESA	Endangered Species Act
ESC	Executive Steering Committee
FACA	Federal Advisory Committee Act
FWG	Federal Working Group
FWS	Fish and Wildlife Service
FY	Fiscal Year
HQ	Headquarters
HQUSACE	Headquarters of the U.S. Army Corps of Engineers

IJC	International Joint Commission
ISAP	Independent Science Advisory Panel
LCA	Louisiana Coastal Areas
MRRP	Missouri River Recovery Program
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
O&M	Operation and Maintenance
OMRRR	Operations, Maintenance, Repair, Replacement, and Rehabilitation
PA	Programmatic Agreement
PCX	Planning Center of Expertise
PDT	Project Delivery Team
PgM	Program Manager
PIR	Project Implementation Report
PM	Project Manager
PMBP	Project Management Business Process
PrOACT	Problem Definition, Objectives, Alternatives, Consequences, Tradeoffs
QA/QC	Quality Assurance and Quality Control
QAPP	Quality Assurance Project Plan
R&D	Research and development
ROD	Record of Decision
ROPE	Reservoir Operations and Planning Evaluation
RPA	Reasonable and Prudent Alternative
RPM	Reasonable and Prudent Measure
RPMA	Recovery Priority Management Area
S&T	Science and technology
SDM	Structured Decision Making
SMART	Specific, Measurable, Attainable, Risk Informed, Timely
SP	Strategic Plan
T&E	Threatened and Endangered
TBD	To Be Determined
TNC	The Nature Conservancy

UMR	Upper Mississippi River
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WG	Work Group
WRDA	Water Resources Development Act

1 Introduction

1.1 Purpose and use

The primary purpose of this technical guide is to present an operational definition of adaptive management and describe a scalable approach to developing and implementing adaptive management plans for USACE ecosystem restoration programs and projects. The guide is intended to support and be congruent with current USACE implementation guidance related to monitoring and adaptive management, including guidance regarding section 2036 of WRDA 2007, section 1161 of WRDA 2016, SMART planning, and risk-informed decision making. It is intended to provide a foundation for adaptive management that can mature and conform to future guidance. The guide is somewhat aspirational, describing practices that are not yet common because adaptive management practice is relatively new, both within the USACE and more generally within the practice of ecosystem restoration.

Adaptive management is an exciting new paradigm for the USACE because it can increase the likelihood of project success, especially in situations where the outcomes of management actions or decisions have a relatively high degree of uncertainty. Indeed, it is the only risk-management tool available after a project's implementation. Adaptive management can be used to enhance the flexibility, robustness, and resilience of USACE projects and programs. The collaborative form of adaptive management promotes conflict resolution among agencies and stakeholders, scientists and managers while moving the state of science and understanding of ecosystem restoration forward in a deliberate way.

Adaptive management applies throughout the full life cycle of USACE programs and projects. Initial consideration of adaptive management begins with the traditional planning process and, except in cases where adaptive management is determined to be unnecessary (Section 0), continues through the construction, operation, and maintenance phase of a project. Adaptive management accommodates (often necessitates) iterative planning, design, and implementation cycles. The adaptive management process typically terminates when monitoring and assessment results demonstrate that goals and objectives have been achieved or are imminent and additional adjustments are no longer needed or anticipated.

This guide is intended for USACE program and project managers, project delivery team (PDT) members, and technical staff involved in efforts related to managing ecosystem restoration, fish, wildlife, and wetland mitigation.

Chapters 1 and 2 provide important context and outline the fundamental aspects and scales of adaptive management; these chapters are relevant to all readers. Individuals charged with planning and implementing adaptive management will find guidance for the development of adaptive management plans in Chapter 3. Appendix C addresses adaptive management implementation, related challenges, and available support.

1.2 Background

USACE civil works missions have historically placed an emphasis on post-project inspections in support of operations and maintenance (O&M) rather than on monitoring and evaluation of performance outcomes relative to project objectives. However, USACE Implementation Guidance for Section 1161 (Monitoring ecosystem restoration) of the 2016 Water Resources Development Act, and Section 2036 (Mitigation for fish and wildlife and wetlands losses) of the 2007 Water Resources Development Act (WRDA; Appendix A) require monitoring sufficient to evaluate ecosystem restoration and mitigation success. Importantly, these guidance documents stipulate the need for adaptive management (or contingency plans) for ecosystem restoration projects and mitigation projects. A principal objective of this Adaptive Management Technical Guide is to provide a comprehensive, defensible, and technical approach for developing and implementing adaptive management in support of the USACE Implementation Guidance and across all relevant USACE missions.

Adaptive management was designed to facilitate effective environmental decision making under circumstances involving incomplete knowledge and scientific uncertainty (Walters 1997). USACE programs and projects often require management decisions to be made under conditions of substantial variability and uncertainty, which carries some risk. Historically, decision-making processes defined by other federal regulatory requirements, for example, the Endangered Species Act (ESA) and the Clean Water Act (CWA), have been relatively inflexible and insensitive to variability and uncertainty. Changes have occurred with ESA consultations, which now frequently demand adaptive management (e.g., the Missouri River and Columbia River system descriptions in Appendix B). Adaptive management approached in partnership with regulatory agencies and interested stakeholders can generate information for developing novel management options and improved decision-making processes that recognize and incorporate the implications of uncertainty.

1.3 Adaptive management defined

Before describing a methodology for undertaking adaptive management, it is necessary to define what adaptive management is and what it is not. A clear definition is required because both confusion and genuine disagreement exists regarding the nature and scope of adaptive management due to its broad and nuanced application, as well as its continued evolution as a concept and practice. In this section, some of the subtleties and complexities of the language in the adaptive management literature are highlighted and a definition consistent with the USACE's application is provided. We also emphasize the fundamental tenets of adaptive management that make it a powerful tool for application to USACE restoration and mitigation efforts.

ADAPTIVE MANAGEMENT

A formal, science-based approach to risk management that permits implementation of actions despite uncertainties. Knowledge gained from monitoring and evaluating results is used to adjust and direct future decisions.

The theory of adaptive management has been around since at least the early 1900s (Taylor 1911), but it was first postulated as a conservation and resource management tool by Walters and Hilborn (1978) and Walters (1986). It was subsequently pursued in the context of harvesting, particularly for waterfowl and fish, and more recently has been explored in numerous areas of environmental management (Hauser and Possingham 2008). The U.S. Department of the Interior developed guidance for identifying the appropriate settings and use of adaptive management within its agencies (Williams et al. 2009); however, the USACE has not previously done so.

The following paragraph presented in *Adaptive Management for Water Resources Project Planning* (National Research Council 2004) provides the conceptual basis for adaptive management used in developing this USACE technical guide:

> "Adaptive management promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes learning while doing. Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders."

For the purposes of this guide, adaptive management is defined as a formal, science-based, risk management strategy that permits implementation of actions despite uncertainties. Knowledge gained from monitoring and evaluating results is used to adjust and direct future decisions. Simply stated, adaptive management is learning while doing in the face of uncertain outcomes.

Regardless of source, certain characteristics are common to most definitions of adaptive management (Walters 1986, Williams et al. 2009, Fischenich et al. 2012). Adaptive management involves the accumulation of understanding over time (that is, learning) and adjustment of management decisions over time (that is, adaptation) to better achieve project goals and objectives. It demands the clear statement of objectives, identification of management alternatives, predictions of management consequences, and recognition of uncertainties. Stakeholder engagement, monitoring of resource response, and modeling are obligatory, as is a governance process that ensures new knowledge is operationalized through decision making. None of these activities by themselves are sufficient to make a decision process adaptive; all must be present in a framework that is tailored to the decision needs.

Adaptive management is a science-based management approach, and scientific knowledge and methods support adaptive management in several important ways:

- Current scientific understanding can be used to help formulate the initial problem statement and planning alternatives as management-relevant hypotheses that can be evaluated through implementation and monitoring.
- Science can be used to translate conceptual models into operational models that in turn can be used to forecast the expected outcomes (benefits, costs, and less-quantifiable risks and benefits) of planning alternatives.
- Implementing management decisions as scientifically rigorous experiments can generate monitoring data and information that can be used to reduce uncertainties associated with future planning.
- Science-based assessments of sensitivity and uncertainty can be used to design monitoring programs that target key sources of uncertainty to improve management capabilities.

Adaptive management is a forward-looking process that unfolds in an anticipated manner; it is not an ad hoc, trial-and-error, or wait-and-see approach to management. The focus of adaptive management is not research per se. Rather, the primary objective of adaptive management is the accumulation of reliable knowledge toward improved and informed decision making (Lancia et al. 1996). However, research can be an important compliment to adaptive management, offering an efficient, focused means for addressing specific uncertainties (particularly where a large number of variables affect outcomes and controlled experiments in a laboratory or mesocosm are needed to obtain response functions).

1.4 Types of adaptive management

Adaptive management approaches have mainly been classified as either passive or active (Parma et al. 1998). The dichotomy between active and passive adaptive management has been discussed widely in relation to ecosystem management, although not without confusion (Westgate et al. 2013). Either approach may be appropriate; in practice a continuum of strategies involving components of both may be utilized, particularly on large adaptive management programs. This section also introduces "collaborative" adaptive management as an evolving approach that can be employed in conjunction with either active or passive adaptive management. Contingency planning is also discussed in relation to adaptive management.

1.4.1 Passive adaptive management

Passive adaptive management has been defined in several different ways (e.g. Walters 1981; Parma et al. 1998; Williams 2001; Pearsall et al. 2005) and we use Williams' (2001) definition, where learning is not accounted for explicitly in determining the optimal management strategy. Model updating and learning can occur "passively" as the system is managed and are secondary to the achievement of the fundamental objectives.

Passive adaptive management addresses variability and uncertainty by using historical and existing information to develop cause-and-effect relationships between a management action and anticipated system responses to alternative management scenarios, optimally represented in the conceptual model (see section 3.4.1.2). The approach traditionally leads to selection of what is believed to be the "best" plan and design for achieving desired responses (e.g., ecological, hydrological, flood control). Actual system response is monitored and, if warranted, the management alternative(s) is adjusted to achieve goals and objectives. Knowledge gained from monitoring of the system or management action performance can be applied to other future projects. Many USACE applications of adaptive management conform to the description of passive adaptive management.

Advantages of passive adaptive management include undertaking management actions in light of current understanding, assessing the utility of the management actions in relation to achieving outcomes consistent with management goals and objectives, and learning to manage effectively by monitoring system conditions (including "natural" patterns of environmental variability). One limitation of this approach lies in developing management actions that are effective only within the range of conditions measured during the program or project. The passive approach might provide competent management capability over a reasonable range of system conditions, yet preclude the identification of management actions or decisions necessary to correctly respond to highly unusual or future circumstances that were not encountered during the project period.

In practice, passive adaptive management approaches have seldom demonstrated that learning has occurred. This has less to do with weaknesses in the passive management strategy than with inadequate monitoring and assessment or a conviction to change when performance lags. Westgate et al. (2012) found that less than five percent of 1,336 articles citing “adaptive” and “management” identified through the ISI web of knowledge explicitly claimed to enact AM. These 61 articles cumulatively described 54 separate projects, but only 13 projects were supported by published monitoring data. Only five projects used the information gained from monitoring to make adjustments to the management actions. An analysis of 217 projects completed under USACE ecosystem restoration authorities from 1986 to 2014 showed results slightly better than found in the general literature; 49 percent had a monitoring plan, 19 percent had collected some data, but only five percent included adaptive management plans (Gardner et al. 2014).

1.4.2 Active adaptive management

In contrast, active adaptive management views management actions as purposeful experimental manipulations of the managed system (e.g., Walters and Holling 1990) designed to increase understanding of system responses in the short term and to increase the chances of achieving management goals and objectives in the long term through improved decision making. Active adaptive management addresses particularly uncertain or risky outcomes by designing management actions (i.e., field tests, physical models) to test multiple hypotheses about system responses to management. Evaluation of these hypotheses can help determine how to efficiently achieve a desired response to management (Gregory et al. 2006). Hypotheses may be tested concurrently, using several designs or operational plans to achieve goals and objectives. This approach requires a more scientifically rigorous experimental design to discriminate cause-and-effect relationships among the management options or questions that are tested. Active adaptive management is often referred to as “hypothesis-driven” or “experimental management” because it treats management actions as actual or de facto experiments.

Active adaptive management is implemented less often than passive adaptive management, but it offers highly reliable information, greater potential for rapid learning, and facilitates acquisition of new management skills (Taylor et al. 1997). Because it emphasizes knowledge as an intermediate objective toward fundamental management objectives, active adaptive management typically forgoes short-term returns for learning, resulting in improved understanding and maximized returns in the long term (Walters et al. 1993). Active adaptive management is widely thought to be the strategy most likely to resolve situations involving high uncertainty and risk and to maximize returns over time.

Examples of an optimal active adaptive strategy in practice are rare, however, and some examples claiming to be active adaptive management have been similar to passive adaptive management in practice (Hauser and Possingham 2008). Additionally, trade-offs between short-term gains in understanding through system manipulation and experimentation must be weighed against the risk that such manipulations might produce substantial and irreversible (undesirable) changes that reduce the likelihood of achieving objectives or that foreclose on future management options.

1.4.3 Collaborative adaptive management

Collaborative adaptive management has emerged as an approach that combines collaborative planning with either passive or active adaptive management. The Collaborative Adaptive Management Network (Sims and Pratt-Miles 2011) defines collaborative adaptive management as:

> . . . a systematic management paradigm that assumes natural resource management policies and actions are not static, but are adjusted based on the combination of new scientific and socioeconomic information. Management is improved through learning from actions taken on the ecosystem being affected. A collaborative adaptive management approach incorporates and links knowledge and credible science with the experience and values of stakeholders and managers for more effective management decision making.

Ecosystem restoration and resource management projects/programs typically present challenges related to information, coordination, communication, and understanding the results of management actions. Collaborative adaptive management is, in part, a response to these challenges. It seeks to merge science, collaboration, and a focus on outcomes. The emphasis on collaboration acknowledges that uncertainty, complexity, and change pertain not only to physical systems but also to human communities (Scarlett 2013).

While the USACE cannot abdicate its decision-making responsibility for actions within its authority, it routinely collaborates with stakeholders in order to consider all views and information, improve the quality of decision making, and increase the perceived credibility, relevance, and legitimacy of the science used to inform decisions. Collaboration results in better adaptive management strategies and improves the likelihood of project success.

1.4.4 Contingency plans

A contingency plan is a strategy devised to address an undesirable outcome (or trajectory). Section 1116 of WRDA 2016 specifically addresses the use of contingency plans when describing adaptive management. While some implementation guidance has used the term contingency plan synonymously with adaptive management, they are technically different. In adaptive management, a project's effects are monitored and then a decision is made regarding whether to make an adjustment and what the nature of the adjustment should be. In contingency planning, the need for and nature of adjustments are predetermined.

Developing a contingency plan usually involves scenario analysis to identify potential circumstances and/or outcomes that might warrant a response and exploring potential adjustments to management actions under particular scenarios. Contingency plans are commonly employed for risk management, but can be utilized as part of an adaptive management strategy when decisions can be specified in advance based on measurable outcomes from the actions. This usually involves the application of decision criteria that, when met, trigger the implementation of a contingency plan. Contingency plans can help reduce uncertainty related to the outcome of an adaptive management program.

1.5 Why adaptive management?

Adaptive management provides a precautionary approach to acting in the face of uncertainty and generally improves the probability of project/program success. Love et al. (2018) identified several benefits from adaptive management: reduced long-term cost, decreased risk of failure, strengthened credibility, increased public trust, objective basis for decisions, chance to test before investing in larger projects, and improved restoration outcomes. Importantly, adaptive management helps move the state of science and understanding of ecosystem restoration forward in a deliberate way.

Adaptive management, particularly in its more progressive forms (i.e. active AM with triggers and contingency plans), promotes collaboration and flexible decision making through deliberately designing and implementing management actions to test hypotheses and maximize learning about critical uncertainties to better inform management decisions (Williams and Brown 2012). A collaborative adaptive management approach incorporates and links credible science and knowledge with the experience and values of stakeholders and managers for more effective management decision making (Sims and Pratt-Miles 2011).

2 Adaptive Management Fundamentals

The USACE has employed the passive form of adaptive management in its traditional mission areas – particularly navigation – for decades without explicitly labeling it so. Increased recognition of adaptive management as an effective tool for risk management has led the USACE to embrace adaptive management as an approach to address management challenges accompanied by high uncertainty under its ecosystem restoration authorities. The first section of this chapter outlines the requirements for and applicability of adaptive management to these authorities. The next section describes the adaptive management process and relates it to other important USACE processes. The chapter concludes with considerations for alternative forms of adaptive management and collaborating with stakeholders.

2.1 USACE requirements for adaptive management

Implementation guidance for Sections 2036 and 2039 of WRDA 2007 (31 August 2009) emphasize new monitoring requirements on certain USACE projects and also provide guidance on adaptive management. The guidance uses the term "contingency plan" synonymously with an adaptive management plan. Paragraph (3)(d) in Section 2039 states that "an adaptive management plan will be developed for all ecosystem restoration projects. . . appropriately scoped to the scale of the project." However, it is recognized that adaptive management may not be warranted in all cases (see Section 2.1.1). The guidance also specifies the following:

- Rationale and cost of adaptive management and anticipated adjustments will be included in and reviewed as part of the decision document.
- Identified physical modifications will be cost-shared and must be agreed upon by the sponsor.
- Changes to the adaptive management plan approved in the decision document must be coordinated with HQ USACE.
- Significant changes needed to achieve ecological success that cannot be addressed through operational changes or the adaptive management plan may be examined under other authorities.
- Costly adaptive management plans may lead to re-evaluation of the project. In other words, if very large uncertainties exist or the potential for very large modifications remain after identification of the initial

selected plan and supporting adaptive management measures, there is the potential that additional planning or evaluation may be required to secure project approval.

Adaptive management might be required by agencies external to the USACE in order to proceed with planned projects (for example, as a condition in a biological opinion). Adaptive management might also be undertaken as part of the operation and maintenance of existing projects. There is also a growing collection of examples for the application of adaptive management for flood risk-management projects, water control and reservoir regulation, water quality, and navigation projects (Davis 2009). Nevertheless, the basic elements and purpose – to increase the likelihood of success – are the same.

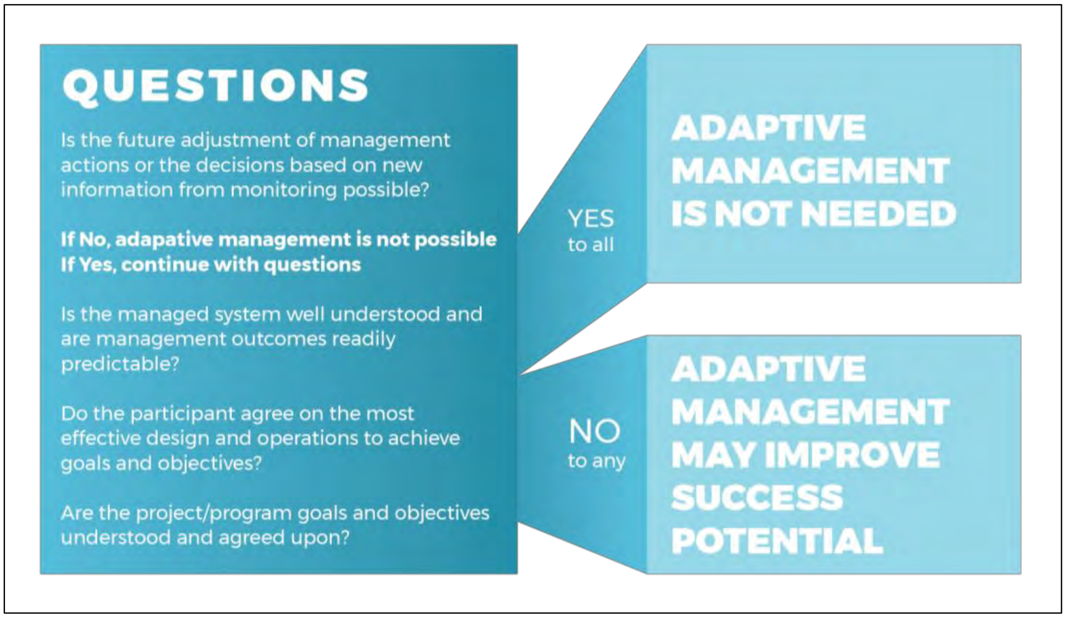
2.1.1 Criteria for determining the applicability of adaptive management to a project

Determining whether a management problem calls for adaptive management, and the complexity and scale of adaptive management, is a crucial step that should be addressed early in project scoping, but that may not be answerable until later in the planning process. While conceptually applicable to almost any problem, there are conditions that favor or hinder adaptive management, and its application to inappropriate contexts will fail to yield expected benefits and likely waste resources (Gregory et al. 2006).

Implementation Guidance for Sections 2036 (Mitigation for Fish, Wildlife, and Wetlands) of 2007 WRDA and Section 1116 of WRDA 2016 (Monitoring for Ecosystem Restoration) require contingency planning (adaptive management planning) and the preparation of adaptive management plans as part of planning for all ecosystem restoration projects. Recognizing that there are cases where adaptive management is unnecessary or even inappropriate, this requirement has been revised in practice to obligate the *consideration* of adaptive management for all ecosystem restoration projects. Projects under related authorities should include adaptive management plans or provide sound justifications for why adaptive management is not warranted.

Four elements must be present for adaptive management to proceed: 1) uncertainty regarding the outcome of a management action, 2) an ability to monitor and evaluate the system response to management actions, 3) capacity to learn from the monitoring, and 4) the ability and will to apply a decision to change management. Independent of the above requirements, if uncertainties are interfering with project planning or preventing successful implementation, adaptive management is an appropriate strategy. Figure 1 presents a decision rubric to help determine whether adaptive management is warranted. Criteria for the rubric are discussed below.

Figure 1. Decision rubric to assess potential for application of adaptive management.



1. *Are there design, operational, or regulatory impediments to future adjustment of management actions?*
   If authorities, funding, or other practical considerations severely limit or prohibit opportunities to adjust a project, it cannot be adaptively managed. For example, a canal intended to alter hydrology and restore ecological function may have been designed to maintain certain minimum and maximum stages to ensure flood control, maintain water supplies or meet water quality standards. Its design constraints may only be minimally changeable under adaptive management, and a small degree of operational flexibility might limit the ability of that project to test different operations to meet a particular goal or objective.

2. *Is the system (or components) to be restored or managed well-understood (hydrologically and ecologically), and are management outcomes accurately predictable?*
   Adaptive management is decision making under managed uncertainty.

If the range of potential responses to a proposed management action are known with a high level of confidence and an acceptable degree of accuracy based on well-established science or engineering, the proposed action might not benefit from adaptive management. Such situations are likely where considerable experience exists with a particular technique applied under a particular set of circumstances. Common sources of uncertainty to consider (not a complete list) include (1) incomplete understanding of the system (environmental or engineering) to be managed or restored, (2) imprecise estimates of the outcomes of alternative management actions, and (3) poor understanding of future boundary conditions such as land-use changes and climate change.

3. *Do participants generally agree on the most effective design and operations to achieve program/project goals and objectives?*
Restoration objectives can usually be met by alternative means (different methods, designs, or operations) with varying costs and trade-offs. In some cases, only one approach is feasible or acceptable. In those instances, an alternative management scheme is improbable at best and adjustments under adaptive management equally unlikely.

4. *Are the goals and objectives understood and agreed upon by all parties?*
The primary purpose for adaptive management in the USACE is to ensure a project achieves its goals and objectives. Ecosystem restoration objectives are often poorly defined. The USACE states that

> "...the purpose of ecosystem restoration activities is to restore significant ecosystem function, structure, and dynamic processes that have been degraded so as to partially or wholly re-establish the attributes of a naturalistic functioning and self-regulating system" (ER1165-2-501).

For ecosystem restoration projects, the extent to which structure, function, and dynamic processes can be restored and the degree of restoration needed for a system to be naturally functioning and self-regulating may be unknown or highly uncertain. The "vision" for a project may differ among stakeholders, or between the USACE and stakeholders due to different expectations regarding outcomes. Adaptive management is well-suited to this situation.

While the four elements listed above are *requisite* for adaptive management, they are not always *sufficient* to determine that adaptive management is appropriate. While most ecosystem restoration and mitigation projects can benefit from adaptive management, the following three considerations can be important in determining whether adaptive management is feasible or unlikely to add value in the planning and execution for specific USACE programs and projects.

First, if institutional or stakeholder support for adaptive management is lacking, adaptive management will be challenging. Adaptive management is conceptually unpalatable to some; it requires an admittance of uncertainty and willingness to regard projects as "incomplete" following implementation. Stakeholders and managers may lack patience for experimental designs that cannot resolve uncertainties for years or even decades.

Second, adjustments to management actions that are conceptually and even technically feasible may not be practically implementable. Constraints to operational flexibility imposed by stakeholder concerns can be persuasive impediments, particularly for multi-purpose projects involving flood management, water supply, hydropower, etc. Stakeholders may regard adaptive management as an unacceptable trade-off of one form of uncertainty (achieving objectives) for another (future management).

Finally, adaptive management is not without cost. The added monitoring, assessment, and governance costs may themselves be prohibitive, and costs to alter management actions (e.g. physical restoration measures) may be excessive. Uncertainty regarding if and when adjustments might be needed and for the associated cost creates planning and implementation challenges. Return on investment should be considered with the costs of adaptive management weighed against the benefits.

2.1.2 Issues of scale

Adaptive management is most often associated with large-scale applications with a high degree of complexity. Adaptive management is scalable, however, meaning that the approach may be appropriately sized to projects ranging from a single management unit to entire ecosystems (Williams et al. 2009). There likely are many more potential applications of adaptive management at more localized scales, not only because there is a preponderance of such problems but also because they often can be more easily framed, key uncertainties can be more readily identified, and stakeholder involvement can be more easily facilitated (McConnaha and Paquet 1996).

While many of the examples cited in the literature and lessons learned from application have been derived from the large adaptive management programs, the approaches and key concepts are equally applicable to small projects pursued under continuing authorities' programs. The steps, while the same in both cases, may involve vastly different levels of effort and time. Complexity and scope of uncertainty – not physical scale or cost – may be the best indicator of the appropriate investment needed to develop and implement adaptive management plans for ecosystem restoration and mitigation projects or programs.

Adaptive management as described here applies equally well to local issues and large-scale systems, as long as the basic conditions are met (see Williams et al. 2007 for examples). The specifics of an adaptive management plan will often differ between an ecosystem restoration program and the projects within that program. This is understandable, given that the objectives, uncertainties, and potential adaptive actions at the project scale may be different than those for the overall program of which it is part.

Several USACE comprehensive ecosystem restoration programs (e.g., Upper Mississippi River, Florida Everglades, Coastal Louisiana; see Appendix B) consist of many focused projects directed at incremental environmental improvements that cumulatively improve or restore ecological function at the system scale. Identifying relevant spatial and temporal scales in adaptive management plans for these applications can be challenging. Within these larger, complex programs, adaptive management processes should be developed and applied that simultaneously monitor and evaluate several related individual projects. Insightful planning and organization can reduce duplication in monitoring efforts, increase efficiency, and reduce overall costs of adaptive management.

System-wide implementation of adaptive management might reasonably result in a nested hierarchical approach to adaptive management wherein the objectives and uncertainties for projects are addressed by one plan component, while the system-wide objectives and uncertainties are addressed by another, with both relying upon the same adaptive management infrastructure (governance, data management, etc.)

Implementation of adaptive management also requires consideration of relevant temporal scales for monitoring, evaluation, and particularly for making adjustments. In some instances (e.g., floodplain forest restoration in the Upper Mississippi River, cypress-tupelo restoration in Coastal Louisiana), the required duration for adaptive management might exceed the USACE authority or funding term, requiring the project sponsor to assume responsibility. Guidance for Section 1116 of WRDA 2016 allows for cost-shared monitoring for up to 10 years; longer periods may be supported by non-Federal sponsors or, in the case of large ongoing programs, through programmatic monitoring activities. The need for adjustment may not be apparent for even longer periods. While this may be accommodated in large programs, it presents challenges to smaller restoration projects.

As noted above, adaptive management expertise and experience in the USACE has been developed mainly from its application to large-scale programs. However, the steps in the process and the underpinning principles are the same, irrespective of scale, and can be applied to smaller projects.

2.2 The adaptive management cycle

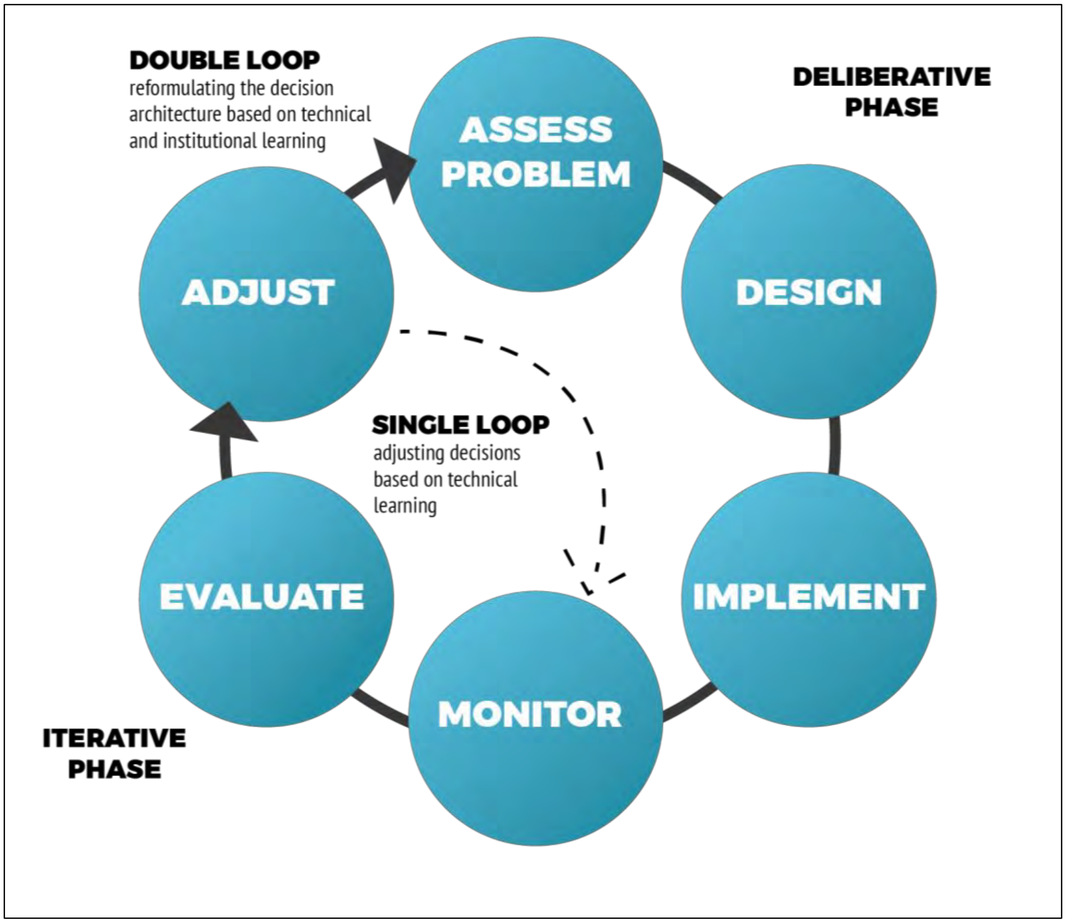
2.2.1 Traditional adaptive management cycle

The basic steps of adaptive management as routinely described include (e.g., Walters 1986):

1. **Assess the problem** by defining the management challenge or opportunity, including the specification of desired goals and objectives and recognition of sources of uncertainty, and formulating a conceptual model incorporating this understanding;
2. Identify or **design** potential management actions to address the challenge or opportunity;
3. **Implement** the selected action according to its design;
4. **Monitor** the results or outcomes of the management action;
5. **Evaluate** the action in relation to specified management goals and objectives and/or assess hypotheses based on the new information; and
6. **Adjust** (adapt) the action(s), conceptual model, or goals and objectives as warranted based on new knowledge.

In this traditional view, the basic steps (and particularly the last four), are performed iteratively until the goals and objectives are achieved, the management action is substantially modified or replaced, or the process is terminated because objectives are met (Figure 2). A development phase includes problem assessment, design of the management action and the decision architecture, and implementation. An implementation phase includes monitoring, evaluation of monitoring results, and adjustment of management strategy.

Figure 2. Basic steps of traditional adaptive management (e.g., Walters 1986). This diagram includes "double-loop" learning reflecting institutional learning, described by Williams and Brown (2018).



Many authors describe this cycle as involving two phases: (1) a deliberative phase involves framing the resource management issue in terms of stakeholders, objectives, management alternatives, predictive models (including measures of the confidence one places in them), and monitoring protocols; and (2) an iterative phase that uses these elements in an ongoing cycle of technical learning about system structure, function, and management impacts. Williams and Brown (2018) identifies an institutional learning phase that focuses on the decision components themselves by periodically interrupting the iterative cycle of technical learning to reconsider project objectives, management alternatives, stakeholder engagement, and other elements of the deliberative phase.

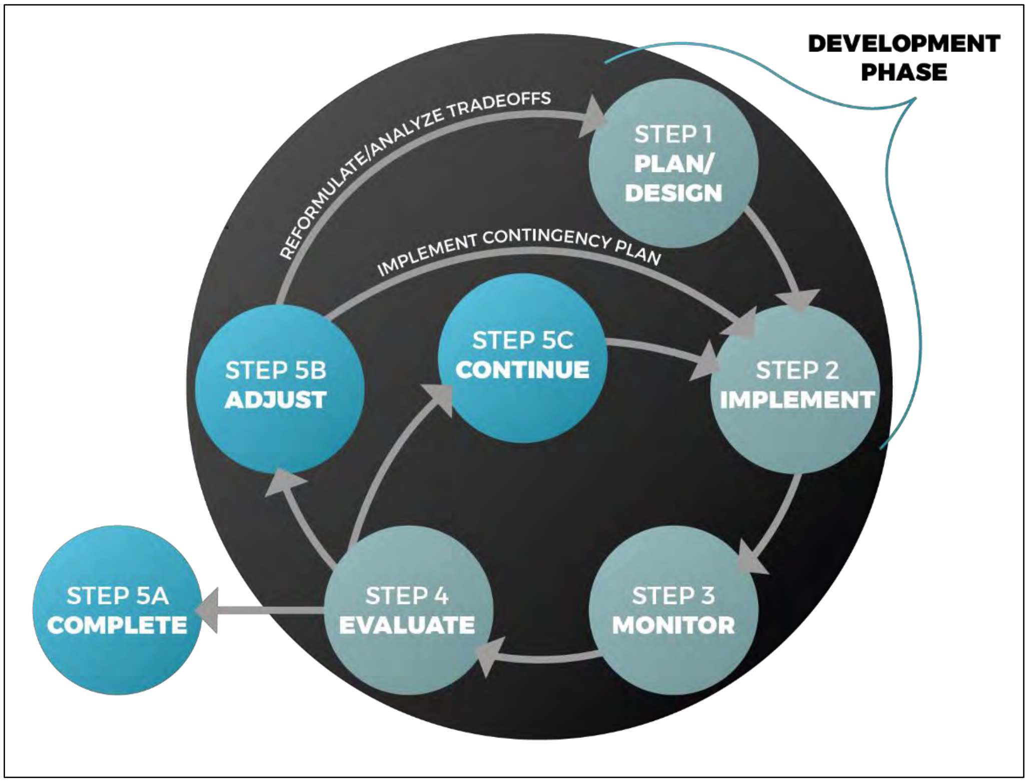
2.2.2 Modification of the adaptive management cycle for the USACE

To support USACE project planning and implementation more effectively, the basic steps of traditional adaptive management have been modified slightly and extended for compatibility with the USACE civil works project life-cycle process and implementation guidance for relevant policies (Figure 3). The elements of the modified cycle parallel the traditional adaptive management process, but the USACE process is more explicit in the assess and design steps, which encompass the Corps' planning process, and in the adjust step, recognizing that the assessment of project performance in relation to desired outcomes can result in decisions to:

- **Continue** project implementation as originally designed or
- **Adjust** the project if goals and objectives are not being achieved or
- Determine that the project has achieved **success** by meeting objectives (or demonstrating a sufficient trajectory toward success), in which case the adaptive management cycle can be regarded as **complete**.

The Adjust step may involve modifications to the current project implementation consistent with the original adaptive management plan (i.e., the alternative remains effectively the same, or a previously evaluated contingency plan is implemented). If adjustments are required beyond the current authority, a new plan might be required (i.e., project reformulation as part of post authorization change process outlined in Appendix G-16 of ER 1105-2-100), potentially involving a new round of scoping and analysis under NEPA). In this regard, the USACE planning cycle is embedded within the adaptive management cycle and may be iteratively addressed.

Figure 3. Adaptive management cycle modified for compatibility with USACE ecosystem restoration and mitigation projects.



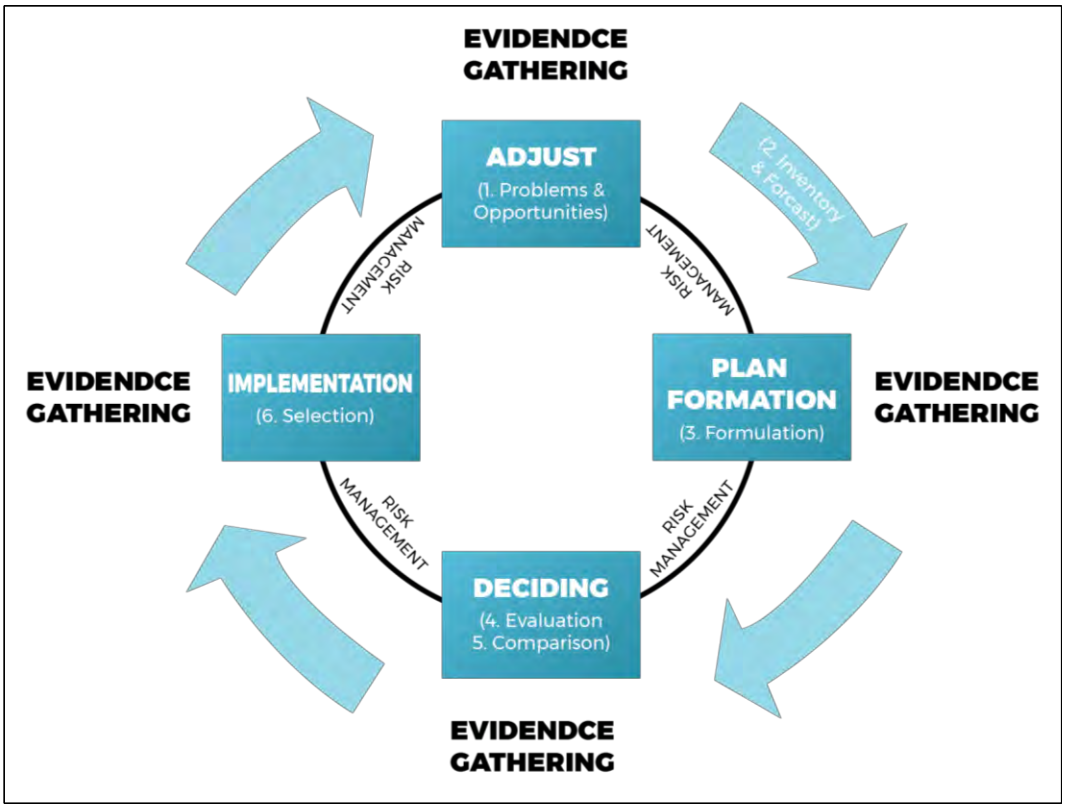
The concept of a two-phase approach to adaptive management helps to delineate the steps for the USACE process. The USACE approach considers a “development phase” in which the adaptive management plan is developed and an “implementation phase” wherein the plan is put into practice. These phases can be iterative; that is, the implemented action and/or the adaptive management plan may be revised as a consequence of learning (see the reformulate/analyze tradeoffs arrow in Figure 3).

2.2.3 Integration of adaptive management with the USACE planning and project management processes

Risk-based decision making and early vertical team engagement are emphasized in two 2012 USACE planning memoranda. SMART planning is the name given to the initiative that implemented the five pillars outlined in the memoranda. The “R” in SMART refers to “Risk-Informed.” Risk-informed planning pays careful attention to uncertainty, and it uses a set of risk-performance measures, together with other considerations, to inform planning. The iterative analytical steps in risk-informed planning reduce, but cannot eliminate, uncertainty. Adaptive management is the tool used to address residual uncertainty and is an integral part of the planning process.

SMART planning has evolved under a risk-management paradigm. Figure 4 depicts the risk-informed planning process as an iterative set of four tasks that begins with scoping and ends with implementation. The six "traditional" USACE planning steps are listed in the figure. The data gathering of Step 2 is shown to be ongoing throughout the planning process, not confined to or described by a single step. Evaluation and comparison of alternatives (Steps 4 and 5) are combined into the "Deciding" task.

Figure 4. USACE risk-informed planning process with the six traditional planning steps shown (from Yoe 2017).



The first two steps in the adaptive management cycle encompass the traditional six-step USACE planning process because the need for adaptive management is identified during these steps and the foundational products for adaptive management overlap with those for planning. This part of the adaptive management cycle is regarded as the development phase (Figure 5). The implementation of adaptive management involves iterations through the remaining steps of the adaptive management cycle (see Figure 3 and Table 1) and are part of the broader USACE project lifecycle management. As such, the planning process -- the first two steps of the adaptive management process -- may be revisited if warranted. Risk management applies to each step of the process, as discussed below. Tasks within each of the steps of the USACE adaptive management cycle are listed in Table 1.

Figure 5. Portion of the adaptive management cycle expanding Steps 1 and 2 to emphasize the USACE planning process.

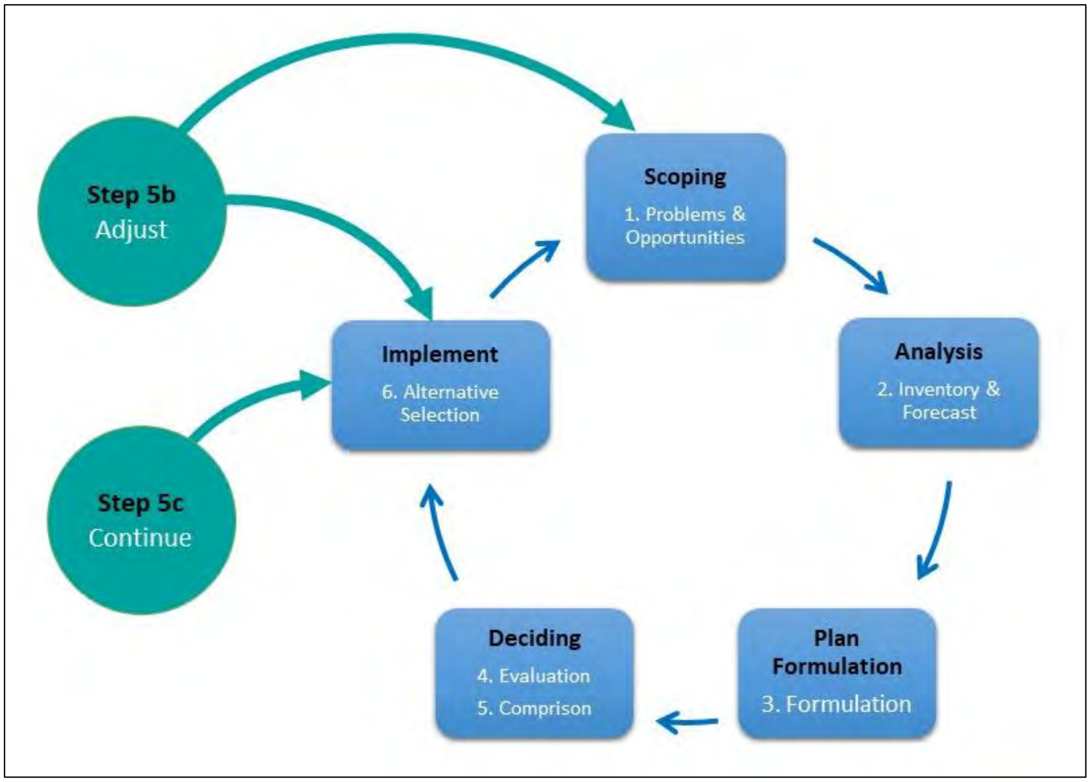


Table 1. Steps and tasks in the USACE adaptive management process[1].

Phase	AM Steps	Tasks within each Step
Development Phase	Step 1: Assess and define the problem	• Clearly state management goals and objectives • Involve scientists, stakeholders, managers • ID spatial/temporal bounds • Build conceptual models • ID key uncertainties (what are the management questions?) • Consider need/potential for AM (three screening criteria) • Articulate hypotheses to be tested • ID relevant metrics and measurable indicators • Explicitly state assumptions • State up front how what's learned will be used
	Step 2: Formulate alternatives and design	• Consider implications of AM to NEPA • Explore alternative management actions (experimental "treatments") • Use active AM when possible; passive AM is OK • Predict outcomes using metrics related to objectives • Estimate costs (including AM costs considering contrasts, replications, controls, monitoring, assessment, and potential remedial actions) • Consider contingency plans and next steps under alternative outcomes • Compare alternatives, contrasting with and without AM • Develop a formal AM plan (determine governance structure, develop a monitoring plan with statistical advice, develop a data management, communications and reporting plan, etc.) • Get the plan peer-reviewed and revise cost estimate as needed
Implementation Phase	Step 3: Implement	• Obtain baseline monitoring (if possible) • Implement contrasting treatments • Implement as designed (or document unavoidable changes)
	Step 4: Monitor	• Obtain and document "as-built" conditions • Conduct training and revisit monitoring protocols as needed • Implement the Monitoring Plan as designed to assess

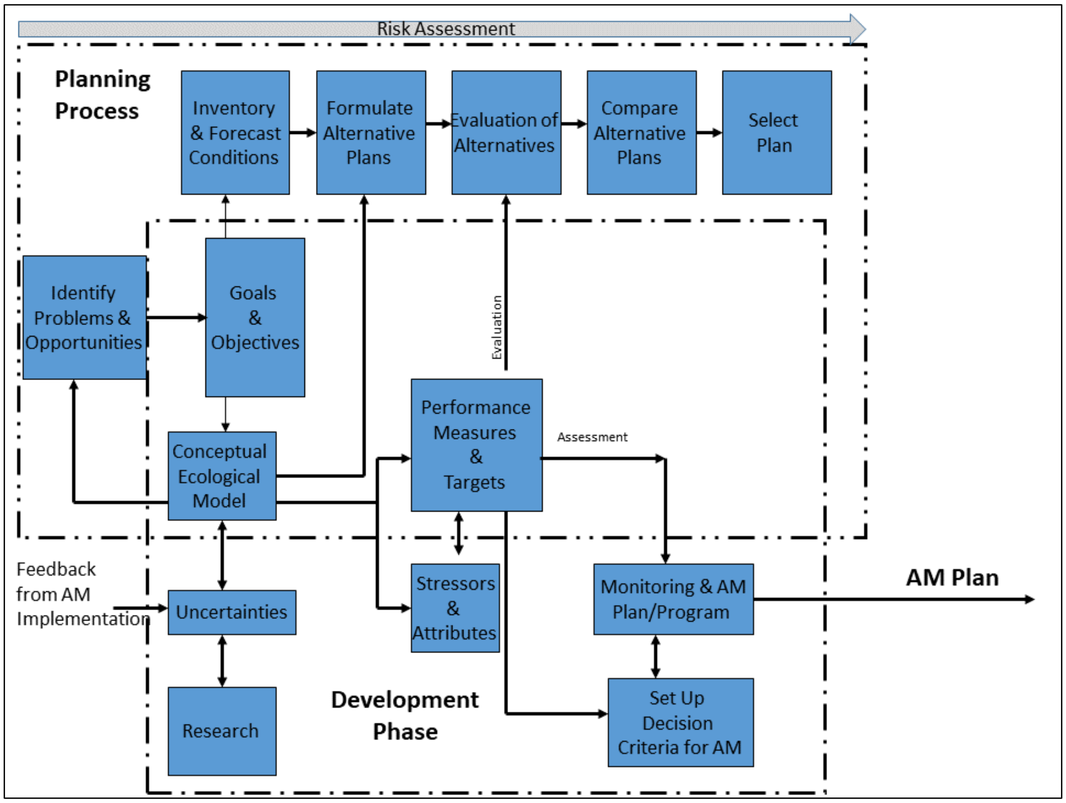
[1] Adapted from Fischenich et al. (2012) and augmented with input from a survey in Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center. Note that the tasks may vary depending on the nature of the project and the type of adaptive management employed.

Phase	AM Steps	Tasks within each Step
	Step 5: Evaluate results	• Compare monitoring results against objectives, assumptions, uncertainties, and hypotheses • Compare actual results against model predictions • Consider outside sources of information (e.g. new science) • Ensure data analysis keeps up with data generation • Obtain statistical/analytical assistance and review as needed
	Step 6: Continue/ adjust/ success	• Ensure meaningful learning occurred, was documented, communicated to decision makers (and others as needed), etc. • Decision criteria/triggers indicate need to implement contingency plans • Decision makers consider whether to continue as planned, or

The development phase of adaptive management, described in Chapter 3, proceeds concurrently with the planning process and is managed as part of the Project Management Business Process (PMBP). Project managers should include the adaptive management plan and team as a functional area of the Project Management Plan (PMP). Adaptive management plan tasks and adaptive management team resources need to be identified in the work breakdown structure. Adaptive management tasks will require schedules and budgets to coordinate with management for approval and track implementation.

When there are significant uncertainties about the future or the effects of plans, phased implementation and adaptive management strategies are viable options to consider during the plan formulation. For ecosystem restoration, this means that adaptive management is a consideration from the onset of scoping. Figure 6 shows the tightly integrated steps of the planning process and those of the adaptive management development phase. They rely upon the same fundamental information, processes, and products (e.g. conceptual models, goals and objectives, Risk Register, projected outcomes, and uncertainty analyses, etc.)

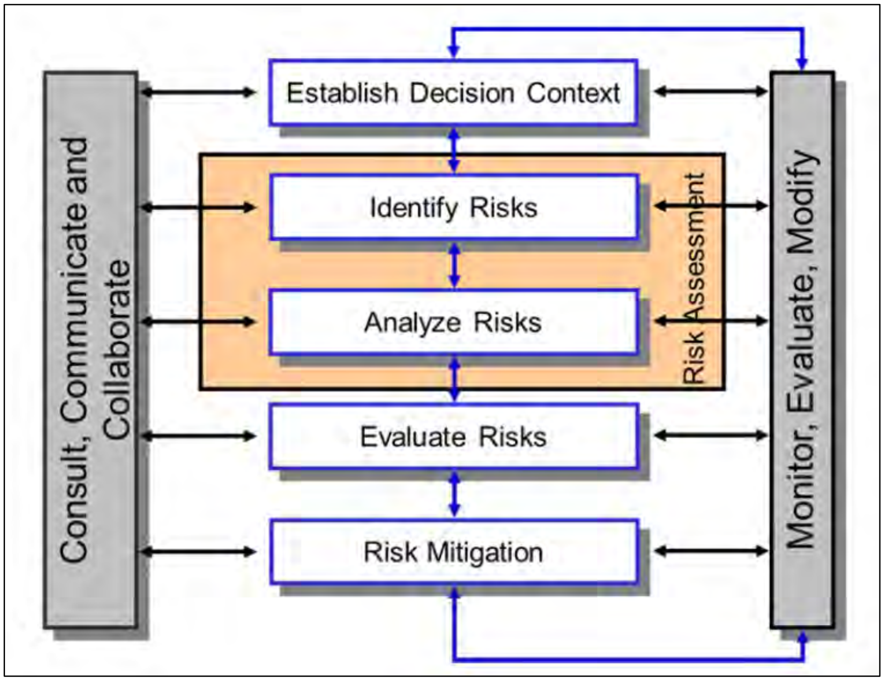
Figure 6. Crosswalk of the six traditional planning steps with the steps in developing the adaptive management plan.



SMART planning and adaptive management are both closely aligned with the USACE risk management strategy. In a risk-informed planning process, risk in some form is a decision criterion and planners must determine what a tolerable level of risk is to the agency and stakeholders. Risk assessment, risk management, and risk communication are components of the USACE risk management model used to support decision-making under uncertainty (Figure 7).

Risk management begins with scoping and the identification of problems and opportunities, each of which have associated uncertainties and risks. It continues throughout the full planning process. A key element of SMART planning is maintaining an appropriate level of detail to make the decision at hand; obtaining additional information is of little use if it is not needed to make a decision or will not improve the decision. Built into this concept of an appropriate level of detail is an implicit notion that the risks associated with not reducing the uncertainty further have been considered. Risk registers, scenario analysis, and uncertainty analysis are all tools to help identify, evaluate, and communicate risks.

Figure 7. The USACE risk management model.



Scenario analysis can be used to consider alternative futures with and without adaptive management. Probing uncertainties and exploring potential outcomes forces the PDT to consider the implications of uncertainties, which helps separate acceptable risks from tolerable risks and unacceptable risks. It also helps the team identify possible risk reduction measures. Broad categories of measures include:

- Eliminating or avoiding the context in which the risk occurs
- Modifying (transforming) the consequences of the risk
- Reducing the likelihood of the risk occurring
- Removing objection to the phenomenon that causes the risk to be perceived as a problem
- Transferring the risk to someone else
- Adaptive management and contingency plans.

SMART planning seeks to reduce uncertainty and associated risks. When the remaining planning uncertainty is not amenable to further reduction through more evidence gathering or where the fundamental direction of the future is in doubt, it is time to consider plans that include adaptive management. Nominally, the Feasibility Report must discuss adaptive management and, if it is not needed or warranted, provide a justification. If adaptive management is justified, a monitoring and adaptive management plan as well as a cost estimate is required. Chapter 3 provides details regarding the integration of planning and the adaptive management development phase.

2.3 Monitoring in relation to USACE planning guidance

The USACE has historically addressed civil works projects such as flood risk management and navigation by planning, designing, and implementing the project, then turning the project over to the local sponsor with identified requirements for operations and maintenance. In most cases, post-project monitoring or assessment was simply conducted under the periodic inspections program as part of normal operations and maintenance (i.e. compliance monitoring). For cost-shared projects, inspections were the responsibility of the non-Federal sponsor.

Directives for monitoring are provided in the implementation guidance documents pertaining to Sections 2036 and 2039 of WRDA 2007 and Section 1161 of WRDA 2016. These documents require that all mitigation plans and ecosystem restoration projects include a monitoring plan. This monitoring may be as simple as basic post-project inspections. However, in many cases, more detailed performance-based evaluations will be necessary. The guidance specifically includes the following:

- Development of a monitoring plan will be initiated during plan formulation, focusing on key indicators of project performance relative to the goals and objectives.
- The decision document must provide the rationale for monitoring, identify specific monitoring parameters, link those parameters to desired outcomes or decisions (typically through the conceptual models), and describe uses of the information.
- The plan must specify the nature, duration, and periodicity of monitoring; disposition of monitoring and analysis; costs; and responsibilities.
- Pre-project monitoring may be necessary to support alternative formulation and design and establish baselines to measure change. Monitoring in support of adaptive management commences upon completion of construction and continues until “restoration success” is documented by the District Engineer in consultation with Federal and state resource agencies and determined by the Division Commander.
- Success will be determined by an evaluation of predicted outcomes vs. actual results.

- The scope and duration should include the minimum monitoring actions necessary to evaluate success and need not be complex.
- Financial and implementation responsibilities for monitoring will be included in the Project Partnering Agreement (PPA).
- Cost-shared (under Construction) components are not to exceed 10 years. Shared monitoring costs must be included as part of the project cost and cannot increase the Federal cost beyond the authorized dollar limit. Monitoring can end sooner if success is determined. Monitoring beyond 10 years is a 100-percent non-Federal responsibility.
- The monitoring plan will be reviewed during Agency Technical Reviews and Independent External Peer Review as necessary during the planning phase.

2.4 Alternative forms of adaptive management

Much of the adaptive management literature in the past two decades has focused on distinguishing passive and active adaptive management. Both forms of adaptive management utilize learning to inform management interventions. The distinction between the two approaches is the extent to which learning is a specific objective and the degree to which management is used proactively to accelerate the rate of learning (Williams et al. 2009). In practice, a continuum of strategies exists and the appropriate approach is dictated by project or program needs and constraints.

Collaborative adaptive management (CAM), which is the combination of adaptive management and collaborative planning, includes stakeholders in the decision process to build trust, establish legitimacy, and reduce delays (Berkley 2013, Pratt-Miles 2013, Scarlett 2013). Successful implementation of adaptive management is considered unlikely without stakeholder buy-in (Green et al. 2013). Stakeholder inclusion is often seen as the greatest challenge to implementation of CAM projects, however (Monroe et al. 2013), and care is needed in clearly defining roles.

While USACE District and Division Commanders cannot abdicate decision responsibilities, CAM provides a forum for scientists, managers, and stakeholders to raise and explain concerns, articulate management goals, and suggest strategies to address concerns and management actions to achieve goals. In contrast with the type of engagement that occurs as part of the NEPA process, CAM involves collaboration in each of the steps of the adaptive management cycle.

The USACE Engineer Pamphlet EP 1105-2-57 (USACE 2019) provides the requirements and guidelines for stakeholder engagement, collaboration and coordination. Early engagement is essential to scoping and the development of goals and objectives. Opinions about these foundational considerations are likely to be diverse at the outset and, while there may be lingering disagreement about their construct, a common and clear understanding of the scope and objectives is essential. Documenting the issues, questions, agreements, and points of view throughout the process helps to build understanding and trust among parties and provides an important record for future use. Other principles for CAM are listed in the text box.

PRINCIPLES FOR DESIGNING COLLABORATIVE PROCESS IN AN ADAPTIVE MANAGEMENT CONTEXT (ADAPTED FROM PRATT MILES 2013).

- Provide forums for interaction between managers, scientists, and other stakeholders
- Invite and document input from affected stakeholders at key junctures in the adaptive management process
- Share data and information with stakeholders
- Identify in advance triggers or points in the process when monitoring results and new information will be evaluated to enable changes in management, if warranted
- Design decision-making structures to incorporate and act on new information

Collaborative processes should be designed to fit the specific needs and circumstances of a project or program. Structures that have been used by other adaptive management programs to collaborate with affected stakeholders can offer insights into possible approaches. The Comprehensive Everglades Restoration Program (CERP) and the Missouri River Recovery Program (MRRP) offer two such examples for large USACE programs (see Appendix B).

Adaptive management programs involving one or more federal agencies and projects on public lands are subject to the provisions of the Federal Advisory Committee Act (FACA). This law requires that federal agencies seeking collective advice or recommendations from individuals or organizations outside government form advisory committees that are diverse and balanced in their makeup and operate in an open and transparent manner (Public Law 92-463 1972).

FACA can present challenges to CAM. While it lays out clear, established guidelines for the establishment of a committee, the creation of a charter, training, and participation in meetings, conducting meetings and getting consensus advice from a diverse array of stakeholders is demanding and often difficult. Certain bodies are FACA exempt, including scientific bodies convened by the National Academy of Sciences, ESA recovery teams, and groups exempted from the act by statute (Public Law 105-153 1997). The collaborative bodies working with the USACE on the CERP and MRRP are FACA exempt. A FACA exemption offers flexibility to tailor process and structure to meet the needs of specific circumstances, but also requires time to develop a customized structure and process.

CAM is not required in every situation and alternative forms of decision making are preferred in many cases. A collaborative approach should be considered when there are multiple jurisdictions, resource users, and viewpoints about the best way to manage a system, and where complexity and uncertainty are high.

3 Developing an Adaptive Management Plan

Adaptive management is foremost and fundamentally a planning process and, as practiced in the USACE, fully symbiotic with SMART planning (see Appendix C). This chapter identifies the critical parts of an adaptive management plan – the product of the development phase of the adaptive management cycle (see Figure 3) – and describes a process for developing plans for USACE ecosystem restoration projects. The approach emphasizes establishing the necessary feedback relationships between management actions (i.e., decision making) and monitored outcomes, central to adaptive management. This approach to planning adaptive management was designed with an emphasis on environmental management and ecosystem restoration. However, the overall approach to adaptive management applies to other USACE mission areas, such as engineering construction projects, or to the operation and maintenance of existing projects. In particular, the approach described in this guide is well-suited to the fish and wildlife compliance concerns associated with conventional USACE projects.

3.1 The Adaptive Management Team

CREATING THE ADAPTIVE MANAGEMENT TEAM

- Identify individuals to serve on the Team
- Determine policies for terms of service, substitution of members, and selection of new members
- Plan for adequate technical and logistical support services

Those individuals responsible for developing and implementing adaptive management are referred to as the Adaptive Management Team (AMT) in this Technical Guide. These individuals will play an instrumental role in developing the adaptive management and monitoring plans and overseeing their implementation. In most cases, the AMT will be responsible for assessing the need for adaptive management, development of the AM Plan, managing data, assessing monitoring results, making recommendations to decision makers, identifying adjustments to actions or the plan, and reporting and communicating results.

The composition of the AMT will be dictated by project complexity and scale, is usually a reflection of the PDT, and will logically consist of USACE planners, scientists, engineers, and decision makers who can add expertise to the mission, program, or project planning and implementation process. For more complex plans with higher degrees of uncertainty about the historic or desired restoration conditions, experts on environmental history and statistics may be needed to better define restoration success criteria and monitoring plan design.

Depending on the nature and complexity of the management or restoration action, the AMT might range from a few USACE staff to a large number of individuals, including from other participating federal (e.g., NMFS, FWS) or state resource or regulatory agencies, as well as stakeholder organizations. It is likely that participating individuals will have other duties. Therefore, the formal invitation should be accompanied by a list of AMT commitments and schedules so that participants' time can be prioritized to support the effort. It should be understood that adaptive management can only be effectively executed if it is based on a formal association of individuals who contribute directly and regularly to adaptive management. Appointment of an individual to serve as an Adaptive Management Project/Program Manager may be necessary for larger or more complex projects.

Provisions should be developed for terms of service, substitution of members, and selection of new AMT members. The AMT might be augmented during the adaptive management process by individuals who possess special technical skills or unique management experience. In addition, the adaptive management and monitoring plans should be reviewed at a minimum as part of agency technical review and as part of an independent external peer review for complex actions. Provisions should be made within the operating procedures of the adaptive management plan that permit the AMT to secure such support as needed. The important point is that the individuals responsible for developing and performing adaptive management are clearly identified at the outset and throughout the course of adaptive management. The members and organizations that constitute the AMT should be identified in the adaptive management plan.

Adaptive management plan tasks and AMT resources need to be included in project management plan (PMP) work breakdown structures. Project managers working with AMT members can identify appropriate schedules and budgets for adaptive management plan tasks. These tasks become part of the approved PMP by USACE and sponsor agency to approve, fund, and track progress. In addition, the schedule needs to be coordinated with external AMT members to ensure their commitment to accomplishing key tasks.

Given the importance of conserving endangered and listed species, the complexity associated with protecting these imperiled species, and the impacts the ESA may have on society and agency decision making, any adaptive management program that may affect listed species or critical habitat is more likely to be successful if it involves FWS and/or NOAA early in the process. Key to efficient species and effective consultation is an initial description of the range of potential adaptations and effects of those actions on listed species and their designated critical habitats.

3.2 Outside expertise and facilitation

There is often value in engaging individuals from outside the organization to provide subject-matter expertise or to facilitate engagements, particularly with the stakeholder community. Outside experts can be used to augment the AMT, providing insights on critical issues such as experimental designs, monitoring strategies, and governance structures. Facilitators can offer novel insights while assisting with stakeholder interactions and are particularly helpful on complex projects or where contentious issues affect stakeholder interactions. Technical experts and facilitators with experience from other adaptive management projects can relate important lessons from those experiences.

3.3 Independent external review

Government-wide standards for the peer-review requirements of scientific information outline the types of peer review that should be considered (OMB 2005). The USACE employs robust, multi-level product review and quality assurance processes and the traditional independent external product review (IEPR) process will be sufficient to assess products of many adaptive management efforts. However, any adaptive management effort could benefit from an independent science panel (ISP) that provides objective input throughout the adaptive management process and the use of such a panel is especially important for complex or contentious problems.

The subject of an ISP should be introduced early in the discussion of adaptive management planning because the expert advice such a panel can provide is particularly useful in the initial stages of adaptive management because it can advise and assess the clarity of hypotheses, the validity of any experimental design, the quality of data collection procedures, the appropriateness and robustness of the methods employed, and the extent to which conclusions follow from the analyses.

Murphy and Weiland (2019) discuss the attributes of successful science review and advice in the context of the Endangered Species Act (ESA). Their recommendations are applicable to the adaptive management of USACE ecosystem restoration projects as well and include the following:

- A deliberative panel of three or more professionals free of conflicts with the skills, expertise, and experience dictated by the project's technical needs.
- A charge or task statement to query the fundamental approaches taken, the pertinence and quality of data and analyses employed, and the conceptual and quantitative models used.
- Direct interaction between the ISP and agency (and sometimes sponsor) subject-area experts and decision makers early and often in the process, emphasizing both advice and review of roles as appropriate.
- Agencies must show their work, allow adequate time and resources for review, and provide responses to review comments and questions. Reviews should occur early enough in the process that changes can be made to products or decisions based upon the review.
- A substantive review panel needs to be availed of the analyses of effects of the action, supporting/justifying documentation, and other scientific information in addition to the AM plan.

3.4 Development phase

Planning for adaptive management consists of an initial comprehensive development phase that is concurrent with project planning and addresses all fundamental components of an adaptive management plan (see Table 6). There are clear linkages between planning for adaptive management and the traditional USACE six-step planning process (see Section 2.6). The feasibility study includes an initial determination of whether adaptive management is required for the project based on the problem identification, conceptual ecological model development, and risk and uncertainty assessment given the restoration goals and objectives. Sections 2.1 through 2.3 address factors in determining the need for adaptive management.

If adaptive management is determined to be necessary, successful completion of the development phase includes the development of a draft adaptive management plan. The plan should sufficiently characterize adaptive management associated with different project planning alternatives that the requirements and preliminary cost estimates for monitoring and implementing adaptive management can be developed.

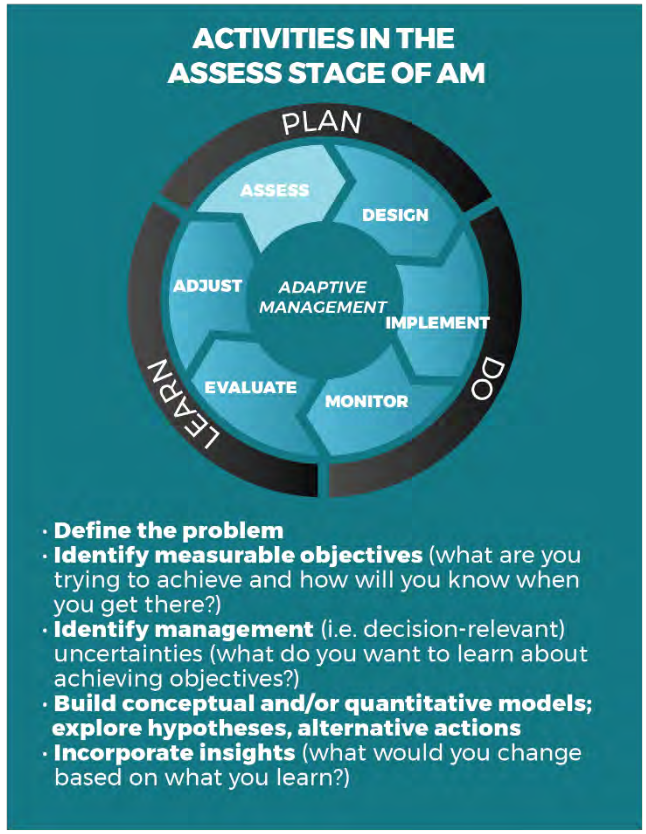
KEY ELEMENTS OF THE AM PLAN:

- Goals and objectives
- Uncertainties
- Hypotheses
- Management actions
- Model predictions
- Decision criteria
- Monitoring program
- Analytical requirements
- Decision-making process and roles
- Contingency actions
- Reporting and communications
- Process and timeline for modification

The development phase of adaptive management is discussed in the following sections. The development phase culminates in the preparation of an adaptive management plan. The process is described in the context of planning for an ecosystem restoration project. However, the process and steps are effectively the same for addressing existing USACE projects in pre-construction engineering and design, operations and maintenance of existing project, or adaptive management mandated external to the USACE for project approval (e.g., Biological Opinions, Terms and Conditions), although the options to adjust may be more limited.

3.4.1 Assess

The assess stage of the traditional adaptive management cycle – often glossed over in discussions of adaptive management – incorporates much of USACE's planning process and is crucial to effective adaptive management planning. In this stage, the PDT/AMT defines the scope of the management problem, identifies project goals and objectives (Step 1 of the Six-Step Planning Process), synthesizes existing knowledge about the system (Step 2: Inventory and forecast conditions), and explores the potential outcomes of alternative management actions (Steps 3-6: Formulate, evaluate, compare, and select management alternatives). Explicit forecasts are made about outcomes to assess which actions are most likely to achieve management objectives.



During this exploration and forecasting process, conceptual ecosystem models are developed and key gaps in understanding of the system (i.e., uncertainties that limit the ability to predict outcomes) are identified. Risks associated with uncertainties are identified and categorized in a Risk Register (see an example of a Risk Register in Appendix E). Goals and objectives are identified and decision criteria for each performance measure that defines project success are also defined. Monitoring and adaptive management needs are explored through scenario analyses for each alternative. Risk management strategies are considered and risk reduction measures incorporated into the alternative formulation, as warranted.

The activities in this step are the equivalent of the "effects analysis" called for by Murphy and Weiland (2011) as a requisite for establishing the best available science when evaluating the effects that actions proposed by federal agencies may have on threatened or endangered species. Best available science should underpin adaptive management, and the principles and practices embodied in an effects analysis are as relevant to AM planning as to ESA compliance. The ESA's best available science mandate reflects a Congressional mandate to ensure that decisions are informed by reliable knowledge using a structured approach.

3.4.1.1 Problems and opportunities

The specific water resource problems and opportunities are identified at the beginning of the six-step planning process. While seemingly straightforward, a clear, evidence-based definition of the problem(s) is challenging. Conceptual ecological models (CEMs) can be used to organize available data and promote a better understanding of potential ecosystem restoration opportunities or potential environmental impacts from water resource projects. CEMs can help expand the problem definition to identify the nature, cause, location, dimensions, origin, time frame, and importance of the problem, as well as an indication of who considers this a problem. An opportunity can be defined the same way.

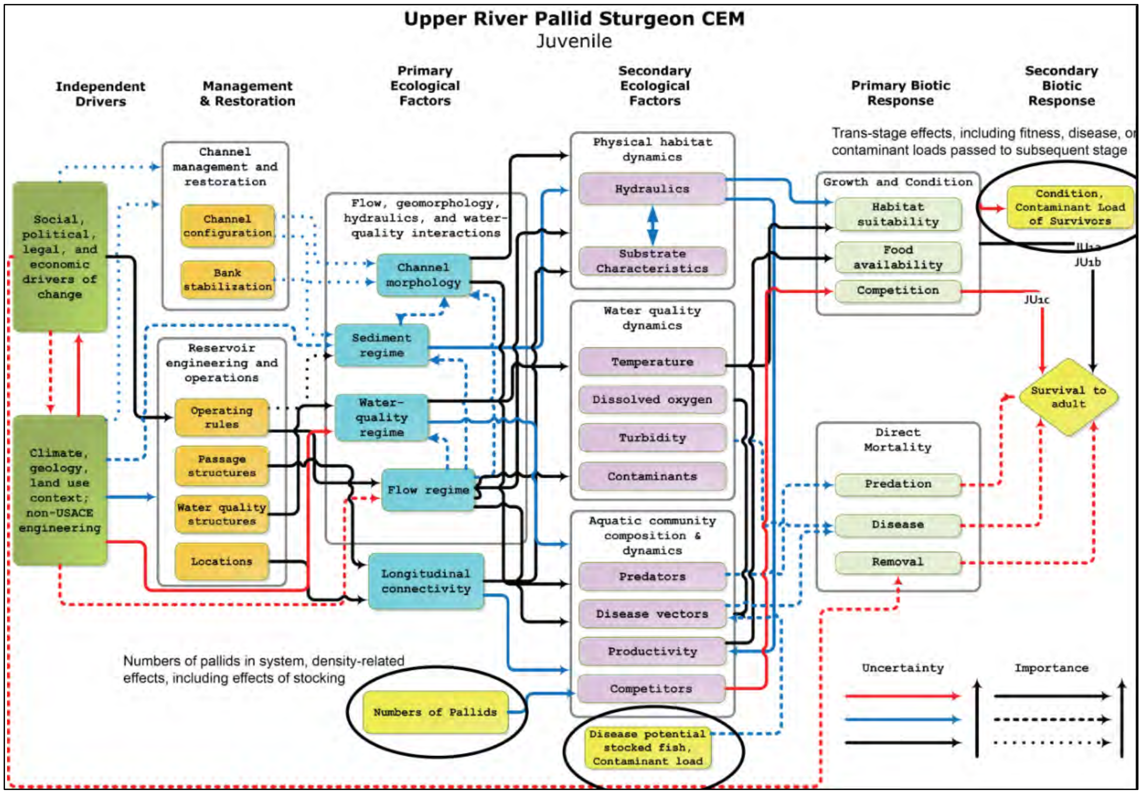
3.4.1.2 Conceptual models

> **DEVELOP CONCEPTUAL MODELS TO SUPPORT THE ADAPTIVE MANAGEMENT PLANNING**
>
> - Identify key components of system to be managed or restored
> - Identify and describe important interrelationships among key model components
> - Construct the conceptual model(s)
> - Use the model(s) to help evaluate alternative management and restoration actions
> - Identify sources of variability and uncertainty

Conceptual models identify the key components and processes of the managed system, their interrelationships, and their expected responses to proposed management actions (Galat et al. 2007). The development and use of conceptual models is recommended at the feasibility study level for ecosystem restoration projects. Because it is a crucial planning tool for adaptive management, ensuring an appropriate level of effort for product development - including obtaining seasoned assistance if needed – is recommended. Guidance on the development of conceptual models for ecosystem restoration can be found in Fischenich (2008).

Conceptual models can take the form of flowcharts, matrices, contributing factors diagrams, or narrative descriptions. Figure 8 provides an example of a conceptual model developed to support adaptive management of a set of actions required for compliance with a biological opinion on the Missouri River. The model explicitly identifies the effects of management actions on pallid sturgeon and includes representation of the uncertainty in the model relationships. These uncertainties form the basis for the adaptive management program.

Figure 8. Example of a conceptual ecological model (note that this is just the graphical depiction of the model – an accompanying narrative describes the components and linking processes).



Conceptual models of ecological systems can help identify and describe the resources of concern (ecological attributes) that might benefit or be placed at risk as a result of proposed management actions affecting stressors in the system. The functional interrelationships among the ecological attributes and stressors included in the conceptual model can help managers understand the potential direct and indirect effects of management actions and help anticipate the effects of management actions that can propagate through complex ecological systems in the face of incomplete knowledge. Similar conceptual models are also an essential tool for engineering projects, operations and maintenance actions, or construction in relation to adaptive management planning.

Once drivers and outcomes have been identified, the cause-and-effect linkages between these two groups can be explored and described (Fischenich 2008). Specific attributes of each linkage should be defined, including:

- Nature and direction of the effect – positive/negative effect: +/-/0 (0 means no effect).
- Importance or magnitude of the effect – displayed using width of line.
- Understanding underlying the effect (degree of uncertainty) – displayed using color/shading of line.
- Predictability of the effect – displayed using solid, dashed, or dotted line.

The more specific indicators of goals and objectives can be used to define performance measures or risk endpoints to use in evaluating benefits for restoration alternatives and monitoring actual restoration success. The level of understanding of the driver and ecological attribute response relationships can be used to identify uncertainties and hypotheses, as well as help inform the type of adaptive management approach needed and the design of monitoring programs for specific management and restoration actions.

Maddox et al. (1999) suggested that conceptual ecological models play three significant roles in monitoring. First, models summarize the most important ecosystem descriptors, spatial and temporal scales of critical processes, and current and potential threats to the system. They provide feedback to and help formulate goals and objectives, indicators, management strategies, results, and research needs. They also facilitate open discussion and debate about the nature of the system and important management issues.

Second, a model plays an important role in determining indicators for monitoring. Because the model is a statement of important physical, chemical, or biological processes, it identifies aspects of the ecosystem that should be measured. If the model is a good reflection of current understanding, but the measurement indicators cannot be seen in the model, then the measurements have little to do with the ecosystem.

Third, a model is an invaluable tool to help interpret monitoring results and explore alternative courses of management. An explicitly stated model is a summary of current understanding of and assumptions about the ecosystem. As such, it can motivate and organize discussion and serve as a "memory" of the ideas that inspired the management and monitoring plan.

3.4.1.3 Goals, objectives, and constraints

The goal for projects pursued under the USACE ecosystem restoration mission has been defined as “to restore significant ecosystem function, structure, and dynamic processes that have been lost or degraded” with the intent of partially or fully re-establishing the attributes of a naturalistic, functioning, and self-sustaining system (USACE 1999). This stated purpose provides context for the establishment of more specific planning objectives. The objectives state what planners intend to do about the problems and opportunities they face. Done well, objectives reflect the most important values in the decision process. Constraints should also be identified and, like objectives, are unique to each planning study.

A GOOD OBJECTIVE/ CONSTRAINT IS:

- Specific; i.e., it is clear and free from ambiguity
- Flexible; it can be adapted to new or changing requirements
- Measurable by some objective means
- Attainable; plans can reach the objective.
- Acceptable; welcomed by key stakeholders

The objectives established for the project planning serve as the objectives for adaptive management as well, noting that some additional objectives and constraints may apply to adaptive management. Assuring success is a primary purpose of adaptive management, so metrics associated with specific, measurable, and attainable objectives are the focus of monitoring efforts that inform the adaptive management process and guide decision making for the project.

As a result of the USACE’s risk-informed planning process, the USACE identifies environmental conditions that it wishes to achieve, risk and uncertainty associated with achieving those conditions, as well as risks and uncertainty to be avoided, minimized, or mitigated. The AMT will generally need to evaluate proposed project alternatives from the perspectives of likely success, level of uncertainties and risks, and suitability for adaptive management. It is possible that much of this evaluation will have been completed by the planning team (e.g., plan formulators, scientists, engineers) during the traditional planning process. Some of those planning team members will also be part of the AMT that will include additional technical skills and/or management experience and will ultimately continue their support beyond the planning phase. Importantly, the planning phase of adaptive management provides additional opportunities for interaction among USACE planners, stakeholders, and the AMT in developing viable management and restoration alternatives to achieve desired future conditions and/or reduce risks. PDTs should consider the use of workshops focused on adaptive management planning that include AMT members. In addition, PDTs should refer to Appendix D for USACE AM support and training of planning and AMT members.

The development phase in planning for adaptive management also provides the AMT with the opportunity to review the goals and objectives for feasibility and compatibility with possible adaptive management actions (e.g., feasibility planning, engineering projects, O&M). There might be instances where a planning alternative has been previously selected or in operation prior to consideration of adaptive management. In this situation, the AMT should interact with the planning team to determine the efficacy of developing a corresponding plan for adaptive management, monitoring, and assessment that is compatible with the construction or ongoing operation and maintenance of an existing or selected project. In any case, it is necessary to determine whether modifications or adaptations can be made after project implementation. If not, then opportunities for adaptive management might be limited to implementing a monitoring plan to obtain data and knowledge that can be applied to other future similar projects. If the proposed management actions are inflexible or incompatible with the fundamental aspects of adaptive management, the AMT can advise managers that adaptive management is not advisable and activities should be limited to monitoring to assess success.

3.4.1.4 Risk and uncertainty

Risk, over a given time, is a product of likelihoods and consequences of adverse outcomes. This definition implies that four aspects are involved in considering risk—a time scale, scenarios, relevant consequences, and corresponding likelihoods or probabilities (Beer 2006). In a typical risk assessment, the questions below are addressed as part of the overall risk management process (after Suedel et al. [2012]). For simple projects, the PDT can address these informally with sponsor input. For larger, more complicated, and collaborative efforts, use of a professional facilitator in a workshop setting is advised.

1. What can go wrong?
2. What is the likelihood that it will go wrong?
3. What are the consequences?
4. What can be done to mitigate the risks?

Uncertainty is a lack of knowledge. This Technical Guide focuses on two types of uncertainty: natural variability and scientific bias. "Variability" refers to natural patterns of spatial and temporal heterogeneity that cannot be reduced by additional sampling or data collection. Variability reflects the dynamic nature of ecological, environmental, and engineered systems. Sampling methods and designs should accurately and precisely quantify variability. Importantly, methods have been developed that use relationships between sample variance and frequency and location of sampling to identify the relevant scale in assessing many ecological performance measures that might be important in planning for monitoring and adaptive management (e.g., Gardner et al. 2001). Thus, variability and scale are interrelated; monitoring and adaptive management plans should characterize the scale dependence of these relationships for the selected performance measures and risk endpoints.

RISK & UNCERTAINTY ASSESSMENT

- Identify uncertainties early in planning
- Residual sources of uncertainty should be classified as to type, analyzed and documented, and then addressed iteratively throughout the planning process.
- Quantify uncertainty where possible, using confidence intervals or probability distributions as opposed to point estimates when describing predicted outcomes.
- The relative uncertainty of alternative plans should be presented, as uncertainty in outcomes may be considered during plan comparison and is an important part of an overall risk management/communication strategy.
- If the recommended plan has uncertainty that can be practically reduced through post-construction monitoring, assessment and adjustment, an adaptive management plan should be developed to manage risks and maximize realized benefits.

"Scientific Bias" refers to bias and imprecision introduced into monitoring and adaptive management planning from several sources, including inadequate sampling designs, improper methodologies in sample collection, errors in sample processing or data analysis, errors in data management and communication, and incomplete scientific understanding of the managed system. The implications of these uncertainties on the overall effectiveness of the adaptive management process will be described and quantified to the extent possible as part of the adaptive management plan outlined in this section.

All restoration projects face uncertainties, and identifying the likely sources is the first step in managing uncertainty. Corps policy requires that uncertainty in water resource planning be evaluated and communicated. Methods for evaluating uncertainty in ecosystem restoration projects continue to evolve, but include sensitivity analyses, scenario planning, and parametric uncertainty analysis. These and other means of identifying, quantifying, evaluating, and otherwise considering uncertainties as part of the planning process provide important information that assists decision making. Although uncertainties can arise at any point in a study, the identification, classification, and documentation of uncertainties is critical during the development of a CEM (note the solid red lines in Figure 8), during modeling and forecasting, and during formulation of the monitoring and adaptive management plan.

Linkages between drivers that are modified by restoration actions are often the factors that pose the most risk to achieving success. Higher-risk links between restoration actions and ecosystem outcomes, where uncertainty may also be moderate to high, are more likely to benefit from adaptive management as a risk management strategy if actions can be adjusted. Assessing risk early on in project planning can help inform project planning to design alternative plans that can be adjusted based on actual performance when implemented. High-risk and uncertainty relationships might indicate the need for an active adaptive management approach that tests multiple competing restoration designs before implementing the best design at full scale.

Importantly, adaptive management will generate data and information from monitoring. This information can be used not only to guide future management and decision making, but also to reduce uncertainties inherent in managing and restoring complex ecological and engineered systems. Adaptive management establishes the critical feedback mechanisms that interject the results of monitoring and assessment into decision making, reduces uncertainties, and increases the likelihood that management goals and objectives will be achieved (risk reduction).

3.4.1.5 Performance measures, targets, and decision criteria

An important part of planning for adaptive management is the translation of the management and goals and objectives into specific performance measures (or metrics), targets, and decision criteria. During the development phase, the AMT should work from the Conceptual Model(s) and with the project planning team and stakeholders to define the physical, chemical, biological, and ecological stressors and attributes that will be evaluated to assess project performance. Specification of the mechanism by which performance will be measured will also require delineation of the spatial and temporal scales relevant to project implementation and management, which might differ among the measures.[1] Target values for success should be identified, but there may also be constraints (sometimes called risk endpoints) for which specific, quantifiable targets that trigger a decision exist.

The term "decision criteria" refers to pre-determined conditions that trigger or guide a decision or the implementation of a contingency plan. They can be qualitative or quantitative based on the nature of the performance metric and the available information. A recent study of judicial decisions on adaptive management programs cited the lack of decision criteria as one of three key deficiencies leading to possible overturning by the courts of agency practice (Fischman and Ruhl 2016).

Decision criteria can play several roles in adaptive management, including:

- defining requirements for success or other compliance purposes (e.g., ESA, NEPA, USACE's policies)
- facilitating complex decisions, or decisions that must be made quickly during implementation
- providing a roadmap for participants (i.e., they define the decision space)
- ensuring that decisions are based upon best available science.

[1] Performance measures and risk endpoints can also be defined for engineering projects or operations. Performance measures might simply pertain to successful construction per engineering specifications. Risk endpoints can be identified as undesired changes in conditions, for example, declines in levels of protection through structure depreciation, changes in land use and other actions that make structures inadequate for protecting habitats, or establishment of invasive species that requires changes in operation.

Decision criteria can come in various forms, including quantitative values that serve as triggers, decision trees structured in IF / THEN form that address various scenarios, and planning rubrics or heuristics that help with decision making when multiple lines of evidence are needed to establish a decision. Criteria cannot be developed for every decision. Some decision criteria may not be evident during the initial planning stages; useful criteria cannot be developed until details of actions are known in some cases. As knowledge grows, it will likely become apparent that some criteria need to be changed. To address these situations, the adaptive management plan should include a process to guide the development and/or revision of decision criteria.

The specification of performance measures and target values provides the necessary focus in designing a monitoring plan that will provide the critical information needed for adaptive decision making. Properly executed, there should be a clear connection between the project's goals and objectives, the metrics, decision criteria and (if applicable) contingency actions taken. Table 2 presents an example from the Louisiana Coastal Area (LCA) showing how one objective with two associated performance measures links to the targets, decision criteria and contingency plans. Table 3 provides another example from the science and adaptive management plan for the MRRP showing the links among hypotheses, experimental design, study questions and methods for evaluation for one management action – interception and rearing complexes (IRCs).

Table 2. Example linking objectives, metrics, targets, decision criteria (triggers), and contingency plans (adapted from the Blind River Project for LCA).

Objective 3: Establish swamp hydroperiod with dry period of sufficient length to improve baldcypress and tupelo productivity, seed germination and survival.
Performance Measure 3a: Depth, duration, and frequency of flooding in the swamp.
Targeted Outcome: Maintain dry periods (moist soils) in the swamp for a minimum 7-35 days during summer and early fall for seed germination and maintain water levels below seedling height to promote seedling survival.
Monitoring Design: Hourly hydrologic recorders will be deployed to measure stage/depth.
Trigger: Depth of inundation fails to drop below target levels for less than 7 days in any one year or less than 10 days for two successive years.
Contingency Action: Modify gate operation to reduce inflow to project area.
Performance Measure 3b: Number of baldcypress and tupelo seedlings and saplings.
Targeted Outcome: A 25% increase in the number of baldcypress and tupelo saplings per acre five years after project implementation and 50% increase after 10 years.
Monitoring Design: Understory vegetation will be measured to determine numbers of baldcypress seedlings and saplings in order to assess regeneration.
Trigger: No measurable increase in baldcypress and tupelo saplings after 5 years.
Contingency Action: None specified. Will evaluate conditions and determine appropriate course of action, if any.

Table 3. Example linking management actions, hypotheses, metrics, and decision criteria (adapted from the science and adaptive management plan for the MRRP[1]).

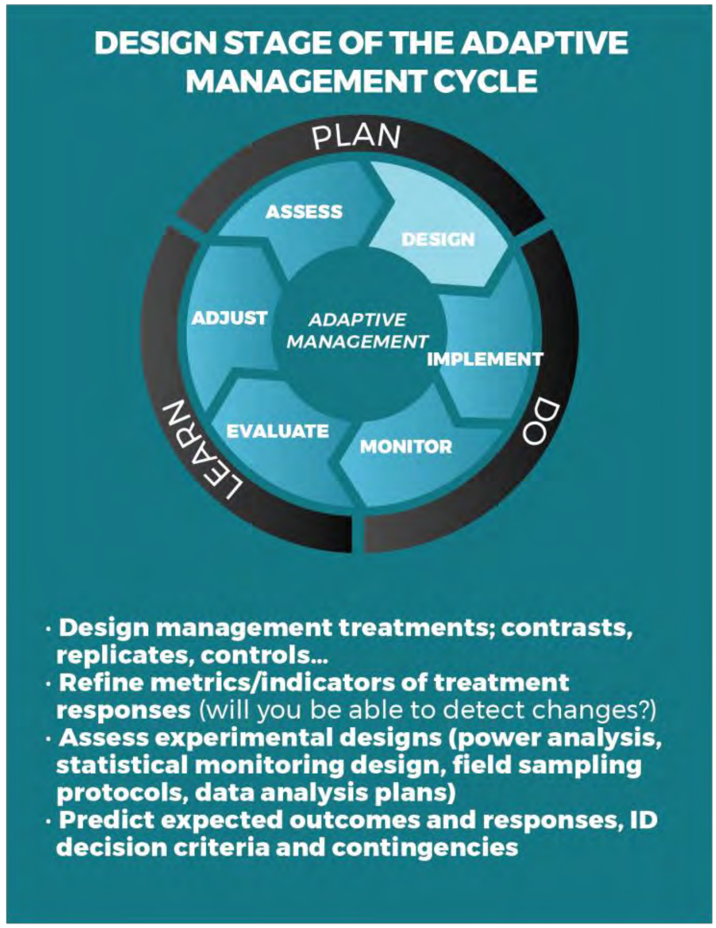
Action	Question	Method for Evaluating
Interception and Rearing Complexes (IRCs) <u>Associated hypotheses</u> Re-engineering of channel morphology will increase channel complexity and: - bioenergetic conditions to increase prey density abundance (invertebrates and native prey fish) for exogenously feeding larvae and juveniles. - minimize bioenergetic requirements for resting and foraging of exogenously feeding larvae and juveniles. - serve specifically to intercept and retain drifting free embryos in areas with sufficient prey for first feeding and for growth through juvenile stages. Experimental design: AM plan sections 4.2.6.3.4 4.2.6.4.4	Do free embryos and exogenously feeding larvae leave the thalweg and enter IRCs? Is there sufficient food in IRCs for exogenously feeding larvae to grow better and maintain a healthier condition than reference areas and times? Do age-0 fish that occupy IRCs survive better than age-0 fish in reference areas and times? What's the population-level effect of improved survival of age-0 fish in IRCs? Is food limiting outside of IRC habitats	Predicted fate of free embryos from advection/dispersion models. Testing of these predictions with field monitoring (see below). Staircase design comparisons of IRC habitat sites with reference areas and times, using the metrics listed in Table 9, section 4.4 (e.g., CPUE, probability of apparent presence, food production/area, condition, growth and survival of age-0 fish), and applying covariates to help explain year to year variation (e.g., index of upstream spawning success). Population model projections of the consequences of improved age-0 survival rates.

3.4.2 Design

The Design stage finalizes the specifications of a selected alternative to ensure a robust project capable of performing under extreme system conditions. Such design ensures the necessary flexibility to adjust management actions in the face of uncertain future conditions. More than

[1] Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

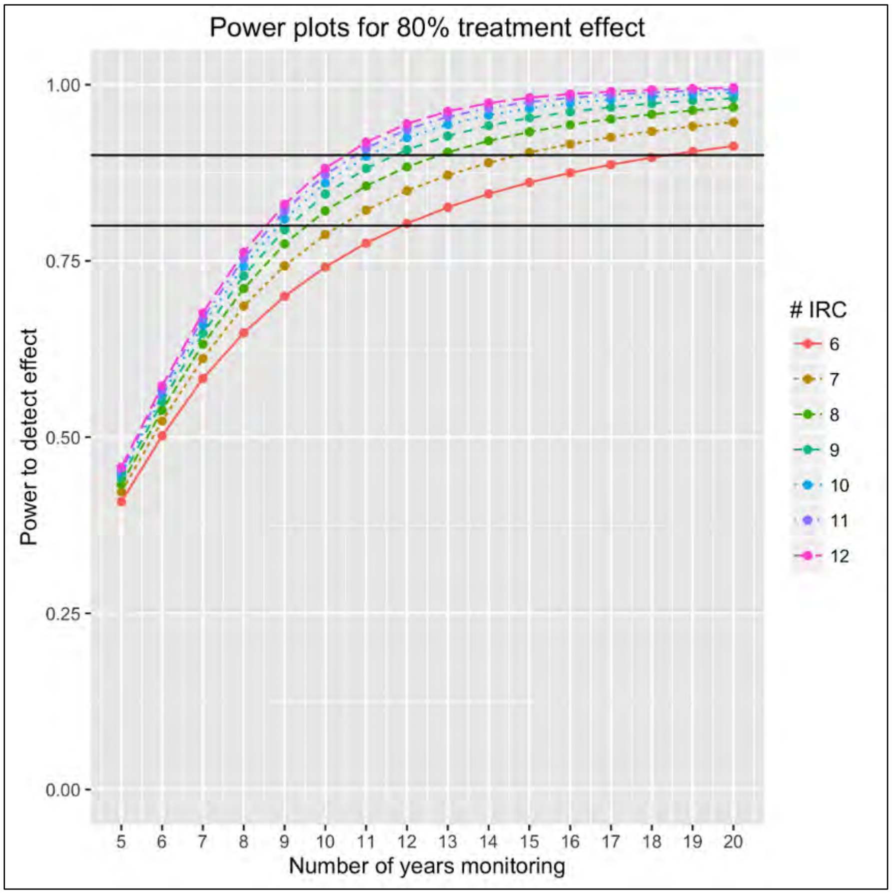
one proposed plan or design should be evaluated in relation to costs, risks, information, and ability to meet management objectives. The design step can be used to iteratively refine the preliminary monitoring plan and adaptive management plan.



In the context of the adaptive management cycle, the Design stage deals with the identification and detailed development of management actions and, in particular, with the complexities of experimental design when the active form of adaptive management is practiced (see Section 4.1 for more detail). Models quantifying outcomes of potential management actions in terms of resource response play an important role in the design stage. Decision making is based on a comparison of management alternatives in terms of their costs and resource consequences.

Models also play a major role in representing uncertainty. Structural and functional uncertainty can be expressed through contrasting hypotheses about system structure and functions as represented by different models (Figure 9). Evidence from monitoring is used to assess the adequacy of each model (i.e., validation analysis) in characterizing resource dynamics. As evidence accumulates, confidence in each model (and its associated hypothesis) evolves, through a comparison of model predictions with actual data from monitoring. Data acquired through monitoring, research or outside sources can be used to re-parameterize models, improving predictions.

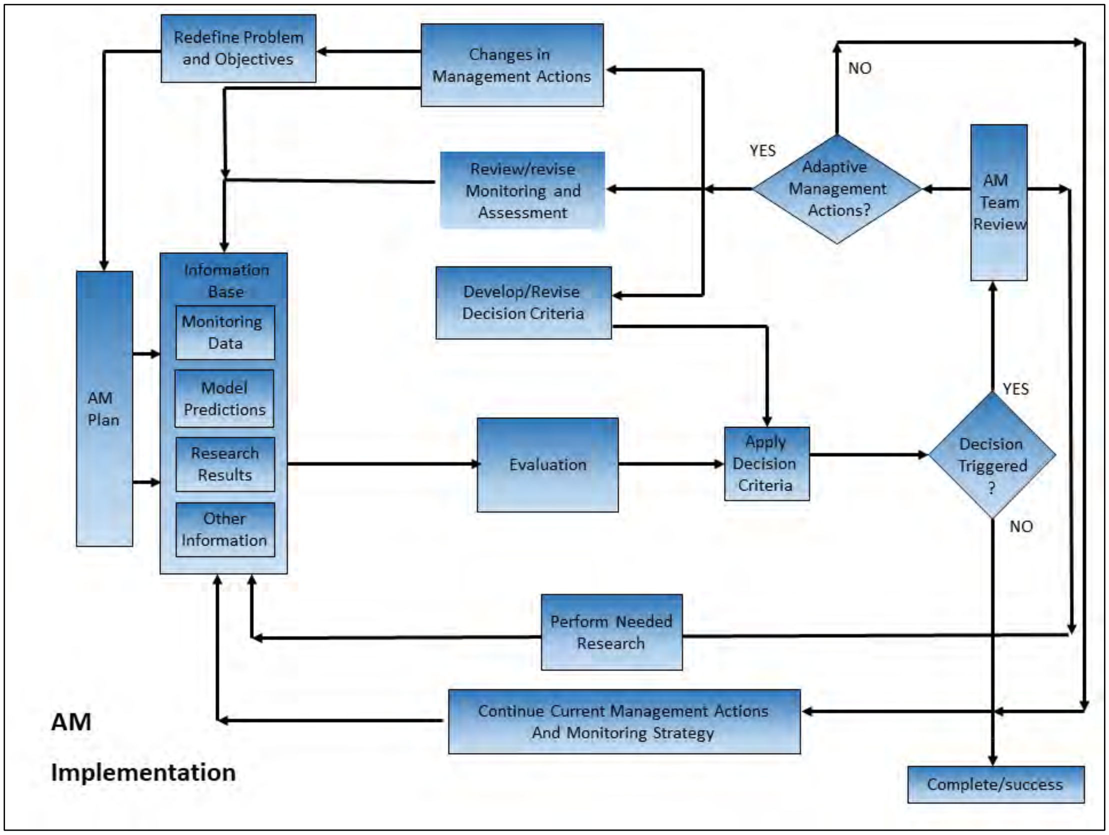
Figure 9. The design stage often involves development of experimental designs. In this example, the number of years of monitoring required as a function of the number of project/control pairs implemented (i.e. # of Randomized Control Trials [RCT]) in order to achieve a 0.8 and a 0.9 probability of detection is computed.



3.5 Planning for the implementation phase of adaptive management

Implementation describes how the adaptive management plan developed for a specific application will be put into action. During the adaptive management development phase, the AMT should determine how the proposed adaptive management plan will be implemented and describe implementation in the adaptive management plan. Monitoring plans, assessment methods, a governance structure, other adaptive management procedures, and data management, communications, and reporting should all be addressed to a sufficient level of detail so as to set expectations and identify costs. Development of schematics, as shown in Figure 10, can help orient the team, USACE management, and sponsors to the tasks required. Assignment of responsibilities, development of a timeline for the activities, and an estimation of the associated costs should also be developed and identified in the plan.

Figure 10. Schematic of the Implementation Phase for USACE adaptive management.



3.5.1 Monitoring

> **PROJECT MONITORING**
>
> "…includes the systematic collection and analysis of data that provides information useful for assessing project performance, determining whether ecological success has been achieved, or whether adaptive management may be needed to attain project benefits."
> USACE CECW-PB, 8/31/09

Effective monitoring is central to the adaptive management process and, whereas adaptive management is an intuitive concept that most grasp, monitoring is inherently complex, widely misunderstood, and rarely practiced in ecosystem restoration and adaptive management (e.g. Bernhardt et al. 2007; Brierley et al. 2010; Chapman 1998; Downs and Kondolf 2002; Walters 2007). The development of a monitoring plan to collect the data and information needed to reduce uncertainties, test hypotheses, and track progress relative to goals, objectives, and decision criteria will likely equal the level of effort needed to formulate all remaining elements of an adaptive management plan.

Monitoring is not surveillance and it is not counting things; it is the purposeful gathering of precisely the data needed to support decisions. Depending upon the application, monitoring under adaptive management supports one or more of the following purposes (adapted from Williams and Brown 2018): (1) to evaluate progress toward achieving objectives; (2) to determine resource status, in order to identify appropriate management actions; (3) to increase understanding of resource dynamics by comparing predictions with actual monitoring data; and, (4) to develop and refine conceptual and numerical models. Monitoring should be designed to meet at least one of these purposes.

Monitoring is conducted according to protocols assembled in the development phase of adaptive management, but is not simply after-the-fact tracking in the absence of any capacity to contrast actual results with predicted responses (Nichols and Williams 2006). Monitoring is a form of applied research, which in service to adaptive management must be approached much as a laboratory experiment is approached—with a rigorous design and application of the scientific method (Noon 2003).

3.5.1.1 Steps in monitoring design

A monitoring scheme must have explicit goals and objectives, direct the gathering of data in a framework adequate to detect meaningful changes in the conditions of ecological resources, and develop reliable, scientifically defensible indicators for measuring change. Development of monitoring schema includes identification and characterization of the complement of environmental attributes and ecological processes that directly and indirectly affect the system of interest. The level of monitoring effort should be scaled to the risks and the needs of management and decision making.

Direct measures and environmental-condition indicators that are efficient at detecting effects of management actions should be identified. Where monitoring uses surrogate or proxy measures, those indicators should be subject to a validation process describing the similarities in responses of the surrogate and target measures to the same environmental phenomena, and describing the accompanying uncertainties (Murphy and Weiland 2014b). In addition, it is necessary to establish detection limits for the variables to be measured and condition indicators that are employed, and contingent decision values must be identified (thresholds or trigger points) for direct measures or indicators that have been validated.

1. *Specify the monitoring purpose and objectives and define the hypotheses to be tested and/or key management questions*. Monitoring purposes should align with one or more of those listed in Section 3.5.1. Objectives should be closely aligned and reconciled with the project/program objectives. To the extent possible, objectives should be expressed in numeric terms.

2. *State the spatial and temporal domain (the sampling frame) of the ecosystem or the population of interest*. The domain for management/conservation actions and policies needs to be clearly bound in space and in time. Monitoring results, and inference to restoration results or population state, are limited to this domain.

3. *Identify the monitoring state variables and indicators; describe why they were selected*. Appropriate state variables will depend on the nature of the project/program, and whether biotic or abiotic objectives have been defined. Selection of the state variable(s) should be based on the information content of the variable(s) (e.g., based on a life-history sensitivity analysis).

Monitoring data are not gathered with the hope that they will somehow prove useful. A frequent justification for monitoring additional variables is that more information about a system must be useful to its management. Although this premise is true to some degree, it does not address the key issues of effectiveness and efficiency (Nichols and Williams 2006).

The feedback required to evaluate and adapt management experiments requires leading indicators, metrics that provide information about the drivers/causal factors shaping future conditions and outcomes, rather than lagging indicators, which mainly provide information about past developments and effects. Leading indicators need to be defined on the basis of detailed change hypotheses showing how management actions are expected to lead to particular outcomes (Margoluis et al. 2013).

4. *Specify the type(s) and magnitude of change to be detected through monitoring*. The nature of the state variable(s) dictates the type of change(s) to be estimated. For example, if the area of a particular habitat type is the state variable, change in the habitat acreage over time is measured. The magnitude of change required in order to detect effect size is essential for sample design decisions. This may be the single most challenging element in the design of a monitoring scheme.

5. *Following (4) specify desired precision for the trend estimate; this uses available (pilot) data and a components-of-variance analysis*. Only after Step 4 is completed can the actual design phase of monitoring begin. Design components include, for example, plot size, number of plots, spatial distribution of plots, and sampling frequency essential for reliable statistical inference.

6. *Generate estimates of uncertainty*. Attributes of an ecosystem or population cannot be thoroughly sampled in most cases. Inference to the target is always subject to sampling variation and frequently to measurement error. Such inferences need to be accompanied by measures of estimation uncertainty.

7. *Optimize the monitoring design for obtaining data*. Develop and evaluate different monitoring designs, examining their ability to meet the required levels of precision at an acceptable cost. Optimization of the design may involve considerable work, including various efforts to refine methods before finalizing the design, which leads to the following principles.
    a. Ensure that important time series are maintained if monitoring protocols are being improved.
    b. Use past data and possibly intensive pilot sampling to gain insight into spatial and temporal variability of key metrics.

c. Perform statistical power analyses to determine how false positives and false negatives vary with sampling effort, number of treatment (management action) and reference sites, the staging of implementation of management actions, and the number of years of monitoring before and after the action is implemented.
d. Allow for an adjustment period with new monitoring needs, and use pilot approaches to discover bugs and solve initial problems.
e. Complete laboratory and mesocosm work as needed to define biological/ecological effect sizes of interest, clarify mechanisms of impact, assess measurement errors, and refine monitoring protocols.
f. Complete modeling studies to simulate different M&E strategies.

8. *Specify the monitoring experimental design and protocols*. A monitoring design describes the combination of logical, statistical, field/logistical, and cost strategies to answer one or more management questions that feed into a management decision. Components of an M&E strategy can include (modified from Hillman 2006[1]):
   a. a “statistical” design, which provides the logical structure for testing hypotheses, using spatial and temporal contrasts, and identifying the minimum requirements for implementation monitoring, process/effectiveness monitoring, and population monitoring;
   b. a “sampling” design that describes the process for selecting sampling sites and sampling times and lays out the details of the work, gear, etc., needed to accomplish the sampling;
   c. a “measurement” design outlining the specific performance measures and the protocols used to monitor them at the chosen sites and times; and
   d. a “response” design that explains how the monitoring data will be analyzed to make inferences in the adaptive management evaluation step.

[1] Hillman, T. W. 2006. *Monitoring strategy for the Upper Columbia basin*. Second draft report. Prepared for Upper Columbia Salmon Recovery Board, Bonneville Power Administration, and National Marine Fisheries Service. Boise, ID.

9. *Update design as needed—make sure objectives, actions, and metrics align (adaptive monitoring)*. Decision-relevance and the evolving tradeoffs between monitoring cost and precision can motivate revisions in an experimental design or monitoring protocols. It may become apparent that previously unmonitored system attributes are crucial to decision making, or that some monitoring results have marginal value. Advances in technology, changes in the spatial extent of the monitoring effort, increases or decreases in per-unit monitoring costs, and the perceived value of having more (or less) precision can lead to a reconsideration of monitoring protocols (Williams and Brown 2018).

3.5.1.2 Monitored parameters

The initial set of performance measures, risk endpoints (constraints such as water quality limits), and associated decision criteria, including triggers, will have been defined as part of the adaptive planning step and should be evident in the supporting conceptual models. However, the design of a monitoring plan provides an opportunity to review and revise these measures and endpoints. It is highly desirable that the selected measures and endpoints be uniquely and unequivocally affected by the management or restoration action. In other words, observed changes in the measures or endpoints should be able to be traced unambiguously to specific management or restoration actions.

The monitoring program should identify one or more direct measures (i.e., monitored parameters or data) that apply to each project performance measure. The level of detail for any selected parameter to be monitored can be reasonably guided by its contribution to assessment and decision making. For example, if a risk endpoint is to minimize the probability of increased algal abundance (i.e., blooms), measures of total chlorophyll might be considered sufficient for decision making. Alternatively, if impacts on algal community structure (e.g., diversity) define the risk endpoint, then more intensive sampling and expensive enumeration of individual algal taxa would be required.

Parameters that provide direct measures of performance are generally preferred for monitoring. However, environmental variability and uncertainties associated with project performance or anticipated management outcomes might limit the degree to which observed changes can be directly related to a specific management or restoration action. Additionally, monitoring of direct measures of performance might be impractical or too costly. In these instances, the use of surrogate or proxy measures might be required.

A validation procedure should clearly articulate the reasoning behind the selection of the surrogate. It should explicitly describe the similarities in ecological responses by the surrogate and target to the same environmental phenomena, link demographic responses to habitat extent and condition, and clearly describe the uncertainties that accompany the relationship between the status and trends of the surrogate and those of the target under common circumstances (Murphy and Weiland 2014b).

3.5.1.3 Methods and protocols

The monitoring plan should identify the technical methods used to obtain the specified data for each of the monitored measures and endpoints. Included are methods for sample collection, sample processing, data management, and communication of monitoring results to decision makers. The methods should be incorporated into a Standard Operating Procedure (SOP) that can be followed by any institution and should include descriptions of sampling designs (i.e., locations, frequency), sampling procedures, sample storage and preservation, and processing of samples to generate data. Scientifically recognized and generally accepted standard methods should be used whenever possible. Novel performance measures might require innovations in methodology. New methods should be rigorously evaluated and offered for appropriate technical review prior to incorporation in the monitoring program. Quality assurance and quality control (QA/QC) protocols should be identified.

If different monitoring plans are implemented for separate but related projects, performance measures or risk endpoints common to the projects should be measured using the same or easily compared methodologies. Opportunities to economize should also be pursued in the design of monitoring for multiple projects. Redundant monitoring can be useful where significant uncertainty is involved and common monitoring across multiple projects would provide valuable information about causes of variable responses; in other cases, it may be avoided or minimized by design. In some cases, resources from multiple projects may be combined to incorporate monitoring measures that are generally desirable and informative but not affordable by the individual projects.

3.5.1.4 Statistical power

The monitoring plan should define the sampling methods and procedures required to develop data of sufficient quality (i.e., accuracy, precision, statistical power) for use in decision making. To achieve high-quality data, the number of sample locations and frequency of sampling should be determined for each measure and endpoint. Given an initial estimate of sample variance, standard statistical procedures are available to calculate the number of samples required to obtain a specified level of performance for hypothesis testing (e.g., Cohen 1988, Thomas 1997).

The decision-making process should estimate the desired statistical power for each monitored parameter. Power analysis is a useful tool in the planning of monitoring schemes and can be used after data analysis to improve the interpretation of non-significant results. Unfortunately, the definition of adequate statistical power in the ecological literature often appears arbitrary with minimal attention to the decision context of the study, and a convention has evolved where significance and power levels are set at 0·05 and 0·80, respectively (Di Stefano 2003). Instead, the relative costs of both Type I and Type II statistical errors need to be considered for each situation (i.e. a Type I error isn't always four times costlier than a Type II error).

The accuracy and precision necessary for an individual measure will depend in part on the ability and cost to obtain quality data, the importance of the measure in the overall assessment, the sensitivity of the measured parameter to the proposed management action(s), the level of uncertainty to be resolved, the level of risk and the nature of the decision-making process, including the consequences of ill-advised decisions. For example, demonstrating simple presence-absence of a species might reasonably require less of a monitoring investment than determining quantitative changes in the abundance of an existing species. Data demonstrating that a population is increasing can be less accurate or precise than data required to demonstrate that a population is increasing by some specified percentage or rate. The necessary result of this activity is the specification and documentation of data quality objectives for each of the performance measures and risk endpoints included in the assessment. The recognition that different data quality objectives can be justified for adaptive management can guide the development of efficient and economical monitoring plans.

3.5.1.5 Monitoring plan and costs

COMPONENTS OF A MONITORING PLAN

- Monitoring objectives
- Parameter identification
- Field protocols for data acquisition
- Sampling frequency and intensity
- Required accuracy and precision
- Sample and data management plan
- QA/QC procedures
- Cost estimates

The key product of the monitoring step is a detailed monitoring plan, with an associated data management plan, QA/QC procedures, and a cost estimate for these activities. The monitoring plan should identify what will be measured in relation to the goals and objectives and the relevant methodologies to be used in acquiring the necessary data and information. The frequency and intensity of sampling should be specified for each performance measure and risk endpoint. Units of measure and degrees of required accuracy and precision (i.e., data quality objectives) should be defined initially for each performance measure and endpoint. A system for data management and quality assurance and control should be provided. Finally, expectations regarding the term, roles and responsibilities, and costs for monitoring must be described.

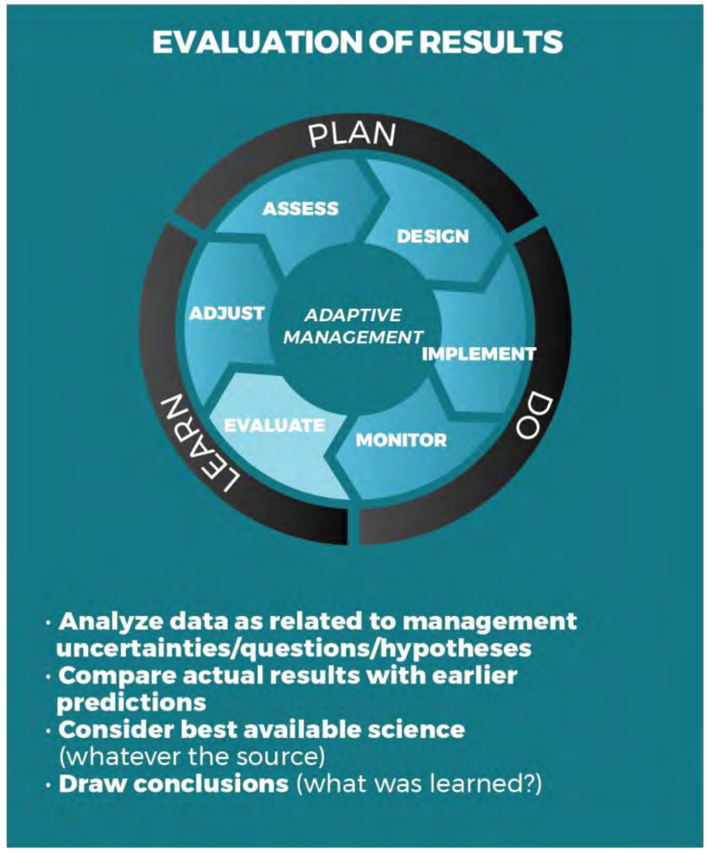
Iteration through development of the monitoring plan is to be expected, and the level of detail at the feasibility stage of a project is usually much lower than is needed for a final plan (which must provide specific protocols, for example). Optimal monitoring may also require iteration following implementation – an adaptable monitoring scheme. Field values are typically required for estimating statistical parameters. Absent such data, preliminary estimates are used for an initial monitoring design. After some monitoring, the AMT should review their initial estimates of the statistical parameters, and update them using the newly obtained data if warranted. These new estimates can then be used to re-evaluate and update the monitoring design.

Depending on the complexity, monitoring plans might be more usefully developed as separate appendices to the adaptive management plan. Tabular descriptions and summaries of the monitoring and information management strategies in the plan can be used to orient the parties to the needs and help ensure that the plan addresses the intended purposes (e.g., Table 4). The monitoring plan should include a discussion of duration for monitoring and supporting data management activities and should describe the roles and responsibilities for the USACE, sponsors, and others.

Table 4. Example table of information to guide development of a monitoring and data management plan.

Goals and objectives	Data quality objectives			Monitoring program – sampling design				Data management			Decision making
Monitored parameter	Units	Data quality	Method	Number of samples	Sample locations	Sampling frequency	Sample processing	Data analysis	Data storage	Data reporting	Decision criteria
Performance measures (examples)											
Restored wetlands	Habitat units	N/A	Aerial imagery	10	UTM coordinates	End of project	Spatial analysis	GIS	GIS files	Maps, statistics	100 HUs
Population size of desired species	Individuals or biomass	25% coefficient of variation (CV)	Permanent quadrats	75	Stratified random samples	Once per month	Individual counts, biomass weighed	Univariate statistical analysis	Spreadsheet database	Simple statistical summaries	50% incremental increase
Plant community diversity	Simpson diversity	15% CV	Field transects	10 transects; 20 samples each	Stratified random locations	Before and after project construction	Individual species counts	Calculation of diversity index	Relational database	Simple statistical summaries	15% incremental increase
Establishment of an invasive species	Presence/ absence	N/A	Standard field sampling	100 random samples	Random quadrats	One sample per year during project	Field data sheets	Simple recording of presence/ absence	Spreadsheet database	Maps, statistics	Eliminate invasive species
Bluegreen algae biomass	Individuals and g/m3	75% CV	Filtered water samples	50 locations; 1 sample per location	Stratified random samples	Monthly Sampling	Species counts, total biomass as carbon	Univariate statistical analysis	Spreadsheet database	Simple statistical summaries	Minimize blooms
Dissolved oxygen	mg/L	2% CV	Standard sampling methods	100 locations; 1 sample per meter	Regular grid over project area	Daily sampling	Standard chemistry methods	Univariate statistical analysis	Spreadsheet database	Simple statistical summaries	Avoid hypoxia

3.5.2 Evaluation



The assessment process compares the results of the monitoring efforts to the model predictions and decision criteria defined as the desired values of project performance measures and/or acceptable risk endpoints (Figure 6). The assessment step defines the frequency and timing for such comparisons of monitoring results to the selected measures and endpoints. Methods for data analysis and summarization should also be identified in developing the assessment process. The nature and format (e.g., qualitative, quantitative) of these comparisons are defined in this step. The resulting assessment methods should be documented as part of the overall adaptive management plan. It is important that the adaptive management plan identify those individuals or organizations that will perform or otherwise be responsible for the assessment. The procedures for documenting and communicating the results of each assessment to managers and decision makers as well as to stakeholders should be described as part of the assessment step.

3.5.2.1 Modeling in support of adaptive management

Modeling plays a central role in adaptive management. As already mentioned, CEMs developed early in the planning process guide the identification of management actions, metrics for assessing performance, and hypotheses regarding key (decision-relevant) uncertainties. They also serve as a basis for the development of numerical models used to assess the effects of alternative management actions and to predict ecosystem response to drivers of change. Management decisions and operations are driven by scenario analyses and model projections based upon changes in the system state. Models are often required to help interpret the implications of data acquired through monitoring as they help us project changes in system state and processes to estimate future conditions. Modeling during adaptive management planning is used to help understand sensitivity and focus management experiments, avoiding the need for management learning by trial and error.

The models developed and applied to effects analysis during the planning stages are indispensable to the implementation under adaptive management. The models are again applied in the evaluation phase to assess the implications of observed performance (e.g. population response due to monitored habitat changes) and determine management needs (using model projections of habitat and population for alternative management actions, for example). The models are used to consolidate information, predict outcomes, quantify performance, and provide information needed by decision makers to determine the best course of action under adaptive management.

Adaptive management recognizes the need for action in the face of uncertainty, and complete or perfect ecosystem models (which are not likely to be perfected in any case) do not need to be crafted in order to support decisions (Walters 1997). A primary mechanism for capturing and applying knowledge is incorporating relevant information into model improvements. Information sources include a) assessments based on monitoring data updated on an annual basis, b) information from research studies or short-term additional monitoring and c) information from external studies deemed to be of sufficient quality and relevance.

Information may support structural changes to the models — adding new mechanisms or changing the scale, for example. These changes require additional time to develop, code, and test. Comparison of old and new model results (using the same parameters) can provide understanding of the consequences of the changes to model structure and function and the decisions informed by modeling.

Model validation procedures test model accuracy and precision by comparing model predictions with observations that were not used to parameterize the model. Model accuracy can be statistically assessed by identifying the percentile of the model distribution at which the observed value falls. Results near the 50th percentile indicate high accuracy, while results near the 0 or 100th percentile indicate low accuracy. Results from model validation may be used to interpret projections, adjust management decisions (to accommodate systematic over- or under-prediction) and to identify information and model development priorities.

3.5.2.2 Frequency of assessment

The implementation plan should specify the frequency and scheduling of assessments. This specification should address:

- Relevant temporal scales of the performance measures and risk endpoints,
- The time required to obtain sufficient monitoring results and analysis for meaningful comparisons with the decision criteria,
- The consequences (ecological, socioeconomic, political, stakeholder) of variances[1] with decision criteria,
- The logistical requirements to perform the assessment,
- The availability of the adaptive management personnel, and
- Funding.

The adaptive management plan should describe procedures for documenting the assessments. Such documentation might include summaries of meetings in which assessments were performed. The results of monitoring and their comparisons with decision criteria should be preserved, for example, in the form of tables, figures, and supporting text for each assessment. Variances determined for any of the performance measures or risk endpoints should be recorded along with suggested actions to address variances (i.e., to adaptively manage or continue the status quo).

3.5.2.3 Actionable science

The term “actionable science,” coined by the Department of Interior’s Advisory Committee on Climate Change and Natural Resource Science (ACCCNRS 2015), serves as a useful concept for guiding the information necessary to support adaptive management decision making while fulfilling the best-available science mandate. Actionable science provides data, analyses, projections, or tools that can support decisions regarding management of the risks and impacts of operations on the Missouri River.

[1] For the purposes of adaptive management, a variance is defined as the difference between a monitored value of a performance measure or risk endpoint and its corresponding decision criterion used in decision making.

Ideally co-produced by scientists and decision makers, actionable science creates rigorous and accessible products to meet the needs of stakeholders.

The following principles, adapted from ACCCNRS (2015), are presented to guide efforts for producing actionable science and are entirely consistent with principles for monitoring and evaluation:

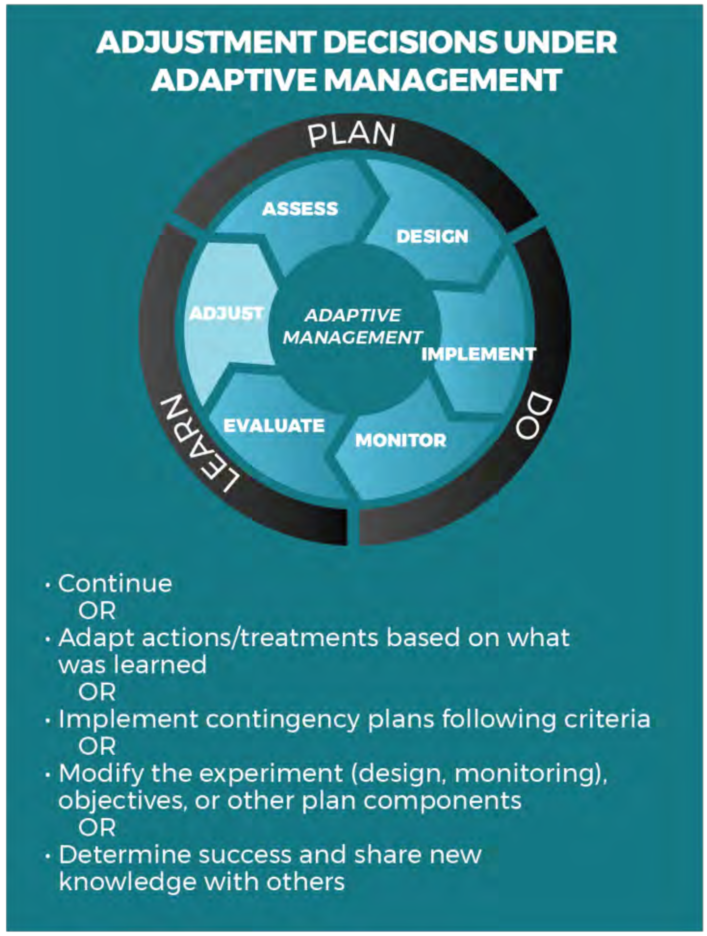
- Scientists, decision makers, and stakeholders working in concert are more likely to arrive at actionable science than scientists acting alone.
- Start with a decision that needs to be made. Research needs are rarely precisely known (and seldom clearly specified) in advance, so they must be identified collaboratively and iteratively.
- Give priority to processes and outcomes over products, and use the process to build connections across disciplines and organizations and among scientists, decision makers, and stakeholders.
- Periodically evaluate the utility of products and processes and the ability to take actions based on the science developed by the program. Use the lessons learned to adjust products and processes as needed and to refine the definition of "actionable" based on evolving views of risk.

This approach recognizes that actionable science is not only actionable information, but also includes longer-term processes and relationship-building to help ensure the appropriate use of that information. Time and resources will be required to develop and maintain interpersonal interactions among scientists, decision makers, stakeholders, and other users of the scientific information. Deploying these services efficiently and effectively also requires building connections across disciplines and among the organizations engaged in the effort. The budgets for the program and individual projects, project evaluations, and staff incentives and evaluations should reflect commitment to this need.

3.5.3 Governance

Governance of an adaptive management plan includes the approach for converting knowledge into improved management through decision making, identifying:

- **what** decisions need to be made
- **who** is involved in the decision process
- **how** decisions are made
- **when** decisions are required.



The adaptive management plan should describe the process whereby the results from monitoring and assessment will be used to make decisions concerning project management. This includes identifying who is responsible for making the decisions, how the decision-making group operates, how they report their decisions, and provisions for the resolution of conflicts. The governance process should: (1) comply with all pertinent legal requirements; (2) maintain transparency and involve all relevant entities in the adaptive management learning process and in the formation of recommendations for decisions; and, (3) help efficiently achieve the project or program's goals and objectives.

There is no "one-size-fits-all" approach to effective governance. An effective governance structure and process will depend on the purpose and needs and will have clear expectations around outcomes (Rijke et al. 2012). Functions served by governance include: (1) trust-building, (2) knowledge generation, (3) collaborative learning, (4) preference formation, and (5) conflict resolution (Green et al. 2013). Although lessons can be learned from other adaptive management programs, an effective system of governance for any application requires consideration of how the above functions apply within the context of the unique ecological and social conditions for that application.

The concept of "adaptive governance" has emerged as an important component of an adaptive management strategy, adding the need for organizational and institutional flexibility to change as a consideration in the decision process. Recognizing that the adaptive management plan itself may need to evolve and providing a process for that change is a key consideration in the development phase.

3.5.3.1 Decision makers

The composition of individuals and organizations making adaptive management decisions for specific USACE applications may differ depending upon the authority, sponsor and scope, and complexity of the project or program. Decisions are typically made by the Corps' Division and District Commanders — subject to their authorities and appropriations — with input from sponsors and the public, as appropriate. Corps commanders cannot abdicate their responsibilities but will often delegate some decisions to other management levels within the organization. The AMT (and sometimes other entities) typically inform decision makers and may make recommendations.

Some decisions should be a joint consideration of USACE leadership and the sponsor or other federal agencies (e.g., changes to targets, decision criteria, or the governance process itself). Joint decisions may be possible in some cases; more often, existing authorities and jurisdictions establish that certain entities are responsible for particular decisions and the governance process is structured to ensure those decisions are informed by the partners. The adaptive management plan should clearly identify the roles and responsibilities of the decision makers in these circumstances. Figures 11 and 12 provide examples of governance structures for a project and program, respectively, where some shared decision responsibilities exist.

Figure 11. Example governance structure for the Poplar Island Environmental Restoration Project (PIERP) (USACE 2005).

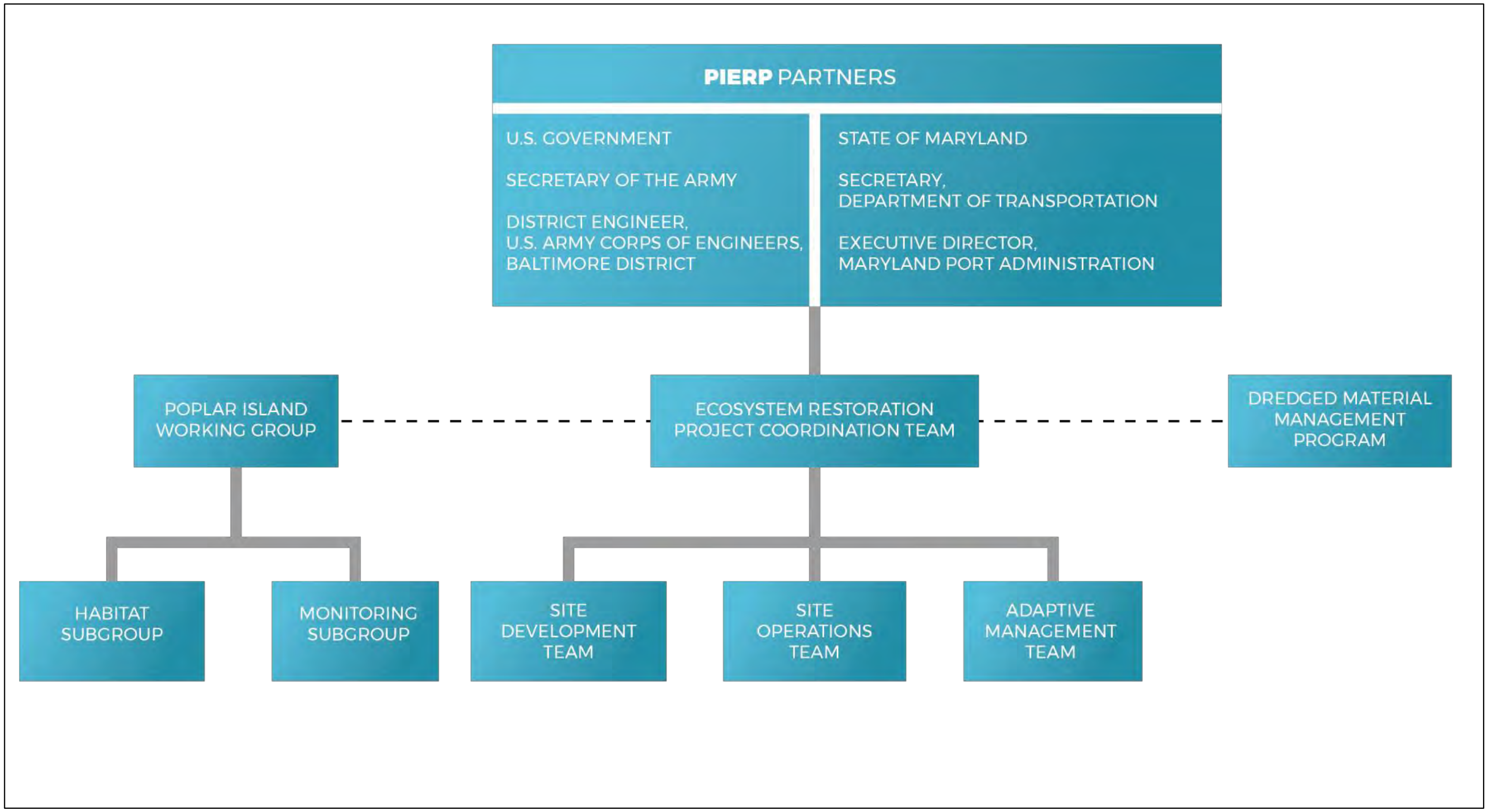
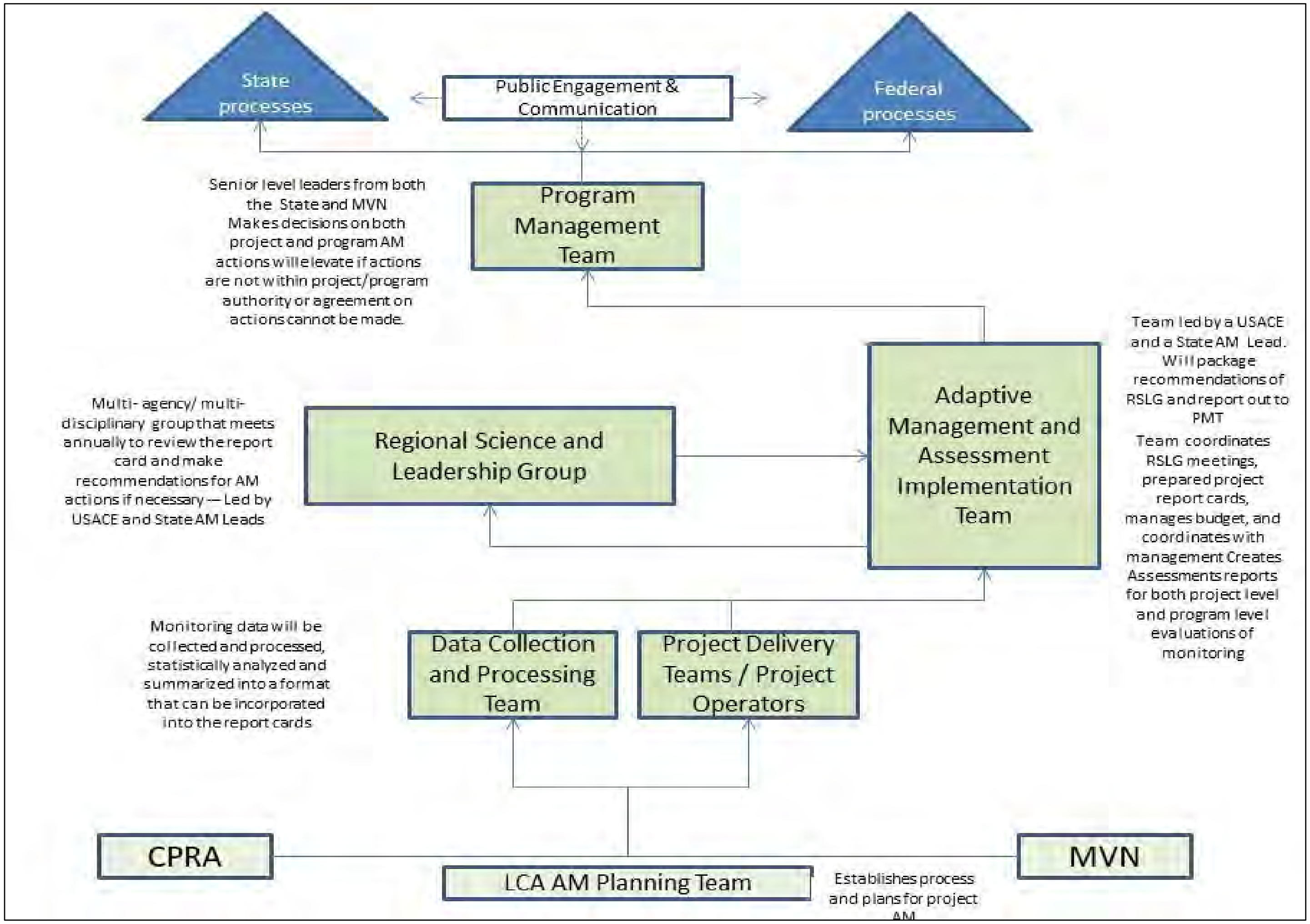


Figure 12. Example governance process for a large program, drawn from Louisiana Coastal Authorities.



3.5.3.2 Decision making

The most evident and essential function of governance for adaptive management is to facilitate effective, transparent decision making. However, decisions may be complicated by several important legal, social, political, and economic dimensions. Therefore, the design of the governance structure and processes must anticipate the range of decisions needed to translate knowledge gained into effective and acceptable management and promote decision making at the lowest practicable level.

Various decision-support frameworks can be used to support adaptive management. Schwartz et al. (2017) discussed five frameworks with broad recognition and applicability: (1) strategic foresight; (2) systematic conservation planning; (3) structured decision making; (4) open standards for the practice of conservation; and (5) evidence-based practice. They emphasize the value of using these decision tools and note that using any framework in isolation may diminish benefits since no one framework covers the full spectrum of potential decision challenges.

Scenario analysis (a strategic foresight tool) can be used in the planning (i.e., development) phase to explore the range of decisions that might be needed and how they will be addressed. The following types of questions can be used to explore situations that might arise and help the team to identify associated governance needs (these exercises often lead the team to revisit objectives, metrics, monitoring strategies, etc., improving the planning process):

- How will project success be determined and what steps are needed to "close out" a project?
- What circumstances might arise that could cause the system response to differ from desired or anticipated response? What could/should be done if this were to occur?
- How much time should it take for a response to be evident or quantifiable?
- Can response be determined directly from monitored data, or will interpretation from multiple lines of evidence be required?
- What role will sponsors and other stakeholders play in the decision process? How will disputes be resolved if there is disagreement over decisions?

- How will interruptions in funding or other impediments to implementation be addressed?

The above list is a sampling of the scenarios and considerations that might be explored. In practice, dozens of similar questions will arise, and it is important that the AMT fully explore these issues with USACE leadership, sponsors, and stakeholders to ensure the decision structure and process are capable of addressing needs. Adaptive management decisions that will be required on a routine (typically annual) basis include selecting from the following:

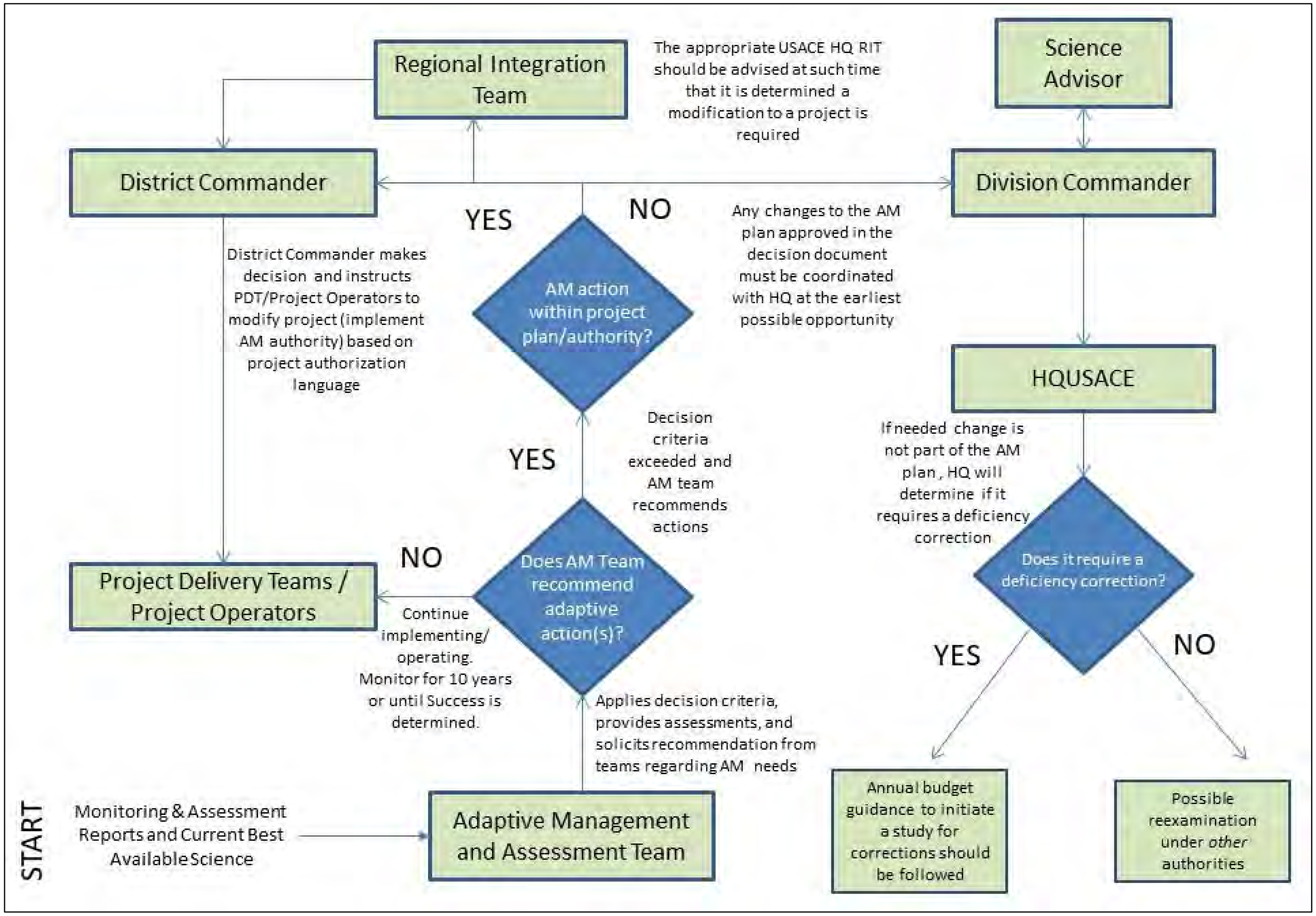
- To continue the current management or restoration action without modification. This decision would be warranted if monitoring results demonstrate that the response to management is as expected or acceptable, if it is too soon to conclude whether response is as anticipated, or if, despite unexpected or unacceptable response, no other option is currently available.
- To modify the implementation of the management or restoration action, if the current implementation is not achieving management or restoration goals, or if risks are not being effectively avoided, minimized, or managed.
- To implement an alternative management or restoration action to more effectively achieve the originally specified management goals and objectives or to minimize or avoid risks. If such actions exceed the scope of the current authorization, it may prove necessary to return to the reformulation stage of the adaptive management process.
- To adjust components of the plan. It may become apparent from monitoring that the initial goals and objectives were unreasonable, and a decision may be made to adjust the goals and/or objectives. Other components of the adaptive management process might also require adjustment, such as monitoring protocols, analysis techniques, and the governance structure or process. Provisions for such change should be anticipated in the adaptive management plan and decision makers should have a mechanism to implement these changes when needed.
- To halt adjustment and prepare a post-authorization change report, general re-evaluation report, or seek new authorization to remediate the problems if the restoration action is not achieving goals or objectives or successfully addressing risks. Such a decision may require informing HQUSACE and sponsors. De-authorization may also be an option in rare cases.

- To declare success and stop federal funding for monitoring and adaptive management if the goals and objectives have been demonstrably achieved or a trajectory to success is assured.

The complexity of the decision-making process can be influenced by the number of performance measures included in the assessment, as well as the rigor of the assessments (Figure 13). Methods of structured decision making supported by multi-criteria decision analysis (e.g., El-Swaify and Yakowitz 1998, Linkov et al. 2006, Andrew et al. 2008), meta-analysis (e.g., Wolf 1986, van den Bergh et al. 1997), or other multi-variate approach can support decision making in adaptive management applications characterized by multiple performance measures and complicated assessment methods.

The adaptive management plan should address the number of variances in any single assessment that would trigger any of the decisions just outlined. It is possible that a single measure or endpoint (e.g., impacts to an endangered species) may be sufficiently important (e.g., human safety, dam failure, impacts to an endangered species) that a demonstrated variance would require a decision other than to continue the current management action. Alternatively, and again depending on their associated consequences, a larger number of variances of lesser impact might be required to change an ongoing management action.

Figure 13. Example of a general decision process for USACE adaptive management projects.



A detailed description of the process whereby results of the project monitoring and assessment are evaluated in relation to the decision criteria and decisions are made is required. The decision-making process can be disaggregated into the components described in Table 5.

Table 5. Components of a decision-making process (Rubenstein 1975).

Goals and Objectives	What the USACE planners and decision makers desire to achieve. Explicit statements of anticipated desired outcomes or performance, as well as risks to be avoided, minimized, or mitigated.
Decision Alternatives	Alternative actions that the managers and decision makers control and select among; for example, proposed planning alternatives developed during a feasibility study.
States of Nature	The broader environmental context wherein the selected alternatives or management actions manifest themselves; for example, climate change, stakeholder values, business cycles, and USACE policy.
Outcome	The results from a combination of a management alternative or management action and states of nature; for example, the acreage of wetlands restored by river diversions during a drought period or in relation to sea level rise or regional subsidence.
Utility	The value of an outcome in relation to achieving the goals and objectives.

3.5.3.3 Conflict resolution

Management and restoration in the public sector often require decisions that involve choosing among alternative actions. The choices can be perceived as competing, incompatible, or even exclusive, but inevitably are a matter of weighing tradeoffs. Decisions can become controversial, and conflicts can arise when participants and/or affected parties (stakeholders) have different philosophies, risk tolerance, values, or goals (Shields et al. 1999).

There are several approaches to conflict resolution (e.g., see Mostert 1998). The decision-making process should include methods for minimizing and resolving conflicts that might arise during implementation of adaptive management. It is important that the process be defined before conflicts arise to ensure the efficient and continued operation of the adaptive management process; clearly describing the approach in the adaptive management plan is important. While intervention or mediation by higher-level authorities in the participating organizations may be needed, it is best if issues can be resolved at lower management or technical levels.

3.5.3.4 Procedures for implementation

Implementation requires the formulation of standard procedures and a governance process that documents how decisions under adaptive management will occur. Practicality suggests that the procedures be neither so formal as to pre-empt action nor sufficiently informal that consistent and productive activity proves impossible. Consensus-based procedures may prove workable and efficient, depending on the makeup of the AMT. Majority-rule or more autocratic approaches to executing an adaptive management program might also be considered, depending on the nature and authorization of the management mission, program, or project. The standard operating procedures should be described as part of the adaptive management plan.

The documented procedures for carrying out the adaptive management plan should include, but not be limited to:

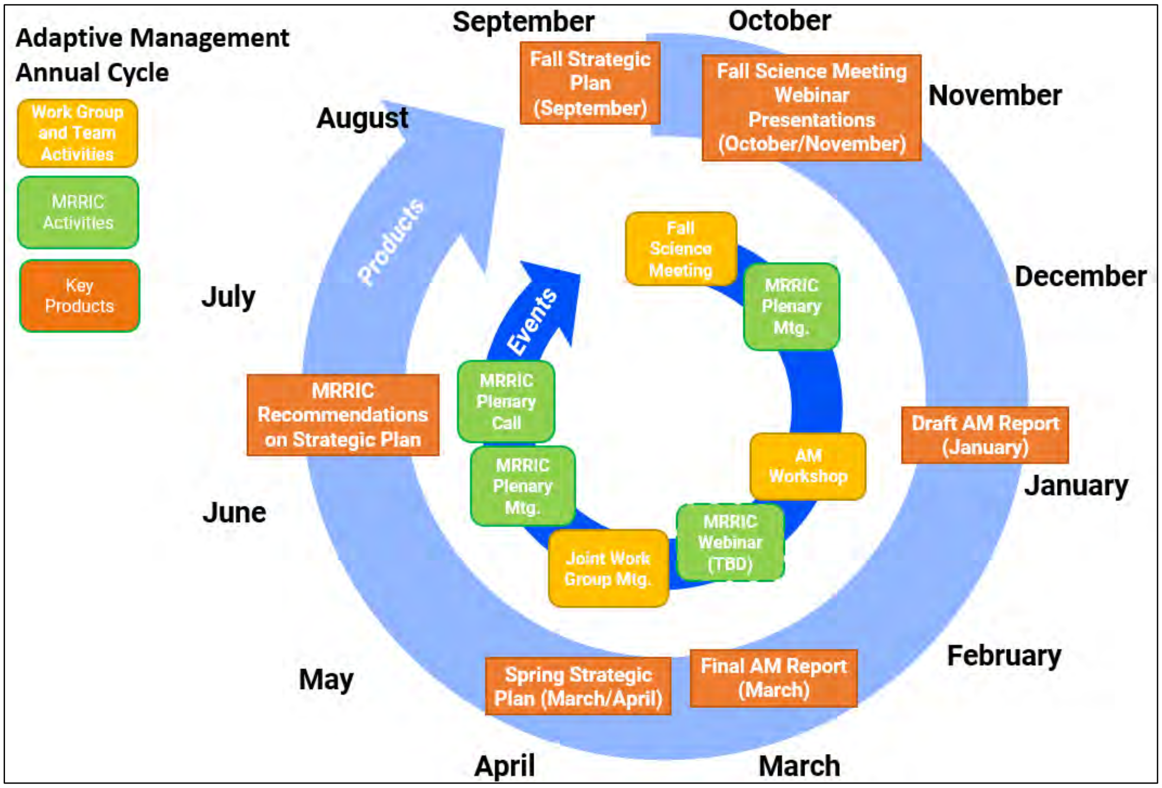
- Specifying the mechanisms for responsible personnel to execute the adaptive management plan and process. These mechanisms might include meetings, teleconferences, web meetings, and electronic or written correspondence.
- Delineating the location and frequency of such interactions, as well as logistic responsibilities necessary for implementing the adaptive management plan.
- Formulating rules or policies that stipulate how the members will interact to conduct business (e.g., evaluation of monitoring results in relation to decision criteria). These interactions might reasonably include provisions for the participation of technical support personnel or stakeholders.
- Communicating the deliberations of the adaptive management team to decision makers.
- Making or participating in adaptive management decisions.
- Providing guidance and assurance for monitoring, analysis, and data management supporting the decision process.

The intent in developing and documenting operating procedures is to produce a coherent process that can be carried forward in a consistent and productive manner independent of changes in the composition of the AMT. Operating procedures can be modified during the course of implementing adaptive management. Understanding the operating procedures is also necessary to establish reasonable cost estimates for the implementation of adaptive management programs.

Development of a timeline – usually on an annual cycle basis – is recommended to set expectations, to help ensure that the necessary time and resources are available to implement adaptive management, and to structure details of the process. Monitoring needs are often seasonal, which provides a convenient basis for establishing a time table. A certain amount of time may be required for QA/QC of monitoring data before analysis can begin. Analysis, reporting and communication of the data will require time, as will any model updates and projections of future conditions that decision makers may require. Decisions must be timely in order to mesh with USACE budgeting processes. The annual cycle may be further complicated if significant engagement with sponsors or other agencies is necessary. Figure 14 shows an example of a timeline involving stakeholder and product development on a recurring annual basis involving engagement with agencies and stakeholders (adapted from the science and adaptive management plan for the MRRP)[1].

[1] Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Figure 14. Example of a recurring annual timeline involving engagement with agencies and stakeholders (adapted from the science and adaptive management plan for the MRRP[1]).



3.5.4 Data management, communications and reporting

A critical component of adaptive management is accurately transforming the best available science into actionable and accessible information and communicating information in the right format and in a timely manner to support decisions regarding implementation of the program. Data management, reporting and communication needs and strategies should be identified in the adaptive management plan, and be developed to a sufficient level of detail to permit assessment of associated costs. Data management includes the collation, storage/retrieval, analysis, summarization, and communication of monitoring results and related information (e.g., published information, model results) used in support of adaptive management. This is typically a task of the AMT. The data management plan should identify the computing hardware and any specialized or custom software used in data management for an adaptive

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[1] Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

management program. The AMT should collaborate with the data managers to identify the types of data and information to be included in the data management system, establish convenient formats for storing and retrieving data, and guarantee the preservation of the data (i.e., backup versions, electronic and/or hard copy).

Adaptive management benefits from an open and transparent management practice wherein the results of monitoring, assessment, and decision making are routinely and consistently documented and communicated. It will be important to develop, implement, and periodically re-evaluate a communication plan that considers all of the different audiences, and the diverse forms of reporting that are most appropriate to each audience (e.g., decision-oriented syntheses, annual reports, reporting sessions, science workshops, peer-reviewed reports and journal articles, fact sheets, videos, presentation summaries).

These topics are discussed further in Appendix E, which describes adaptive management implementation.

4 Summary and Key Take-Away Points

Implementation guidance for Sections 2036 and 2039 of WRDA 2007 and Section 1161 of WRDA 2016 provide monitoring requirements for certain USACE projects and require that either ecosystem restoration projects include appropriately scoped adaptive management plans or provide sound justification for why adaptive management is not warranted. Criteria in Section 2.1.1 define the circumstances when adaptive management is not needed.

Adaptive management is an iterative process for managing natural resources (Gunderson and Holling 2002, Gray 2000, Walters 1986, Holling 1978). Under adaptive management, decisions are based on the best available (yet often incomplete and imperfect) scientific data, information, and understanding, recognizing uncertainties that introduce risks to the achievement of goals and objectives.

Adaptive management aims to overcome the limitations of static management approaches by institutionalizing cycles of evaluation and subsequent change. A management plan is considered temporary, with revision based upon information garnered from ongoing monitoring and evaluation possible. The emphasis is on learning by doing and being responsive to new information and system feedback. This requires new approaches to management and decision making that are flexible and support ongoing learning.

Adaptive management should not be mistaken as a “trial-and-error” management approach. Adaptive management uses performance-related hypotheses, conceptual or other causal models, and directed monitoring and assessment to confirm and improve understanding of ecological processes and help explain why the goals and objectives were or were not achieved. The active form of adaptive management, which is generally preferred, treats projects as experiments and applies the scientific process to their evaluation.

Adaptive management’s true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders (NRC 2004). These benefits come with added costs from the monitoring, assessment, and governance that accompany adaptive management.

Adaptive management can be regarded in terms of two principal phases; the development phase wherein the adaptive management strategy is developed, the plan prepared concurrently with traditional Corps' planning activities, and an implementation phase during which the strategy is executed. Adaptive management adds several considerations to the traditional planning process, but is harmonious with SMART planning.

Adaptive management planning requires consideration of the flexibility and reversibility of alternatives and a determination of what adjustments to the project restoration actions may be needed. Plans must also be made for the acquisition and management of data, as well as the analysis and decision making required to implement management decisions. These requirements force planning teams to contemplate objectives and project performance at a high level of detail, and the resulting plans inevitably benefit from this additional degree of thought.

The explicit treatment of uncertainty as part of planning, the development of conceptual and numerical models to evaluate management actions, and the treatment of management decisions as experiments with monitoring to assess performance are at the core of adaptive management. Decisions are based on the current best available scientific information, overlaid with other relevant policy and socio-economic considerations following a governance process laid out in the plan. If the adaptive management is collaborative, sponsor and stakeholder engagement occur as part of the process. In any case, objectivity, transparency, and effective communication are used.

Current guidance provides for federal funding of monitoring and adaptive management for up to ten years, or until the project has been deemed successful. Success for ecosystem restoration projects occurs when decision criteria suggest that the objectives have been met, or that specific thresholds have been crossed and the ecosystem is on a recovery trajectory that will result in the achievement of the objectives.

4.1 Key points

Adaptive management works best when: (1) management flexibility is incorporated into the design and implementation of programs or projects; (2) projects and programs can be implemented in phases to allow for course corrections based on new information; (3) interagency collaboration and productive stakeholder participation are fostered; and,

(4) scientific information is introduced into the decision-making process and guides managers not only during planning, but also after project implementation (Fischenich 2012).

Projects planned under ecosystem restoration authorities must include adaptive management plans or sound justifications for why adaptive management is not warranted. For programs and projects not subject to these requirements (e.g., certain environmental management actions and engineering projects), application of adaptive management should be evaluated on a case-by-case basis.

To be effective, adaptive management nominally requires 1) one or more critical uncertainties affecting outcomes; 2) the ability to monitor and assess the effects of management; and, 3) the ability and will to change management decisions based on new knowledge. Absent any of these attributes, a decision process and risk management strategy other than adaptive management is required. Even if the above criteria are met, the decision to employ adaptive management should be made with the understanding of the limitations and costs of adaptive management.

Adaptive management has a critical planning component that requires careful consideration of uncertainties and outcomes. It is not strictly a post-construction consideration, but instead is foremost a planning activity that integrates fully with other USACE planning activities.

The site specificity of environmental and natural resource management problems and the diversity of authorities, scales, stakeholder interests, etc., means that there is no one-size-fits-all prescription or blueprint for adaptive management. The adaptive management plan, implementation strategy, and governance structure must be adapted to the needs of each situation.

Despite the unique attributes of individual projects, the basic process, underpinning principles, and aims of adaptive management remain the same and provide a foundation for developing and implementing effective adaptive management plans that meet USACE needs.

Adaptive management is most effective when it is collaborative in nature, engaging stakeholders early and at all stages. Failure to keep stakeholders involved, and their interests accounted for, can lead to loss of support for necessary decisions. Adaptive management can only be successful when decisions are grounded both in good science, and political and practical realities. Engagement of external expertise and facilitation services can help with any adaptive management effort and may be crucial for establishing trust with stakeholders. Use of independent science panels are encouraged for the same reasons.

Monitoring and adaptive management plans should be scoped to match the level of assessed risk and the needs of management and decision making. Up-front investment in the development of sound experimental designs for project implementation and monitoring may be the best hedge against excessive project costs. This may require the engagement of expertise not commonly found in Corps districts.

The aspects of adaptive management discussed in the development phase and implementation phase should be integrated and documented in the form of an adaptive management plan. The adaptive management plan should serve as an open (i.e., generally available) and transparent document that describes the basis for the plan, roles, and responsibilities of those involved with its execution, the governance structure, monitoring and assessment requirements, and any relevant metrics and decision criteria. The adaptive management plan should clearly describe the objectives, hypotheses, metrics, monitoring, and assessment strategies that will be used to assess the restoration or mitigation actions (Figure 15).

Figure 15. A well-constructed adaptive management plan should make a clear connection between the plan components.

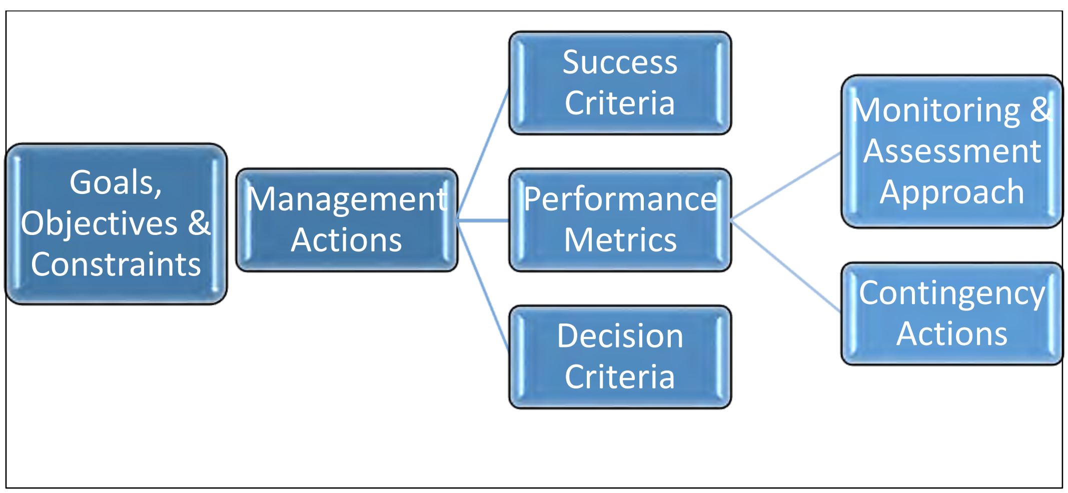

Figure 16 provides an example outline for an adaptive management plan that includes the essential components. For relatively simple ecosystem restoration projects where other planning documents are referenced, the adaptive management plan may be described in a few dozen pages. Large programs with many diverse projects and complicated governance structures may require considerable documentation (see the adaptive management plan for the MRRP[1]).

[1] Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Figure 16. Example for an outline for an adaptive management plan.

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SUPPORTING APPENDICES

4.2 Enabling characteristics for effective adaptive management

Following is a set of ten enabling characteristics for effective adaptive management summarized from a more comprehensive treatment by Fischenich and Murphy (2019[1]).

1. *Clear articulation of adaptive management objectives and program scope*. Objectives set expectations and guide decisions. Objectives can be expressed in either aspirational or operational terms, where the former generally reflect ethical, cultural, and ideological values and the latter are intended to guide management decisions and therefore must be linked to feasible and measurable metrics that serve as performance indicators for management. Adaptive management cannot simultaneously maximize all the objectives and, as a practical matter, focuses on those objectives for which uncertainty and operational flexibility are greatest.
2. *Documentation of the best available science*. A formal, quantitative analysis of the effects of an action is an obligatory step in the planning process. A crucial component of an effects analysis is the development of an analytical framework that supports quantification of the effects of alternative actions and management responses (Murphy and Weiland 2011). A thorough effects analysis, and particularly a conceptual ecological model, provides the information base and template for the monitoring that is required to assess the effectiveness and efficacy of the adaptive management framework.
3. *Monitoring in an experimental framework*. Best available science has a second portal into adaptive management through the design and implementation of monitoring and the interpretation and assessment of data that is summarily gathered. Monitoring is a form of applied research, which in service to adaptive management must be approached much as a laboratory experiment is approached — with a rigorous design and application of the scientific method (Noon 2003). A monitoring scheme must have explicit programmatic goals and objectives, direct the gathering of data in a framework adequate to detect meaningful changes in the conditions of ecological resources, and develop reliable, scientifically defensible indicators for measuring change.

[1] Fischenich, J. C., and D. D. Murphy. 2019. *The enabling characteristics of adaptive management on big landscapes: observations from implementing the Endangered Species Act in the Missouri River Restoration Management Program*. Draft. Prepared for Journal of Environmental Management.

4. *Identifying appropriate metrics and contingent decision criteria*. Performance measures derived from project objectives should: 1) be measurable; 2) have a relatively strong degree of predictability (i.e., targets specified by predictive models); 3) change in response to project implementation; and 4) help verify progress and evaluate hypotheses through monitoring and assessment. Decision criteria presented in the form of targets and decision triggers directly related to program/project objectives should be established prior to implementation to assist with governance.
5. *Modeling to forecast outcomes from proposed management actions*. Models linking potential management actions to resource consequences play a decision-support role in virtually all adaptive management applications. They also play a key role in representing uncertainty, with hypotheses imbedded in different models forecasting resource changes through time. As evidence accumulates over time, the confidence placed in each model (and its associated hypothesis) evolves, through a comparison of model predictions against monitoring data.
6. *Applying structured decision-making strategies to acknowledged trade-offs*. Structured decision-making approaches aid in the implementation of key elements of an adaptive management plan by (1) identifying a range of conservation, economic, and social objectives and linking them to management alternatives, (2) making key decision tradeoffs explicit, and (3) highlighting considerations that are and are not important in the selecting of management actions from among alternatives.
7. *Integrating human considerations into all aspects of risk assessment*. There are socio-economic ramifications – and hence tradeoffs – to most decisions on restoration and mitigation projects. Related considerations should be woven into all facets of adaptive management, from the objectives through monitoring and the analysis and forecasting that supports governance efforts.
8. *Adaptive management governance structure and process*. Governance structures and processes should be symbiotic with existing organizational realities and tailored to the specific needs of an adaptive management project or program so as to be efficient and effective. Use of decision criteria, triggers and contingency plans promote decision making at the lowest effective administrative level, permitting senior leaders to focus on only the most contentious decisions.

9. *Independent scientific advice and review.* A standing panel of “outside experts” engaged during development of an adaptive management plan and extending into its implementation can provide critical insights on conceptual models, effects analyses, hypotheses, monitoring designs, and other key products as well as provide perspective on the adaptive management process. The panel can help build trust within and between agencies and stakeholders.
10. *Stakeholder engagement in adaptive resource management*. Stakeholder involvement from the point of project initiation through implementation facilitates mutual learning, provides alternative insights and competing management hypotheses, and is the most effective route to avoiding litigation that can delay the resolution of environmental challenges.

4.3 Benefits of adaptive management

Adaptive management promotes collaboration, flexible decision making through deliberately designing and implementing management actions to test hypotheses and maximize learning about critical uncertainties to better inform management decisions (Williams and Brown 2012). A collaborative adaptive management approach incorporates and links credible science and knowledge with the experience and values of stakeholders and managers for more effective management decision making (Sims and Pratt-Miles 2011).

Adaptive management plans developed as part of a feasibility study add thoroughness to traditional planning and increase the likelihood of success in USACE management and restoration. The adaptive management process requires planners and stakeholders to consider a range of potential problems and outcomes at a level of detail not required in more traditional USACE feasibility studies. Such in-depth examination leads to improvements in the statement of management objectives, formulation of planning alternatives, and analysis of the implications of uncertain outcomes on management decisions.

Adaptive management has been shown to reduce long-term costs, decrease risk of failure, strengthen credibility, increase public trust, and improve restoration outcomes (Love et al. 2018). It helps move the state of science and understanding of ecosystem restoration forward in a deliberate way. Table 6 briefly outlines characteristics of adaptive management and corresponding benefits.

Table 6. Characteristics of an adaptive management strategy and associated benefits.

Characteristic	Associated Benefits
Management flexibility is incorporated in the design and implementation of programs or projects	Flexibility to address uncertainty through monitoring, assessment, and adjustments to management actions increases the robustness of a project and its effectiveness under future scenarios, improving the likelihood of success across a broad range of future conditions.
Scientific processes are used to support project planning, implementation, assessment, and management.	Adaptive management tests hypotheses identified in conceptual models to address the uncertainties inherent in project implementation. Information learned from this process is conveyed to managers and stakeholders to support decision making and evaluate progress toward achieving goals and objectives. This provides a forum for dialogue between scientists and managers to interpret monitoring results, allowing managers to seek clarification about scientific and technical questions that may affect implementation. The process also reduces costly delays from legal actions and policy clarifications by effectively addressing uncertainties and promoting stakeholder engagement and interagency collaboration.
Interagency and stakeholder participation and collaboration occur as part of the AM forum	An open and inclusive atmosphere facilitates interagency participation, aids in acknowledging the full range of stakeholder interests and values, and ensures that new ideas are considered in the decision-making process. This builds trust and increases the likelihood of support for the restoration process by providing a common vision of success and effective and timely conflict resolution.

Glossary

Accounts – Objectives and performance criteria are organized into four accounts in accordance with U.S. Army Corps of Engineers Planning Guidelines. The four accounts are as follows:

- Environmental Quality (EQ)
- National Economic Development (NED)
- Regional Economic Development (RED)
- Other Social Effects (OSE)

Active adaptive management – An adaptive management approach that reduces uncertainty by using multiple designs or operational criteria as management experiments (i.e., field tests, physical models) to test hypotheses about system responses to management. Active adaptive management allows rigorous assessment of the cause-and-effect relationships between management actions and environmental responses, generally providing more comprehensive and rapid knowledge than can be obtained through passive adaptive management. Learning to support future decisions is an explicit objective.

Adaptive action – A course of action to be implemented as defined in the Adjust step (Step 5b of the adaptive management process; see Figure 3) if the performance of a particular management action is not as anticipated and requires correction. In cases where the action is pre-defined, it is referred to as a “contingency action.”

Adaptive Management (AM) – A decision process that promotes action in the face of uncertainties and adjustment as outcomes from management actions and other events are better understood. Careful monitoring of these outcomes advances scientific understanding and helps adjust policies or operations as part of an iterative learning process.

Adaptive Management Team (AMT) – Individuals who will be responsible for developing and implementing adaptive management.

Alternatives – A specified combination of management actions that collectively are deemed to meet the goals and objectives. In the Problem Definition, Objectives, Alternatives, Consequences, Tradeoffs (PrOACT) process, the trade-offs associated with various alternatives on multiple interests are explored in order to find the alternative(s) that minimize unnecessary negative impacts and is/are otherwise thought to be the “best balance” of impacts on a wide range of interests. Alternatives are used to address the objectives.

AM report – Annual or periodic report that documents new learning based on monitoring results, evaluates progress towards meeting species objectives, and contains recommendations for adjustments to management actions.

Annual Work Plan (AWP) – A document that includes real estate actions, habitat creation actions, monitoring of physical and biological responses to actions, and research activities for a particular fiscal year (FY). It is used by project delivery teams to budget and implement management actions annually.

Assessment – Process by which the results of the monitoring efforts will be compared to the project performance measures and/or acceptable risk endpoints (i.e., decision criteria).

Biological Assessment (BA) – Information prepared by, or under the direction of, a Federal agency regarding listed and proposed species and designated and proposed critical habitat that may be present in the action area and the evaluation of potential effects of the action on such species and habitat.

Biological Opinion (BiOp) – Document stating the opinion of the U.S. Fish and Wildlife Service (USFWS) or the National Marine Fisheries Service (NMFS) as to whether a Federal action is likely to jeopardize the continued existence of a threatened or endangered species or result in the destruction or adverse modification of critical habitat.

Collaboration – Working together to define and solve problems to achieve common goals.

Conceptual Ecological Models (CEMs) – Depictions of an ecosystem used to communicate the important components of the system and their relationships. They are a representation of the current scientific understanding of how the system works, often presented in graphical form with accompanying descriptions of the system components and processes.

Conflict resolution – The methods and process of negotiation, arbitration, and institution-building for alleviating or eliminating sources of conflict.

Contingency action – A pre-evaluated adaptive action that is implemented when triggered by defined decision criteria without the need for further deliberation or decision.

Critical uncertainties – Uncertainties that impede the identification of a preferred alternative management action.

Critical Engagement Point (CEP) – Specific points in the development or implementation phases of adaptive management when the agencies engage for input.

Data management – Development, execution, and supervision of plans, policies, programs, and practices that control, protect, deliver, and enhance the value of data and information.

Data quality objectives – Values of acceptable bias and precision specified for performance measures and risk endpoints.

Decision context – Involves defining what decision (question or problem) is being made, why it is being made, and also describing the scope of the playing field (bounds) for the management decision as well as its relationship to other decisions previously made or anticipated.

Decision criteria – A broad reference to the set of pre-determined criteria used to make adaptive management decisions. Performance metrics, targets, and decision triggers are considered to be different types of decision criteria. They can be qualitative or quantitative based on the nature of the performance metric and the level of information necessary to make a decision.

Decision space – A term used to characterize a range of operational discretion for flows (or potentially other actions) that is "acceptable" to stakeholders, effective in achieving objectives, and within the bounds of actions evaluated under NEPA. Management actions would generally occur within this region, and any operation outside this decision space would require further coordination and approval.

Decision trigger – A pre-defined commitment (population or habitat metric for a specific objective) that triggers a change in a management action. Decision triggers are addressed in the Evaluate step (Step 4 of the AM process) and specify the metrics and actions that will be taken if monitoring indicates performance metrics are or are not reaching target values. In some cases, a decision trigger may be learning a new piece of information that triggers the Continue/Adjust/Complete step (Step 5 of the AM process).

Delphi process – A method of eliciting expert opinion (Normand et al. 1998). While many variations of the process exist, there are generally three common features: (1) qualified experts provide their responses to a set of questions in a structured format; (2) the answers to these questions are synthesized across all respondents and presented back to the same set of experts; and (3) the experts jointly discuss the reasons for variation in the first set of responses (or lack thereof) and, through dialogue, potentially revise their opinions. A modified Delphi process was applied by Jacobson et al. (2016) to prioritize candidate hypotheses.

Design – Plans and specifications of a selected planning alternative.

Ecosystem – The complex of a community of organisms and its environment functioning as an ecological unit.

Ecosystem restoration – Active human intervention that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity, and sustainability.

Effects Analysis (EA) – This effort's purpose is to conceptually and quantifiably make explicit the effects of proposed actions on a resource or species by specifically evaluating the effects of management actions on the ecosystem or the status and trends of the listed species and their habitats.

Environmental Impact Statement (EIS) and Environmental Assessment (EA) – An EIS is a detailed document pursuant to the National Environmental Policy Act that describes and analyzes the environmental effects of the alternatives for a proposed major Federal action; the decision document for an EIS is a Record of Decision. Refer to 40 CFR 1502.4 for examples of major Federal actions that require the preparation of an EIS. An Environmental Assessment is a less detailed document pursuant to the National Environmental Policy Act that describes and analyzes the effects of a project that is not deemed to be a major Federal action; the decision document for an EA is a Finding of No Significant Impact.

Evaluation – Conduct analyses to compare measured results with anticipated outcomes related to decision criteria for specific management actions to determine whether the implementation should be continued, adjusted, or completed.

Event-driven reporting cycle – In addition to the annual and periodic AM reports (on a routine reporting schedule), reporting may also be event-driven, where new observations or data resulting from an unforeseen event suggest a decision trigger or targets have been reached.

Feasibility study – The project formulation phase during which all planning activities are performed that are required to demonstrate that Federal participation in a specific project is warranted, culminating in approval of the decision document. All plan formulation must be completed during this phase, including all technical analyses, policy compliance determinations, and Federal and non-Federal environmental and regulatory compliance activities required for approval of the decision document.

Flood risk management – Actions to reduce the likelihood and/or the impact of floods.

Formal consultation -- A process between the USFWS or NMFS and a Federal agency that commences with the Federal agency's written request for consultation under Section 7(a)(2) of the Act and concludes with the USFWS/NMFS issuance of the biological opinion under Section 7(b)(3) of the Act.

Fundamental objectives – Objectives used to formalize the desired outcome the program or project is seeking to achieve. They are distinct from means objectives.

Global hypotheses – Set of possible, biologically important hypotheses, relevant to population dynamics that are derived from conceptual ecological models.

Human Considerations (HCs) – A set of objectives with associated metrics addressing the wide array of uses and stakeholder interests for a project or program.

Hypothesis – An idea or explanation that is tested through study and experimentation. A hypothesis is usually based on evidence, making it more than a wild guess but less than a well-established theory.

Investigations – Planning or research activities intended to generate information that will fill the key gaps in understanding and reduce uncertainty associated with implementation of management actions.

Jeopardy – As defined by the Endangered Species Act (ESA), jeopardy occurs when there is an action that reasonably would be expected, directly or indirectly, to reduce appreciably the likelihood of both the survival and recovery of a listed species in the wild by reducing the reproduction, numbers, or distribution of that species.

Limiting factor – A factor that controls the growth, abundance, or distribution of an organism.

Management actions – Proposed or potential actions to be taken by the USACE that contribute to meeting objectives; one or more management actions constitute an alternative.

Management hypotheses – Statements (in affirmative hypothesis form) that a specific management action will be effective in achieving objectives.

Means objectives – Describe ways of achieving the fundamental objectives and specify the way and degree to which the fundamental objectives can be achieved. They are used to further develop management actions and alternatives and are potentially useful in tracking progress towards fundamental objectives in the near-term when a response in the fundamental objectives may not be detectable in shorter time frames due to a delayed species response to management actions or other reasons.

Monitoring – The process of measuring attributes of the ecological, social, or economic system. Monitoring has many potential purposes, including: to provide a better understanding of spatial and temporal variability, to confirm the status of a system component, to assess trends in a system component, to improve models, to confirm that an action was implemented as planned, to provide the data used to test a hypothesis or evaluate the effects of a management action, and to provide an understanding of a system attribute that could potentially confound the evaluation of action effectiveness.

Multi-criteria decision analysis – A comprehensive, structured process for selecting the optimal alternative in any given situation, drawing from stakeholder preferences and value judgments as well as scientific modeling and risk analysis.

National Environmental Policy Act (NEPA) – Requires Federal agencies to integrate environmental effects and values into their decision-making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. To meet NEPA requirements, Federal agencies prepare an Environmental Impact Statement or Environmental Assessment.

No-action alternative – The Council on Environmental Quality defines no action as "no change" from current management direction or level of management intensity. The no action alternative is required in all NEPA documents pursuant to 40 CFR 1502.14

Objectives – Concise statements of the interests that could be affected by a decision — the "things that matter" to people. Objectives define an endpoint of concern and the direction of change that is preferred. In PrOACT, objectives typically take a simple form such as minimize costs and increase population number, increase habitat availability.

Passive adaptive management – An adaptive management approach that reduces uncertainty by using a single design or operational plan to test hypotheses about system responses to a management action. The management hypotheses are modified and tested iteratively by adjusting the project design or operations, using built-in flexibility. Passive adaptive management reduces uncertainty over time, but it does not permit the kind of rigorous testing of the cause-and-effect relationship between management actions and environmental responses obtained with active adaptive management. In passive AM, management actions are focused on achieving resource objectives; development of knowledge through monitoring and assessment for improved decision making is secondary.

Performance measure – A physical, chemical, biological, or ecological measure used to assess progress towards achieving project/program goals and objectives. Performance measures can be used to help determine whether project response (e.g., slow, no, or decreasing performance trends) require adjustments through adaptive management to improve success.

Performance metric – A specific metric or quantitative indicator that is monitored and can be used to estimate and report consequences of management alternatives with respect to a particular objective.

Preferred alternative – The alternative that the agency believes would best fulfill its statutory mission and responsibilities, giving consideration to economic, environmental, technical, and other factors.

PrOACT decision-making model – An organized, structured decision-making approach to identifying and evaluating creative options and making choices in complex decision situations. PrOACT is a decision analysis approach used to provide analytical structure and rigor to values-based questions by clarifying the consequences of alternate solutions, including the impacts on multiple objectives. The unifying features of PrOACT analyses are that they involve: (1) clarifying the Problem to be solved, (2) listing Objectives to be considered (usually with associated performance metrics), (3) developing Alternative solutions to the problem as stated, (4) estimating the Consequences of each of the alternatives on each of the objectives in terms of the metrics (usually in the form of a consequence table of alternatives vs. objectives) and (5) explicitly evaluating the Trade-offs that are revealed to exist between the alternatives, usually in a discursive setting.

Problem – A question or concern that is being addressed in the decision-making process.

Program – Refers to USACE activities involving the implementation of multiple projects over time. Examples include the Comprehensive Everglades Restoration Program and the Missouri River Recovery Program.

Project Implementation Report (PIR) – Contains site-specific information, alternative designs and project features, the anticipated benefits of the project, and documentation for compliance with the National Environmental Policy Act (NEPA) disclosing the potential affects to the quality of the human environment from project implementation.

Project Management Business Process (PMBP) – USACE approach for the planning, development, and management of projects and programs.

Proxy metric – Type of performance metric. Generally, a proxy metric is an indirect metric used to represent a natural metric like population number (e.g., number of boat ramp days). Proxy criteria are those that correlate well with objectives that are otherwise difficult to measure or estimate.

Quantitative predictive models – Numerical models used to predict biological and ecological responses as a function of management or restoration actions.

Recovery plan – A document drafted by the USFWS or NMFS that serves as a guide for activities to be undertaken by Federal and state agencies or other entities in helping to recover and conserve species listed under the Endangered Species Act.

Risk – An uncertainty coupled with an adverse consequence, ideally expressed as the product of the two components, with uncertainty represented as a probability.

Risk endpoint – Measure of an undesirable outcome of a management or restoration action.

Robustness – The quality of being able to withstand stresses, pressures, or changes in procedure or circumstance and still maintain function and desired performance.

Scenario Analysis – A process used in Contingency Planning to identify potential circumstances and/or outcomes that might warrant a response, and exploring potential adjustments to management actions under particular scenarios.

Section 7 – The section of the Endangered Species Act that requires all Federal agencies, in "consultation" with the Service, to ensure that their actions are not likely to jeopardize the continued existence of listed species or result in destruction or adverse modification of critical habitat.

Selected alternative – The alternative identified in a Record of Decision that the agency intends to implement.

SMART Planning – A modernization to the Corps of Engineers' feasibility study process that improves efficiency and effectiveness in considering risk in making study decisions.

Stakeholder – One who is affected by a management action.

Structured Decision Making (SDM) – Organized approach to identifying and evaluating creative options and making choices in complex decision situations. It is used to inform difficult choices and to make them more transparent and efficient. PrOACT is a specific application of SDM to collaborative problem solving.

Sub-objectives – Sub-objectives are aspects of the fundamental objective described in more detail that need to be addressed to achieve the fundamental objective. They are intended to provide direction in the short term, provide objectives meaningful for AM, and focus efforts on the desired short-term outcomes while contributing to the fundamental objective.

Success – Achievement of goals and objectives.

Success criteria – A qualitative or (preferably) quantitative description of the conditions for which the parties agree that the objectives have been sufficiently met. Usually expressed in terms of the performance metrics.

Target – A specific value or range of performance metric that defines success. Targets can be quantitative values or overall trends (directional or trajectory).

Trade-offs (also Trade-off analysis) – A trade-off occurs when one alternative performs well on one metric but poorly on another relative to another alternative. Reasonable people may disagree about which is the best alternative because they value the two metrics differently; thus, value trade-offs involve making judgments about how much you would give up on one objective in order to achieve gains on another objective. By analyzing trade-offs, the PrOACT process tries to help find the alternative that (1) eliminates unnecessary trade-offs and (2) that people agree is the "best balance" of trade-offs possible.

Trigger – A form of decision criteria serving as a threshold or condition that, when met, initiates some action or decision.

Uncertainty – Circumstances in which information is deficient. Learning while doing under the adaptive management process provides a framework for reducing program uncertainties over time.

Variability – A measure of how much a set of conditions differs from the mean or median state.

Variance – The difference between a monitored value of a performance measure or risk endpoint and its corresponding value used in decision making.

Water Resources Development Acts (WRDA) – Public laws enacted by Congress to manage aspects of water resources such as navigation, flood risk management, coastal storm risk management, and environmental restoration. The most recent Water Resources Development provisions are included in Title I of the Water Infrastructure Improvements for the Nation Act (WIIN 2016; Public Law 114-322 2016), which amends relevant sections of previous WRDAs. Section 1161 of WRDA 2016 (Completion of Ecosystem Restoration Projects) amends Section 2039 of WRDA 2007 (Monitoring Ecosystem Restoration), for example. The USACE develops and maintains Implementation Guidance for Sections of these authorizations in coordination with the Assistant Secretary of the Army (Civil Works).

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Appendix A: Implementation Guidance Related to Monitoring and Adaptive Management

Implementation Guidance for Section 1161 of the Water Resources

Development Act of 2016 (WRDA 2016), Completion of Ecosystem Restoration Projects can be found at the following address.
http://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll5/id/1212

Appendix B: Example USACE ecosystem restoration programs and projects

The Adaptive Management Technical Guide references several USACE ecosystem restoration programs that have/are implementing adaptive management. This appendix provides a brief overview of those cited and concludes with a table of other projects or programs employing adaptive management. The reader is encouraged to obtain the listed references and visit the web sites for those of interest to further understand how adaptive management is being applied in support of ecosystem restoration efforts.

Table B1 lists the legislation, direction, policies, and guidance for several large-scale programs: CERP, the Louisiana Coastal Area (LCA) program, MRRP, the Columbia River Channel Improvement Project (CRCIP), the Great Lakes-International Adaptive Management Programs, and the Upper Mississippi River (UMR), and Illinois Waterway System.

These programs reflect varying sources of authority, funding levels, and requirements for adaptive management. A clear recognition of the need for adaptive management and a strong emphasis on using adaptive management to ensure program success is common to all of these efforts. Each program is described in detail following Table B1.

Table B1. Summary of major ecosystem restoration plans and relevance of adaptive management.

Program	Description
Comprehensive Everglades Restoration Plan (CERP)	WRDA 2000 included specific legislative direction and funding for an Adaptive Assessment and Monitoring Program, at a total cost of $100 million over 10 years. The WRDA language also called for promulgating programmatic regulations, which further specified implementation requirements for adaptive management by formalizing processes for developing goals, a monitoring program, and an adaptive management program. A RECOVER Office has been established to oversee efforts and formalize a monitoring and adaptive management approach and activities. Additional information is available at: http://www.evergladesplan.org/pm/program_docs/adaptive_mgmt.aspx.

Program	Description
Louisiana Coastal Assessment	Legislation in WRDA 2007 was not specific on including adaptive management, but it did include related items: a Science and Technology Component was authorized at $100 million, allowing for monitoring and collection of data, and demonstration projects were authorized at $100 million to test key applications for potential broader use. Adaptive management was specifically called for in the Chief's Report. An adaptive management program is under development. Additional information is available at http://www.lacoast.gov and http://www.lca.gov.
Missouri River Recovery Plan	Adaptive management has not been included in the Corps' authorizing legislation for this program. The Biological Opinion Reasonable and Prudent Measures recommend adaptive management to meet Endangered Species Act requirements. The record of decision for the Missouri River Master Water Control Manual also requests adaptive management. Currently, annual funding of several million dollars is directed to threatened and endangered species monitoring and completion of special studies. An adaptive management program is under development. Additional information is available at http://www.moriverrecovery.org.
Navigation and Ecosystem Sustainability Program	WRDA 2007 program authorization calls for the development of goals, performance measures, and performance indicators. The authorization also provides up to $10,420,000 per fiscal year in system long-term resource monitoring funding if not separately funded under a related program. Per implementation guidance, the 1-percent monitoring limit and prohibition on adaptive management does not apply, but monitoring and adaptive management must be accomplished within the framework and the costs must be authorized for those purposes as reflected in the feasibility report (total cost of about $300 million). An adaptive management program is under development. Additional information is available at http://www2.mvr.usace.army.mil/UMRS/NESP/default.cfm.
Great Lakes–International Adaptive Management Programs	Adaptive management is being considered for larger use on the Great Lakes. The International Joint Commission (IJC), which was established under the 1909 Boundary Waters Treaty between the United States and Canada, plays a vital role in the management of the waters of the Great Lakes. As such, the IJC has and continues to investigate the possibility of utilizing adaptive management practices in its Great Lakes regulatory operations. As part of its basic mission, USACE provides scientific, engineering, and management support to the IJC and directly participates in IJC studies and investigations. Through participation in the IJC's 2005 International Lake Ontario St. Lawrence River Study, International Upper Great Lakes Study (initiated in 2007 by the IJC), and ongoing investigations under the recently formed Lake Ontario Working Group, USACE staff continue to evaluate options for the regulation of Great Lakes levels and flows toward the development of a comprehensive adaptive management plan for the Great Lakes.

Program	Description
Columbia River Channel Improvement Project	Adaptive management was not included in the USACE authorizing legislation for this project. Adaptive management was part of the terms and conditions of the Biological Opinion Reasonable and Prudent Measures. The States of Oregon and Washington Water Quality and Coastal Zone Consistency Regulations also require adaptive management. An interagency adaptive management team developed an adaptive management plan in 2003 and continues to implement that plan. Additional information is available at https://www.nwp.usace.army.mil/issues/crcip/home.asp.

B.1 Comprehensive Everglades Restoration Plan (CERP)

The CERP vision states that “The overarching objective of the Plan is the restoration, preservation, and protection of the South Florida ecosystem while providing for other water-related needs of the region, including water supply and flood protection” (WRDA 2000). Success for the natural system will be to recover and sustain those essential hydrological and biological characteristics that both defined the original pre-drainage greater Everglades and made it unique among the world’s wetlands. These defining characteristics include the great extent of naturally interconnected and interrelated wetlands, sheet flow, extremely low levels of nutrients in freshwater wetlands, high levels of estuarine productivity, and great resilience of the plant community mosaics and abundance of many of the native wetland animals. CERP is being planned, implemented, assessed, and refined using the principles of adaptive management.

An adaptive management program will assess responses of the South Florida ecosystem to implementation of CERP. Adaptive management will determine if these responses match expectations, including the achievement of the expected performance levels and the interim targets. It is anticipated that adaptive management will help determine if the project operations, or the sequence and schedule of projects, should be modified to achieve the goals and purposes of CERP. CERP is intended to increase net benefits, improve cost effectiveness, and seek continuous improvement of the South Florida ecosystem based on new information resulting from changed or unforeseen circumstances, new scientific and technical information, and new or updated modeling.

The CERP web site is http://www.evergladesplan.org/. The CERP adaptive management web site is http://www.evergladesplan.org/pm/program_docs/adaptive_mgmt.aspx.

B.2 Louisiana Coastal Area (LCA)

The coastal wetlands of Louisiana are among the Nation's most productive and important natural assets in terms of habitat, wildlife diversity, storm protection, port commerce, and oil and natural gas production. Unfortunately, Louisiana coastal wetlands account for 90 percent of the total coastal marsh loss occurring in the United States. Hurricanes Katrina and Rita in 2005 accelerated the loss of Louisiana wetlands, with deleterious effects on the ecosystem. In 2007, Congress authorized the LCA program to address wetlands loss threats in this important region. The program includes authority for 15 ecosystem restoration projects, three programs (Beneficial Use of Dredged Materials, Science and Technology, and Demonstration Projects), investigations into modifications of existing structures, and additional large-scale and long-term studies.

The LCA program emphasizes the use of restoration strategies directed at achieving and sustaining a coastal ecosystem that can support and protect the environment, economy, and culture of southern Louisiana. This will be done by maximizing restoration strategies to reintroduce historic flows of water, nutrients, and sediment to wetlands. The LCA program recognizes the importance of integrating the best available science and technology into restoration strategies and the use of demonstration projects to reduce scientific uncertainties. WRDA 2007 language (Section 7007) specifically includes authorization for a Science and Technology (S&T) program and a Demonstration Project program. The purposes of the S&T program shall be to identify any uncertainty relating to the physical, chemical, geological, biological, and cultural baseline conditions in the coastal Louisiana ecosystem; to improve knowledge of the physical, chemical, geological, biological, and cultural baseline conditions in the coastal Louisiana ecosystem; to identify and develop technologies, models, and methods to carry out this subsection; and to advance and expedite the implementation of the comprehensive plan.

The WRDA authorization supports adaptive management by directing the Secretary of Defense to carry out the LCA program in accordance with the report to the Chief of Engineers dated 31 January 2005. Language from the Chief's report calls for feasibility studies to identify specific sites, scales, and adaptive management measures and to optimize features and outputs necessary to achieve the restoration objectives. The authorization identifies monitoring and adaptive management as critical elements of LCA projects. The 2004 LCA Ecosystem Restoration Study began to formulate a framework for adaptive management by identifying basic elements of adaptive management and defining the role of the S&T program in the implementation of an adaptive management plan/program.

The LCA web site is http://www.lca.gov/.

B.3 Missouri River Recovery Program (MRRP)

The MRRP seeks to create a sustainable ecosystem that supports populations of native species while providing for current social and economic values. The primary problem on the Missouri River is the alteration and degradation of riverine processes and habitat that has jeopardized the existence of the three Federally listed species: the interior least tern (endangered), the piping plover (threatened), and the pallid sturgeon (endangered). The MRRP includes areas along the Missouri River and is designed to improve these ecosystems and help the Federally listed species recover.

The major program components include habitat creation, flow modifications, science, and public involvement. The Integrated Science Program (ISP) of the recovery efforts is also implementing efforts targeted at long-term monitoring of the listed species, special studies to answer specific research questions, and ongoing development of a program-specific adaptive management program.

The MRRP has not been provided program-specific legislation or HQ USACE guidance specific to adaptive management, but the program has received direction on the incorporation and application of monitoring and adaptive management as part of the 2000 and 2003 Amended Biological Opinions under the Endangered Species Act. The use of adaptive management was also included in the Record of Decision (ROD) for the Missouri River Master Water Control Manual. The Master Manual ROD for the operation of the Missouri River Reservoirs discusses application of adaptive management. Decisions regarding actions proposed through the adaptive management process will meet the Corps' treaty and trust responsibilities to Native American Tribes represented in the Missouri River watershed and conform to all of the applicable requirements of Federal laws, including the National Environmental Policy Act, the Endangered Species Act, and the Flood Control Act of 1944.

The current situation on the Missouri River Basin highlights a two-fold need for adaptive management. For ongoing habitat creation activities and existing monitoring, adaptive management is being integrated with existing processes to ensure that management actions are driven by specific goals and objectives aimed at recovering species while meeting other authorized purposes. The second need is for adaptive management to inform and guide the development of the ongoing Missouri River Ecosystem Restoration Plan and EIS. Specifically, within the planning process, adaptive management will provide a structure for broader evaluation of actions to address the uncertainty. Within this process, adaptive management will influence the identification and implementation of the preferred alternative.

The MRRP web site is http://www.moriverrecovery.org/mrrp/f?p=136:1:1265668070615376. The MRRP adaptive management web site is http://www.moriverrecovery.org/mrrp/f?p=136:17:1265668070615376::NO:::.

B.4 Navigation and Ecosystem Sustainability Program (NESP)

The Upper Mississippi River System (UMRS) is a nationally significant transportation system and river ecosystem that provides economic, environmental, cultural, and spiritual benefits to the Nation. UMRS stakeholders are a diverse group, spread over 1,200 miles of river and a 190,000-square-mile basin, with interests ranging from transportation and agriculture to tourism, recreation, and conservation of natural resources. The many agencies charged with river management have individual missions and geographic areas of jurisdiction. The need for integrated system management of the UMRS has long been recognized. That integrated approach to management and restoration has taken the form of NESP. Congress authorized NESP in the Water Resources Development Act of 2007.

NESP is an ambitious 50-year effort based on recommendations from the Upper Mississippi River-Illinois Waterway Navigation Study (USACE 2004). NESP will be implemented under an incremental adaptive management approach that will focus on delivering meaningful navigation and restoration benefits as early as possible, scheduling projects to provide early benefits, and generating knowledge that can be applied to future projects. A reach planning notebook has been developed to standardize and guide adaptive management at multiple scales for NESP. Program language includes directives about sustainability and selecting projects that restore natural river processes.

These three large ecosystem management and restoration programs will be implemented using adaptive management as required by their authorizations. In practice, these large-scale comprehensive programs consist of many individual, yet interrelated and differently scaled projects. Adaptive management can be applied to each of these projects or combinations of projects.

The relevance of project-level application of adaptive management is reinforced by the fact that the only operational adaptive management program implemented thus far by the USACE is the application to the Columbia River Channel Improvement Project.

The NESP web site is http://www2.mvr.usace.army.mil/UMRS/NESP//. The NESP adaptive management web site is http://www2.mvr.usace.army.mil/UMRS/NESP/Documents/Water%20Level%20Management%20Report_Final%2028Oct2010.pdf.

B.5 Columbia River Channel Improvement Project (CRCIP)

The CRCIP Adaptive Environmental Management Program was initiated as part of the terms and conditions defined by the 2002 NMFS Biological Opinion concerning the Corps proposal for channel improvements on the Lower Columbia River and estuary. Similar requirements for adaptive management were promulgated by the FWS and the states of Washington and Oregon. In addition, issues concerning 401 coastal zone certification required by the states were incorporated into the CRCIP Adaptive Environmental Management Program. Representatives from Federal and state agencies constitute the CRCIP Adaptive Management Team (AMT), which has been chartered to develop and implement the program.

The CRCIP adaptive management approach differs from programs aimed at ecosystem restoration. While there are ecosystem restoration actions associated with this program, the main emphasis lies in assessing potential negative impacts (risks) posed by channel improvements on listed native salmonids and otherwise valued ecological resources (e.g., Dungeness crab, smelt, sturgeon). As a result, a passive adaptive management approach has been undertaken. The program has been designed to monitor the possible impacts posed by channel dredging, where the main driving force for dredging is to increase the opportunity for commercial navigation.

The general adaptive management approach is described in the CRCIP Adaptive Environmental Management Plan, which is publicly available. In addition, while the CRCIP AEM program is narrowly defined by the goals and objectives of the CRCIP, the AMT recognizes that this adaptive management program can contribute to the development of more comprehensive adaptive management programs for the Lower Columbia River and estuary. The continuing CRCIP AEM program has been in operation since 2003.

The CRCIP AEM program is in the process of transition from the project construction phase to a correspondingly appropriate adaptive management program for post-construction and operations and maintenance activities by 2013.

The CRCIP web site is http://www.nwp.usace.army.mil/environment/aem.asp.

B.6 Great Lakes–International adaptive management programs

Although less developed than the previous examples at this time, adaptive management is being considered for larger use on the Great Lakes. The International Joint Commission (IJC), which was established under the 1909 Boundary Waters Treaty between the United States and Canada, plays a vital role in the management of the waters of the Great Lakes. As such, the IJC has investigated, and continues to investigate, the possibility of using adaptive management practices in its Great Lakes regulatory operations.

As part of its basic mission, USACE provides scientific, engineering, and management support to the IJC and directly participates in IJC studies and investigations. Through participation in the IJC's 2005 International Lake Ontario St. Lawrence River Study, the International Upper Great Lakes Study (initiated in 2007 by the IJC), and ongoing investigations under the recently formed Lake Ontario Working Group, USACE staff continue to evaluate options for the regulation of Great Lakes levels and flows toward the development of a comprehensive adaptive management plan for the Great Lakes.

Table B2. Additional projects or programs employing adaptive management.

AM Program	Location	Context	Stage of AM	References
Trinity River Restoration Program	Trinity River, USA	Water management recovery of species of conservation concern (fish).	Implementation of AM plan ongoing, learning occurring.	US Fish and Wildlife Service and Hoopa Valley Tribe. 1999. Trinity River Flow Evaluation: Final report. USFWS and Hoopa Valley Tribe. http://www.trrp.net/ http://odp.trrp.net/FileDatabase/Documents/TRRP_2014_AnnRept1.pdf
Glen Canyon Dam Adaptive Management Program	Colorado River, USA	Large river water management for recovery of endangered species (fish).	Implementation of AM plan ongoing, learning occurring.	Melis T.S., Korman J. and C.J. Walters. Active adaptive management of the Colorado River ecosystem below Glen Canyon Dam, USA: using modeling and experimental design to resolve uncertainty in large-river management. In Proceedings of the International Conference on Reservoir Operation and River Management, Guangzhou, China 2005 Sep 18. http://www.usbr.gov/uc/rm/amp/

AM Program	Location	Context	Stage of AM	References
Platte River Recovery Implementati on Program	Platte River, USA	Large river water management for recovery of endangered species (birds).	Implementation of AM plan ongoing, learning occurring.	Smith, C. B. 2011. Adaptive management on the central Platte River—Science, engineering, and decision analysis to assist in recovery of four species. Journal of Environmental Management 92: 1414–1419. https://www.platteriverprogram.org/Pages/Default.aspx
Middle Rio Grande Endangered Species Collaborative Program	Middle Rio Grande River, USA	Large river water management for recovery of endangered species (fish).	Plan developed but not yet implemented.	Murray, C., Smith, C., and D. Marmorek. 2011. Middle Rio Grande endangered species Collaborative Program Adaptive Management plan Version 1. Prepared by ESSA Technologies Ltd. and Headwaters Corporation for the Middle Rio Grande Endangered Species Collaborative Program, Albuquerque. 108 p.
NA	Murray-Darling River, AUS	Water management to enhance the environmental benefits of altered flow regimes.	Implementation of AM plan complete, learning occurred and management adjusted.	Allan C, Watts RJ, Commens S, Ryder DS. 2009. Using adaptive management to meet multiple goals for flows along the Mitta Mitta River in southeastern Australia. In Adaptive Environmental Management 2009 (pp. 59-71). Springer Netherlands.

AM Program	Location	Context	Stage of AM	References
NA	North West Coast, AUS	Multi-species commercial trawl and trap fisheries management.	Implementation of AM plan complete, learning occurred and management adjusted.	Sainsbury, K. J. 1991. Application of an experimental management approach to management of a tropical multispecies fishery with highly uncertain dynamics. ICES Marine Science Symposia, 193: 301–320 Sainsbury, K. J., Campbell, R. A., Lindholm, R., and W. Whitelaw. 1997. Experimental management of an Australian multispecies fishery: examining the possibility of trawl-induced habitat modification. In Global Trends: Fisheries Management, pp. 107–112. Ed. by E. L. Pikitch, D. D. Huppert, and M. P. Sissenwine. American Fisheries Society Symposium 20. Bethesda, Maryland, USA.

AM Program	Location	Context	Stage of AM	References
Effects of Line Fishing (ELF) Program	Great Barrier Reef, AUS	Commercial and recreational fisheries management.	Implementation of AM plan complete, learning occurred and management adjusted.	Mapstone, B.D., R.A. Campbell and A.D.M. Smith. 1996. Design of experimental investigations of the effects of line and spear fishing on the Great Barrier Reef. CRC Reef Research Centre Technical Report No.7. Townsville: CRC Reef Research Centre. Davies C.R., Little L.R., Punt A.E., Smith A.D., Pantus F., Lou D.C., Williams A.J., Jones A., Ayling A.M., Russ G.R. The effects of line fishing on the Great Barrier Reef and evaluations of alternative potential management strategies. Townsville, Queensland, Australia: CRC Reef Research Centre; 2004. McCook LJ, Ayling T, Cappo M, Choat JH, Evans RD, De Freitas DM, Heupel M, Hughes TP, Jones GP, Mapstone B, Marsh H. 2010. Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. Proceedings of the National Academy of Sciences 107:18278-85.

Appendix C: Regulations Relevant to Adaptive Management Applications

Regulations relevant to adaptive management applications listed in Chapter 5 are discussed in more detail below, with references to previous chapters where appropriate.

C.1 National Environmental Policy Act

NEPA compliance and timely execution can be critical to a successful field adaptive management application. The key to successful integration of NEPA and adaptive management is a well-planned and thorough up-front consideration of the range of potential consequences and the subsequent management actions within the scope of NEPA. Expanding the NEPA process to include adaptive management principles requires the integration of learning-based strategies into the existing framework of NEPA (Williams et al. 2007).

C.2 Federal Advisory Committee Act

Stakeholder engagement is a necessary component of any successful adaptive management process. However, one legal constraint to consider for non-Federal stakeholder involvement is compliance with the FACA (5 U.S.C. § 552 [1994]). Under FACA, Federal agencies may not receive advice from a group that the agency has established or that it utilizes (i.e., manages or controls) unless the agency complies with the provisions of FACA. The FACA is a procedural statute that requires certain actions to set up and operate a committee or similar group to provide group-based (rather than individual) advice to Federal officials.

To meet FACA exemption, teams can follow FACA guidance from the FACA web page at http://www.gsa.gov/portal/content/104514 and encourage stakeholder engagement throughout the adaptive management process in the following ways:

- Include all interested stakeholders in team meeting distribution lists.
- Post all meeting dates, agenda information, and working documents on a publicly available web site.
- Allow time for public comment after each important agenda topic.

- Hold face-to-face meetings with stakeholder groups to obtain their input and understand changing societal values.

C.3 The Clean Water Act

Adaptive management plans must adhere to all applicable regulatory permitting activities (e.g., state water quality and wetland mitigation permits). An adaptive management process that is clearly explained and supported by staff within the regulatory authorities may aid the permit process, implementation, compliance, and ability to adjust. Sec. 2036 of WRDA 2007 also indicates that any USACE water resource project report must contain specific recommendations with a specific plan to mitigate fish and wildlife losses if there are adverse impacts. Mitigation plan components include:

- Monitoring until successful,
- Criteria for determining ecological success,
- A description of available lands for mitigation and the basis for the determination of availability,
- The development of contingency plans (i.e., adaptive management),
- Identification of the entity responsible for monitoring, and
- Establishment of a consultation process with appropriate Federal and state agencies in determining the success of mitigation.

AMT decisions need to be consistent with any Section 401 or 402 CWA certifications that are issued for the project. Clearly identifying risk endpoints, uncertainty, monitoring and assessment, decision criteria, and contingency options to improve performance with respect to risk endpoints can help give assurances to regulatory authorities in order to issue permits.

C.4 The Endangered Species Act

The Endangered Species Act of 1973 (ESA) provides a broad, comprehensive approach to the conservation of threatened and endangered species. By Congressional direction, the ESA is administered by the U.S. Fish and Wildlife Service (FWS) and NOAA Fisheries (National Marine Fisheries Service). In general, the FWS deals with terrestrial and freshwater species, while NOAA Fisheries deals with anadromous fish and marine species.

In cases involving large-scale Federal programs, consultation is appropriate at both a broad programmatic level and at the level of individual projects or actions that may affect listed species. Careful consideration of effects and alternatives can set the stage (for example, through adoption of best management practices or design standards) for expedited consultation on later individual actions (Williams et al. 2009).

The Council on Environmental Quality's *Handbook for Integrating NEPA and Adaptive Management* (CEQ 2007) provides case studies to demonstrate various approaches to integrating adaptive management into NEPA and can be found at the following web site: http://www.whitehouse.gov/administration/eop/ceq/. The CEQ case studies demonstrate that an adaptive management model with these features works well on a wide variety of resource management projects and project scales.

Appendix D: Support Organizations and Capabilities

D.1 Technical support within the USACE

Both institutionally, and as a field of practice as a whole, adaptive management as applied to ecosystem management and restoration is relatively new and requires time, training, and resources to evolve to a standard set of practices. The USACE will likely need additional research and guidance as the science advances, with the further likelihood of evolving policy to refine the approach and application.

The USACE has access to professional scientific, technical, and management capabilities within its organization to help bridge scientific and technical gaps as the fields associated with adaptive management become more established. Involving USACE individuals and collective resources with relevant skills and experience can increase the likelihood for successful application of adaptive management. The U.S. Army Engineer Research and Development Center (ERDC), Cooperative Ecosystem Studies Units (CESU) National Network, and professional facilitators should be considered for technical support and collaboration during the planning and implementation of adaptive management.

In August 2003, the Director of Civil Works designated five National Planning Centers of Expertise (PCXes) to enhance the Corps' planning capability. Currently, PCXes have been established for Coastal Storm Risk Management; Flood Risk Management; Inland Navigation; Deep Draft Navigation; Small Boat Harbors; Ecosystem Restoration; and Water Management and Reallocation. The role of the PCXes is to focus on plan formulation and the complex technical evaluation associated with formulation, including model certification, training and technical assistance, policy support and peer review. Each PCX is led by a team of experts in plan formulation, environmental sciences, economics, and related technical disciplines.

USACE PLANNING & CENTERS OF EXPERTISE LINKS

USACE PLANNING URL:
- https://www.usace.army.mil/Missions/Civil-Works/Project-Planning/

PLANNING COMMUNITY TOOLBOX-CENTERS OF EXPERTISE URL:
- https://planning.erdc.dren.mil/toolbox/people.cfm?Id=0&Option=Planning%20Centers%20of%20Expertise

FLOOD RISK MANAGEMENT URL:
- https://www.iwr.usace.army.mil/Missions/Flood-Risk-Management/Flood-Risk-Management-Program/
- https://cops.usace.army.mil/sites/PLAN/pcx/FRMPCX/

ECOSYSTEM RESTORATION URL:
- https://www.erdc.usace.army.mil/Missions/Water-Resources/
- https://cops.usace.army.mil/sites/PLAN/pcx/ecorest/

INLAND NAVIGATION URL:
- https://www.lrd.usace.army.mil/Missions/Civil-Works/Navigation/Inland-Waterways-2/

DEEP DRAFT NAVIGATION AND SMALL BOAT HARBOR URL:
- https://www.sam.usace.army.mil/Missions/National-Centers-in-Mobile/Deep-Draft-Navigation/

COASTAL STORM RISK URL:
- https://www.nad.usace.army.mil/About/National-Centers-of-Expertise/Coastal-Storm-Risk-Management-Planning/

WATER MANAGEMENT AND REALLOCATION URL:
- https://www.swd.usace.army.mil/About/Water-Management-Center-of-Expertise/

D.2 Engineer Research and Development Center

The U.S. Army Engineer Research and Development Center (ERDC) is one of the most diverse engineering and scientific research organizations in the world. The ERDC conducts research and development (R&D) in support of the Soldier, military installations, and the Corps of Engineers' civil works mission, as well as for other Federal agencies, state, and municipal authorities, and U.S. industry through innovative work agreements. Their mission is to provide science, technology, and expertise in engineering and environmental sciences in support of our Armed Forces and the Nation to make the world safer and better.

The ERDC synergistically addresses R&D in four major areas: Military Engineering; Geospatial Research and Engineering; Environmental Quality/Installations; and Civil Works/Water Resources through the capabilities of seven laboratories: the Construction Engineering Research Laboratory in Champaign, IL; the Cold Regions Research and Engineering

Laboratory in Hanover, NH; the Topographic Engineering Center in Alexandria, VA; and the Coastal and Hydraulics, Geotechnical and Structures, Environmental, and Information Technology laboratories in Vicksburg, MS. ERDC has a staff of approximately 2,300 Federal employees and supporting contractors.

ERDC scientists and engineers provide a wealth of experience and expertise, and they can assist the Districts as:

- Problem solvers: ERDC provides customers with interdisciplinary technical expertise and institutional knowledge. Because they are part of the USACE and Army teams, they have detailed understanding of District, Division, and installation responsibilities and mandates.
- Technology advisors: ERDC knows the state of the science and helps customers make the right technology choices. ERDC scientists and engineers have been on the leading edge of wide-ranging research and development activities addressing a multitude of water resources and environmental issues.
- Technology developers: ERDC develops innovative technology or modifies existing technology to meet customer needs. The ERDC develops cutting-edge tools, models, and supporting guidance to solve a wide range of water resource and environmental problems.
- Business development partners: ERDC gives customers a competitive advantage via technology and access to ERDC personnel and its unique partnering authorities. These capabilities provide rapid access to critical science and technology expertise wherever it resides, in other Federal labs, nongovernmental organizations, academia, and the private sector.
- ERDC has employees who are trained in adaptive management facilitation. More information can be found at the following web site: http://www.erdc.usace.army.mil/.

D.3 Cooperative Ecosystems Studies Unit

The Cooperative Ecosystem Studies Units (CESU) National Network is a network of cooperative units established to provide research, technical assistance, and education to resource and environmental managers. CESU emphasizes that multiple Federal agencies and universities are among the partners in this program. Ecosystem studies involve the biological, physical, social, and cultural sciences needed to address natural and cultural resource issues and interdisciplinary problem solving at multiple scales and in an ecosystem context.

The basic relationship between the Federal government and the scientific community is shifting. The fiscal limits imposed by the Federal budget are long term, and support of science throughout the government will continue to be constrained. There is increased demand for usable knowledge and research applied to the national interest. Federal agencies must husband their science resources in creative ways that limit cost and magnify value to managers, scientists, Congress, and the public. Universities, private research institutions, and the broader scientific community face similar pressures and must respond and adapt to this new environment for science.

The CESU Network provides opportunities for Federal agencies, nongovernmental organizations and universities to collaborate on research, technical assistance, and education, which can help provide information to address key uncertainties related to ecosystem restoration projects. Any Corps office, with the appropriate authority, can participate in CESU activities and have work performed under a cooperative agreement by the four CESUs of which the Corps is a member. The Engineer Research and Development Center has joined several CESUs on behalf of the Corps of Engineers Civil Works Program under the authority of Title 10 U.S.C. 2358 (http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=browse_usc&docid=Cite:+10USC2358). The process for USACE offices to initiate work with CESUs is found under the “policy and procedures” button at the following URL: http://corpslakes.usace.army.mil/partners/cesu/cesu.cfm.

D.4 Facilitation for adaptive management

Facilitation is often used by the Corps to assist in implementing an adaptive management plan. A trained facilitator’s services can be used in many ways, but the most important aspect that they can provide is their neutrality during the adaptive management process. Several resources are available to assist with adaptive management programs. Some of the resources are free, and others are available as contract services. Below is brief list of available resources at the time publication of this guidance:

D.5 National Resource Management Gateway

The National Resource Management Gateway has a database that provides contact information for individuals within USACE who have experience in facilitation and are willing to provide that service for others.

D.6 Environmental Conflict Resolution

The Collaboration and Public Participation Center of Expertise (CPCX) develops and maintains collaborative tools to assist the USACE in preserving the public interest and managing stakeholder interactions by anticipating, preventing and handling water-related conflicts and decision making. With approaches such as alternative conflict resolution (ACR), the CPCX seeks to prevent or minimize conflict by optimizing participation. Additional information can be found at the Center's website: https://www.iwr.usace.army.mil/About/Technical-Centers/CPCX-Conflict-Resolution-Public-Participation/.

The U.S. Institute for Environmental Conflict Resolution (ECR) was founded in 1998 as part of the Morris K. Udall and Stewart L. Udall Foundation. ECR is an independent and impartial Federal program that assists Federal agencies in resolving environmental conflicts. Additional information on ECR can be found on their web site: http://www.ecr.gov.

Appendix E: Adaptive management considerations for program and project implementation

This chapter addresses considerations for the implementation phase of adaptive management not previously covered. Potential challenges to adaptive management are introduced, suggestions for surmounting these challenges are offered, and descriptions of additional capabilities and resources to support adaptive management efforts are provided.

Implementing adaptive management is simply putting the plan into action. In so doing, it should be remembered that a fundamental tenet of adaptive management is that the entire process is adaptable. If the AMT determines that specific aspects of monitoring, assessment, and decision making are not meeting needs, those aspects can be adjusted. The adaptive management plan can be correspondingly revised and the process of implementation continued until the goals and objectives are achieved.

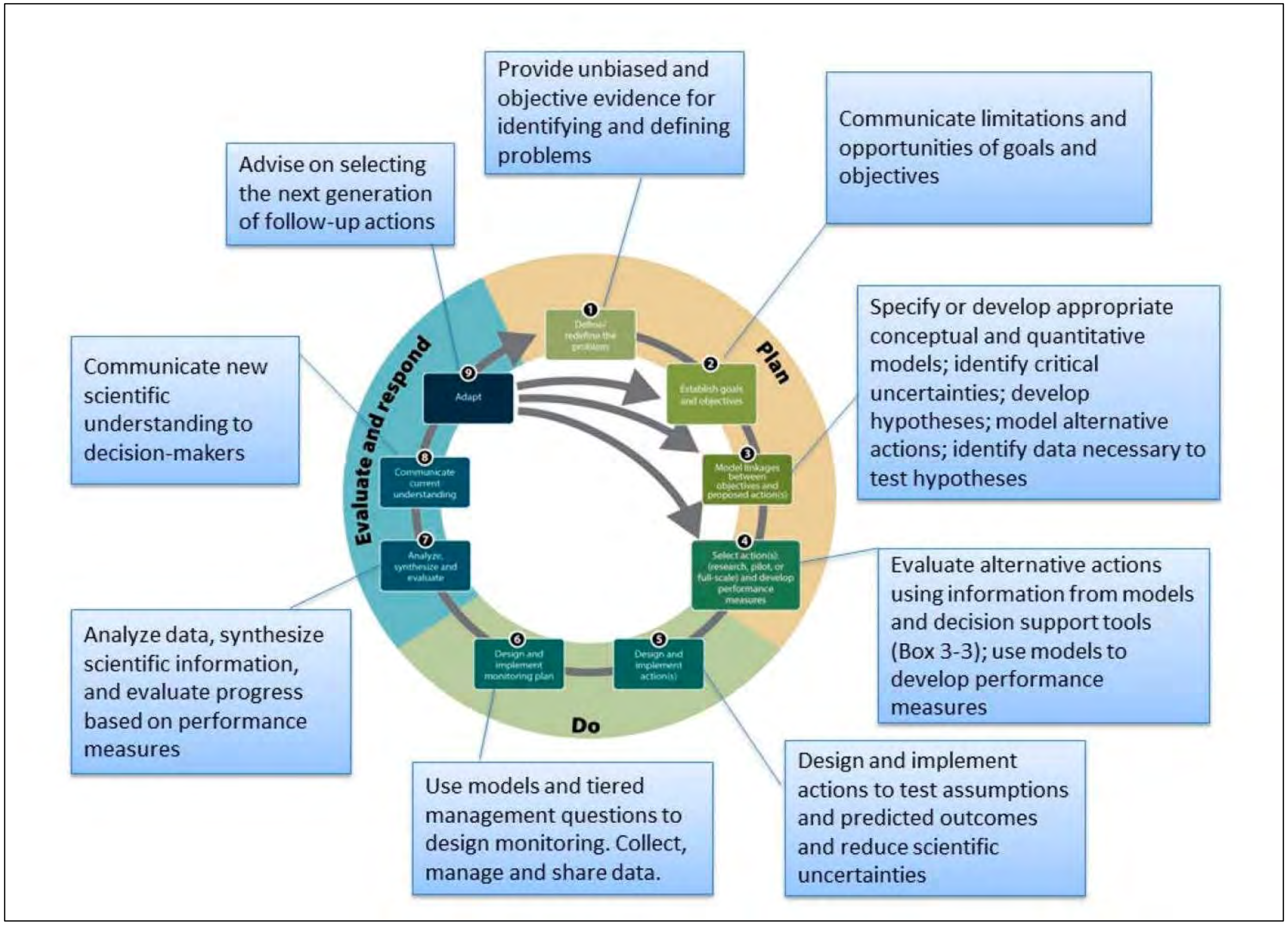
E.1 Executing the adaptive management cycle

Implementation of adaptive management nominally involves monitoring, assessment, and at least one decision. The simplest circumstance involves a single project where monitoring and assessment confirm that success has been achieved (or a reliable trajectory toward success is established) and the decision consists of a declaration of success and cessation of federal funding for further monitoring or adaptive management. The project is turned over to the sponsor for operation and maintenance (if required).

More commonly, ecosystem restoration projects will demonstrate a trajectory toward success, but success will not be assured for some time. This may be due to lingering uncertainties, long response times for ecosystems, or myriad factors. If the 10-year time limit for federal funding of monitoring passes before success can be established, the sponsor should assume responsibility for further monitoring and adaptive management.

Planning is an ongoing (if intermittent) part of adaptive management implementation. There are many types of planning decisions, but one of the most common occurs when a problem or opportunity is identified, an analysis is undertaken to evaluate alternative adjustments to management, and a preferred alternative selected. These steps often benefit from a structured decision making process, described below. Other considerations for implementing adaptive management are shown in Figure E1.

Figure E1. Considerations for implementing adaptive management.



E.1.1 Structured decision making under adaptive management

Adaptive management is primarily a response to planning situations that contain decision-relevant uncertainties, and the planning steps are often revisited as part of the adaptive management implementation. There are many types of planning decisions, but one of the most common occurs when a problem or opportunity is identified, an analysis is undertaken to evaluate alternative solutions, and a preferred alternative selected. These steps often lead to the development of a consequence table of the type shown in Table E1, which is reproduced from the USACE Planning Primer (Orth and Yoe 1997).

Table E1. Illustrative Consequence Table Source (USACE Planning Primer).

	PLAN A	PLAN B	PLAN C
ECONOMIC EFFECTS	+$ 30	-$ 5	+$ 10
ENVIRONMENTAL EFFECTS	-100 acres	+ 70 acres	+ 200 acres
SOCIAL EFFECTS	moderate growth	low growth	moderate growth
OTHER EFFECTS	+	- -	+ + +

In the present context, there are several features of this table that are worth considering:

1. The rows in the table contain *predicted* outcomes of effects across a broad range of objectives and constraints for various alternatives (columns). The table is not just limited to the primary objective of the project (which in the context of habitat restoration may often be beneficial environmental effects, rather than the negative impacts implied in this example). Rather, it is the *trade-off* between benefits to objectives and the impacts on constraints that informs rational management decision making.

   Looking at some of the trade-offs shown in this table, Plan A has the best economic benefit, but causes the loss of 100 acres of some environmental resource. Plan B creates 70 acres of something, but at a direct cost of $5 and with other negative social and economic impacts. Plan C generates $10, creates the most acres, has no *negative social effects, and has other benefits. Plan C can be said to dominate Plan B; that is, if we agree that the table represents the spectrum of things that matter, and if we agree that the estimates are accurate enough for the decision context, then there is no rational reason to select Plan B since Plan C beats it in every respect. One could rationally select Plan A over Plan C, however, but only by judging the importance of (30 – 10 =) $20 of economic effects to be more important than the net 300 acres of environmental difference and whatever significance is captured in the difference between their 'other' effects. Suppose, for the sake of discussion, that this is not the case, and the decision-maker expresses a preference for Plan C over Plan A based on an evaluation of this trade-off.*

2. There will be *uncertainty in the estimates of the consequences* (i.e. in the values that are portrayed in the table for both objectives and constraints).
3. All predicted estimates are uncertain to some degree, but only some could make the difference between preferring one plan over another, i.e. because they are decision-relevant uncertainties.

For example, suppose Table 9 was modified to incorporate communication of two large uncertainties (Table E2).

Table E2. Modified Illustrative Consequence Table; differences from Table 9 shown in bold.

	PLAN A	PLAN B	PLAN C
ECONOMIC EFFECTS	+$ 30	-$ 5	+$ 10
ENVIRONMENTAL EFFECTS	**-100 to +200** acres	**+ 70 to +150** acres	+ 200 acres
SOCIAL EFFECTS	moderate growth	low growth	moderate growth
OTHER EFFECTS	+	- -	+ + +

The uncertainty presented in Plan B's environmental effects may be relatively large, but it is <u>*not decision-relevant*</u>*, because Plan C still dominates Plan B regardless of this value as long as the true value remains within this range estimated range. However, the uncertainty in environmental performance for Plan A could create a very real* *conundrum for the decision maker. If the actual value were at one end of this range, at -100 acres, we have previously stated that the decision maker would choose Plan C. But if the value were at the other end of the range of uncertainty, at +200 acres, then the decision maker has a very different trade-off to consider. This that case, she must decide if the difference in 'other effects' is worth the $20 difference in economic effects. Suppose, again for sake of discussion, that if Plan A would actually result in +200 acres, then that would be the preferred choice in the decision-maker's opinion.*

In some (but not all) decision contexts, it may be possible to avoid the irreversible commitment of resources to one alternative over another until greater clarity is brought to such decision-critical uncertainties. Examples include:

- Repeated decisions (e.g. dam flow releases, habitat construction programs)
- Decisions for which experiments to reduce uncertainty could be undertaken in advance of an irreversible commitment of resources (e.g. major infrastructure projects)

Adaptive management, then, may often (though not exclusively) be used to fill such gaps. In these cases, adaptive management *is in service of* planning decisions, rather than something that is different to or independent of planning decisions.

A disciplined approach to structuring decisions to identify *decision-critical* uncertainties may take a little additional effort, but as the previous example showed, could help avoid unnecessary expenditures on investigating irrelevant uncertainties and, more importantly, help decision-makers make more responsive, and ultimately better, decisions.

The USACE six-step planning process is a rational decision model rooted in the decision sciences. It is very closely related to a planning approach known as PrOACT, which itself a subset of a collection of tools and approaches of decision analysis sometimes collectively referred to as structured decision making (SDM). Since adaptive management is increasingly referred to as being designed to function within the context of a structured decision making (SDM) process (e.g. Williams et al. 2009), a short discussion on the similarities between the six-step process and these others may be valuable.

PrOACT is an acronym for a decision process with the following steps (e.g. Hammond et al. 1999):

- Problem Definition
- Objectives
- Alternatives
- Consequences
- Trade-Offs

These steps can readily be mapped to the USACE planning steps, and the two processes can be considered functionally equivalent with a small number of important differences, some of which include:

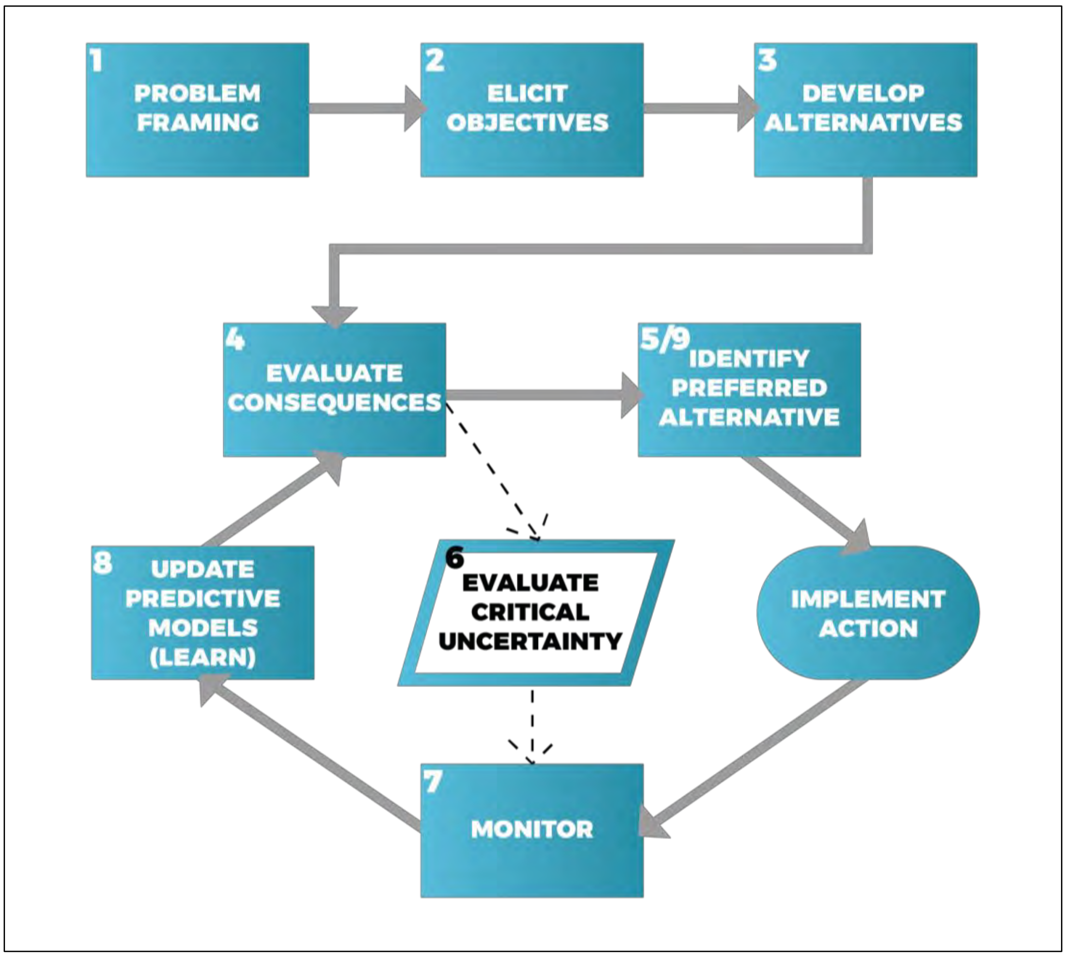
- The USACE six-step process distinguishes between objectives and constraints ('do good, don't do bad'). In PrOACT, these are both simply considered objectives – some with positive directionality (more is good) and some with negative directionality (more is bad).
- In the USACE six-step process, objectives can sometimes be articulated as targets, e.g. "create 1,000 acres of habitat." In PrOACT, objectives never have associated targets; instead the 'things we care about' are stated as simple, directionally unambiguous verb-noun combinations, such as "maximize habitat," "minimize costs" etc. If minimum thresholds of performance are mandatory, these are stated as requirements of the decision context in the first step and used to constrain the definition of viable alternatives. The reason for this is that targets can unnecessarily constrain (why stop at 1,000 acres when 1,200 might be just as easy?) and they also embed trade-offs that might not be clear (perhaps 1,000 acres costs $x, but 990 acres costs ten times less).
- In the USACE six-step process, the criteria used to evaluate the alternatives are developed at a relatively late stage in the process, as part of Step 4. In the PrOACT process, objectives are closely tied to 'performance measures' and both are addressed sequentially earlier, before developing alternatives (although iteration makes differences between the two processes largely ones of philosophy and emphasis rather than practical difference). The reason for this is that through 'value-focused thinking' (Keeney 1998), objectives can be used to create

imaginative alternatives, by challenging planners to design new alternatives that push as hard as possible on each objective – 'how could we create an alternative that maximizes habitat creation?' 'how could we create one that minimizes cost?' etc.

- In the PrOACT process, a much greater emphasis is placed on the use of consequence tables to articulate and communicate trade-offs for discussion purposes particularly with stakeholders, as illustrated in the earlier discussion and as discussed at length in Gregory et al (2012).

The link between a typical PrOACT process and adaptive management is captured effectively in the schematic Figure E2 (Runge 2011).

Figure E2. PrOACT and Adaptive Management (Source: Runge 2011).



The first five steps in this figure are the PrOACT process. Having identified a preliminary preferred alternative, the action is implemented and an adaptive management cycle is initiated to investigate decision-critical uncertainties.

Learning occurs at different rates in different decision contexts, depending on ecological and institutional considerations. For some decisions, responses to treatments occur rapidly and key uncertainties may be reduced in just a few seasons or years. In such cases the learning is used to update models and new management actions may be selected and implemented without reconvening a full decision process. This fast-learning cycle has been termed “single loop learning” (Conroy and Peterson 2013). However, in many resource management contexts, the time required to reduce key ecological uncertainties is measured in decades rather than years. In such cases, by the time models can be updated, many things will have changed. In addition to new information about predictive modeling assumptions, there may be new legal or policy constraints, new stakeholders that need to be involved, new management objectives arising from new stressors or changes in social values, and new management alternatives that need to be considered. In such cases, a whole new cycle of decision making is triggered. This slower learning cycle is sometimes termed “double-loop learning.”

E.1.2 Productive stakeholder participation

Meaningful stakeholder participation increases the effectiveness and probable success of adaptive management. Ideally, stakeholders are engaged in every aspect of the program/project adaptive management implementation process, from initial problem formulation to identification of objectives and design of monitoring and assessment. EP 1105-2-57 provides guidance on stakeholder engagement (USACE 2019).

If key stakeholders are not initially or appropriately engaged, program/project managers may need to coordinate with agency outreach specialists to re-engage stakeholders and determine what issues might be limiting involvement with PDT and/or technical team efforts. This outreach effort may require additional information sharing to address any gaps and clearly identify each stakeholder’s role in contributing to adaptive management decision making. Effective stakeholder engagement also requires a commitment by program/project implementing agencies to consider stakeholder views and respond with reasons when agency decisions appear inconsistent with stakeholders’ perspectives.

Public involvement in adaptive management should begin as early in the planning process as possible. Engaging the public early in the process allows them to become vested in the project and project decisions.

Traditional USACE planning usually involves stakeholders early in the public review of either an Environmental Assessment or an Environmental Impact Statement or at public meetings where testimony is taken regarding the draft environmental documents. There are additional pathways for public stakeholder engagement in the adaptive management process, including open or facilitated workshops, task force or other public meetings, committee assignments, or written comments on draft environmental documents, typically as part of official public comment periods. Some Congressional authorizations may specify more direct roles for sponsors and stakeholders.

Identifying additional stakeholders for a project will depend largely on characteristics of the project and consideration of Federal Advisory Committee Act (FACA) requirements (see Appendix B for additional detail). For example, small noncontroversial projects can involve a small group of stakeholders from state and Federal agencies who meet periodically to review and concur on project goals and objectives. For large projects, such as the CRCIP and CERP (see Appendix B), FACA may become a consideration in constituting an adaptive management team. USACE Districts should check with their Office of Counsel to help determine how the team should be set up and how to comply with FACA requirements.

E.1.3 Demonstrating success in monitoring and achieving goals and objectives

Clearly stated program and project goals and objectives are crucial in decision making, performance evaluation, monitoring, assessment, and adaptive learning. Management objectives are particularly important in decision making, especially where project actions are based on predicted system responses that best correspond to overall program management objectives. In addition, clearly defined objectives guide comparisons of actual responses with modeled/predicted responses to facilitate learning and assess performance.

The following criteria can be used by USACE program and project managers to assess the success of adaptive management with specific reference to achievement of goals and objectives in specific applications:

- Monitoring and assessment have led to modifications in management practices,

- Success in achieving goals and objectives has been demonstrated.

Documenting that management practices as part of a project have been adjusted based on improved understanding – one of the important objects of project monitoring that leads to effective evaluation and provides evidence to support learning and decision making – will be evident based on answers to the following questions:

- Are monitoring and assessment efforts being focused to determine how and whether projects and the program are meeting project goals and objectives?
- Are uncertainties being addressed and conceptual models being used and refined?
- Are assessments able to indicate performance status and a need to adjust?
- Is project performance information being conveyed to managers and are options being developed and/or analyzed through a collaborative process to adjust project/program implementation if necessary?
- Are recommended modifications to project/program plans or operations being implemented?
- Has adaptive management increased the effectiveness of the project or program in achieving the stated goals and objectives?
- Have stakeholders demonstrated an increased understanding of technical issues and/or modified their positions on issues? Have the agencies?
- Have lessons learned been conveyed to other USACE districts, agencies, or practitioners so as to improve ecosystem restoration or fish and wildlife mitigation on other systems?

If the responses to these questions are largely positive, then the adaptive management process is working, new knowledge is being gained and applied, and USACE programs, projects, and operations are being adjusted (if or as needed) to more efficiently meet goals and objectives.

It is important to recognize that management objectives may change as learning accumulates during implementation of the process. Refinement of objectives as understanding accumulates and stakeholder perspectives change is fundamental to the adaptive management process. Periodic reassessment of objectives is a necessary part of the iterative adaptive management and learning cycle.

E.1.4 Demonstration of adaptive management principles

Specific applications of adaptive management will be effective to the extent to which the principles outlined in Chapter 1 are followed. Productive applications generally share the following characteristics:

- Key uncertainties have been identified and are being reduced through rigorous monitoring, assessment, decision making, and technical support as needed;
- Current and updated scientific understanding provides the basis for all aspects of the adaptive management process;
- Program and project plans and designs are sufficiently flexible to permit structural or operational modifications suggested by adaptive management to meet goals and objectives;
- Established roles and responsibilities are followed in gathering scientific information (e.g., monitoring, research), assessing performance of management measures and success progress, and communicating project achievements (e.g., evaluation reports) to decision makers;
- Decisions to continue or modify project implementation derive from a clearly defined decision-making process with well-defined decision criteria; and,
- Responsible agencies are willing and able to execute recommended adaptive management actions to improve progress towards stated goals and objectives.

E.2 Data management, reporting, and communications

E.2.1 Data management

Data management includes the collation, storage/retrieval, analysis, summarization, and communication of monitoring results and related information (e.g., published information, model results) used in support of adaptive management. This is typically a task of the AMT, and individuals with responsibility for data management activities (data managers) should be identified during the development phase of adaptive management.

The information base provided by the data management system includes existing data and information that were used in the development phase, the results of monitoring, modeling and analysis results, and additional scientific and technical information that accumulate during the course of the adaptive management process. The information base will importantly serve as an archive of the process upon completion of adaptive management. A growing archive of adaptive management programs will serve as a valuable resource in future USACE planning and applications.

Data management for small or uncomplicated projects might be addressed with a simple collection of data spreadsheets that is periodically updated and analyzed by one or two personnel following scheduled monitoring activities. Larger-scale, complex adaptive management processes may require correspondingly more sophisticated relational databases and complex analysis. This may necessitate engagement of support beyond the AMT.

The data management plan should identify the computing hardware and any specialized or custom software used in data management for an adaptive management program. The AMT should collaborate with the data managers to identify the types of data and information to be included in the data management system, establish convenient formats for storing and retrieving data, and guarantee the preservation of the data (i.e., backup versions, electronic and/or hard copy). The data management plan should include preservation of the results of all analyses used in performing assessments for an adaptive management program. Programs used to perform the analyses should be verified, documented, and preserved (archived) within the data management system.

E.2.2 SMART Planning Risk Register and example

The Risk Register is an important risk management tool for USACE. The RR is a log (spreadsheet) in which one records the relevant details of the risks that could result from actions taken or not taken during each stage of a project's life cycle (Table E3). RR includes outlining the uncertainty of risk. Adaptive management may be an appropriate risk mitigation strategy associated with achieving actual project performance.

Table E3. Risk Register Example - Loxahatchee River Watershed Restoration Project.

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
7/26/2018	ENV-3	Redesign		TSP.	Environment	Using Lake Okeechobee water from L-8 basin	Water quality of water in the forested areas of the L-8 basin is good. Water quality in the L-8 Canal is good when Lake Okeechobee is not releasing water to the canal. Water quality is poor (high nutrients) when Lake Okeechobee is releasing. There is a water quality compliance risk.	Flowing nutrients through Grassy Waters Preserve (GWP) and causing aquatic nuisance vegetation. Could affect state water quality certification resulting in an unimplementable project.	H
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Issue identified in prior planning effort and likely to occur with Lake Okeechobee water supply flows routing through GWP.	L	TSP does not directly use water from L-8 Canal. Lake Okeechobee water supply releases are still likely to occur during the dry season.	L	M	During planning, minimize the cascading effects of water quality issues by incorporating flexible features in the design and operations., Evaluate potential water quality effects to identify which alternatives may have less risk., Develop operational measures/alternatives to reduce risk., Consider storage with sufficient residence time to reduce nutrient concentrations before release..	None	TSP does not rely on Lake Okeechobee water; only minimal Lake Okeechobee water would be used. Water Quality tool shows that TSP does not reduce water quality in receiving waters.	At Alternatives Milestone, this risk was scored High (H, M). For TSP milestone, risk reduced to Medium (H, L).

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
7/26/2018	EHH-4	Analytical Error		TSP.	Eng. - H&H	Use existing model (LECSR-NP) for plan evaluation	Calibration may be difficult to achieve. May not be able to quantify all hydrological changes due to project alternatives in different parts of the study area	A. High uncertainty of ecosystem benefits. B. Level of resolution/assumptions of existing (H&H) models/detailed modeling information related to hydraulic design may not be available for all management measures. C. Loss of project support with respect to flood damage risk reduction and water support analysis. D. Schedule and cost increase to do additional detailed modeling earlier in the planning process.	H
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Based on past planning experience on this project, stakeholders were very interested in flood control and water supply and wanted detail early on in the plan formulation process.	L	Based on prior planning experience with the Loxahatchee project this is likely to occur.	L	M	Incorporate new LIDAR (from Martin County) into the model., Early and clear coordination of project scope and level analysis at each stage of planning with all stakeholders., Clear decision-management plan on when and how much modeling/detailed design analysis will occur., Move from less detail to more detail during PED., During planning, create inset model that uses approved code and good calibration and verification for aquifer storage and recovery..	None	Intensive collaboration among modelers (significant time and budget) resulted in significant improvement in LECsR model performance. Added LIDAR data. Modeled existing conditions are very close to existing conditions data. Model outputs are suitable to evaluate alternatives and identify TSP.	As a result of the improved model performance, the Risk Rating of this action for the TSP Milestone was reduced from High (H/M) to Medium (M/M).

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43040	PFM-15	Analytical Error		TSP.	Plan Formulation	Climate Change	Accurately predicting climate change effects on rainfall and hydrology, and saltwater intrusion in the aquifer.	Under or over-estimating the amount of water available for the environment, and not achieving actual restoration benefits during implementation.	M
	Evidence for Consequence rating	**Likelihood rating**	**Evidence for likelihood rating**	**Uncertainty rating**	**Risk Rating**	**Risk Management Options**	**Affected Study Component**	**Outcome**	**Notes**
	Recent years (2000-2014) have seen a higher frequency of dry years, and extreme rainfall events.	M	Recent years (2000-2014) have seen a higher frequency of dry years, and extreme rainfall events.	L	M	Design structures that may alleviate or have the ability to integrate greater operational flexibility., Utilize the POR analysis for extreme events (dry and wet years) to describe impacts on TSP if those conditions become more frequent..	None		no cost or time impacts. multiple risk types. no risk management recommendation.

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43048	ENV-19	Project Performance Risk		TSP.	Environment	Limited Optimization of Reservoir Operations to determine benefits during comparison of alternatives	Current tools are limited in the capability of optimizing operations of storage features to improve achievement of performance measure targets.	Benefits of project are not optimized as high as could be	M
	Evidence for Consequence rating	**Likelihood rating**	**Evidence for likelihood rating**	**Uncertainty rating**	**Risk Rating**	**Risk Management Options**	**Affected Study Component**	**Outcome**	**Notes**
	Optimizing operations with additional flexibility added by project can improve restoration benefits. In addition, there is some uncertainty with restoration response that might point towards additional improvements through operations to be achieved during implementation.	M	We have good understanding of ecology and hydrology, but will likely need to test operations.	M	M	Characterize uncertainty in benefits calculations in qualitative way., Build in flexibility to operations plans and NEPA coverage to allow for adaptive management tests to improve operations during implementation, refine operations of TSP after the Agency Decision milestone.	None		

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43040	ENV-21	Study Delays		TSP.	Environment	Communication/Expedited BO/BA & other detailed analyes	Potential for limited review of natural resources when developing the BO, BA, or other detailed analyses.	Less detailed assessment of potential impacts to habitat and wildlife which could lead to identifying an incorrect plan or impacting T&E species.	M
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	There has been initial coordination on this project in the past. We have several planning aid letters through 2006.	M	In past experience, we have found ways to reduce this problem. Make sure to do the mitigation to have medium likelihood.	L	M	Use information from prior planning aid letters., Coordinate early and often with FWS/FWC on trust resource issues, determine how to screen measures to address their concerns, and evaluate alternatives that address their concerns.	None		no cost or time impact in excel sheet. no risk management recommendation.

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43047	PFM-26	Study Cost Increase		TSP.	Plan Formulation	Sea Level Change. Using one sea-level scenario to evaluate all project alternatives, then apply all sea level change curves to the TSP.	May be required to assess all three sea level rise scenarios on all project alternatives. Increase .	Additional sea-level rise change curves may indicate projects benefits are significantly reduced. EC requires significant amount of time and effort modeling various sea level rise scenarios. Requires evaluation of all alternatives - impacts schedule	M
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Portion of project benefits affected by sea-level rise is low: however, nationally significant portion of project area is at risk. Objectives of project are consistent with mitigating for sea level rise.	L	Based on experience, reviews not likely to require substantial changes to plan formulation. Will have substantial public involvement and frequent vertical team reviews. Restoring flows to Loxahatchee Northwest Fork is consistent with mitigating the effects of sea-level rise.	M	L	Present a narrative and GIS based evaluation of sea level rise scenarios on the TSP. Include an explanation of how formulation and plan selection would not be impacted by sea level rise..	None		

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43305	ENG-27	Study Delays		TSP.	Eng. - General	Incorporate new storage technologies (e.g. ASR) to improve timing and increase volume of water deliveries	Understanding effectiveness of Aquifer Storage and Recovery (ASR) storage not yet tested in this location.	ASR might be ineffective in this area. Without adequate storage, increased flow volume and improved flow duration to the Loxahatchee River may not be realized, resulting in limited ecosystem restoration benefits	H
	Evidence for Consequence rating	**Likelihood rating**	**Evidence for likelihood rating**	**Uncertainty rating**	**Risk Rating**	**Risk Management Options**	**Affected Study Component**	**Outcome**	**Notes**
	Past planning effort concluded that storage location (relative to the Loxahatchee River), volume, and timing of delivery affect benefits to river.	L	Existing subsurface data and existing groundwater flow models indicate potential for successful use of ASR.	M	M	Desktop analysis of ASR integrated with reservoir to demonstrate capability., Gather additional site specific data (exploratory bore hole during PED)..	None	Analysis completed to reduce number of ASRs (8 to no more than 4 in a cluster) and location away from utility cone of influence on aquifer. Desktop analysis completed. ASR is feasible in this area. Concurred Mr. Coleman during IRC (3 June 2016). Revised Risk Rating - Low	Based on desktop analysis, likelihood is reduced and Risk Rating revised to Medium (H/L). At start of study it was rated High (H/M).

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43041	RES-37	Analytical Error		Alternatives.	Real Estate	Land Ownership Constraints	Real Estate: Absence of full ownership information. Full impact on existing land use conditions.	Increase risk of flooding private lands. Delay in implementation. Increased costs to relocate affected parties.	H
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Based on prior CERP studies.	L	past studies have indicated that this doesn't always occur.	M	M	Upfront coordination with local sponsor; state and local governments responsible land ownership/real estate to identify real estate ownership, Go ahead with current information level and risk into TSP phase..	None	Real estate records are being compiled early on in coordination with local sponsor.	multiple risk types no cost or time impact.

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43311	EGT-38	Redesign		CWRB.	Eng. - Geotechnical	Perform preliminary seepage modelling on selected features of the TSP.	Selected features may not perform as designed. Insufficient conveyance of surface flows due to extensive seepage. Impacts to adjacent roadways. Inaccurate estimate of flowway performance due to seepage losses or gains.	Re-design structure, re-grade, relocate features during PED. Potential increase of cost and schedule of PED. Potential increase cost of construction.	M
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	unknown cost increases of PED and/or construction.	M	Sufficient geotechnical data exists at relevant features to enable feasibility-level analysis.	L	M	2-D seepage analysis will be performed on those features most susceptible to seepage effects. Use existing geotech evaluation and seepage modeling to inform this new effort..	None		

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43311	EHH-40	Redesign		CWRB.	Eng. - H&H	Evaluation of alternatives for Savings Clause (flood) used period-of-record POR) modeling data.	Modeling using POR analysis may underestimate flooding during short-term, high precipitation events. Design storm analysis would provide better description of TSP performance.	If flooding is underestimated in the modeling, design of TSP may be insufficient to maintain existing level of flood protection (Savings Clause).	H
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Final report has legal requirement to demonstrate compliance with Savings Clause for flood protection. Private property might be flooded. Public may oppose a report that relies only on POR analysis for the Savings Clause for flood protection.	L	the project will not flood private lands. If design storm analysis is not done during feasibility level design, it would be performed during PED.	L	M	Recommend HEC-RAS modeling of design storms during feasibility level design between draft and final report., Do not recommended deferring design storm analysis to PED..	None		

Date	Risk Number	Risk Type	POC	Milestone	Discipline	Scoping Choice or Event	Risk and its cause	Consequence	Consequence rating
43311	EHH-41	Project Performance Risk		CWRB.	Eng. - H&H	Limited optimization of reservoir operations during evaluation and comparison of alternatives and selection of the TSP. Incorporation of ASR operations will add more flexibility.	There was not enough time to do additional sensitivity runs to optimize performance of storage features to improve achievement of performance measure targets.	Ecosystem benefits of the TSP are not as high as they could be.	M
	Evidence for Consequence rating	Likelihood rating	Evidence for likelihood rating	Uncertainty rating	Risk Rating	Risk Management Options	Affected Study Component	Outcome	Notes
	Optimizing operations with additional flexibility added by project can improve restoration benefits.	M	We have good understanding of ecology and hydrology, but will likely need to test operations.	L	M	Build in flexibility to operations plans and NEPA coverage to allow for adaptive management tests to improve operations during implementation, refine operations of TSP after the Agency Decision milestone..	None		

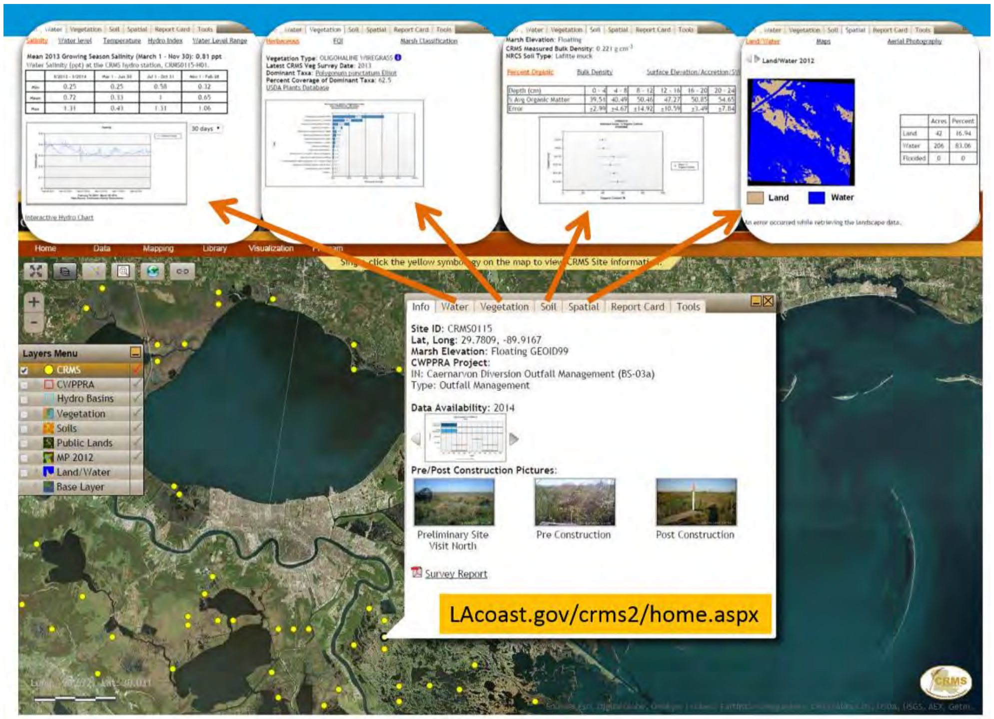
E.2.3 Communications and reporting

One of the most important aspects of an adaptive management process is reporting and communication, which provides information needed for decision making as well as fosters understanding of stakeholders and the general public. Each audience has somewhat different needs, and therefore requires different forms of information with varying levels of detail. A user-needs assessment can be used to identify requirements. Development of a communication plan that considers the different audiences and diverse reporting appropriate to each audience (e.g., decision-oriented syntheses, annual reports, reporting sessions, science workshops, peer-reviewed reports and journal articles, fact sheets, videos, presentation summaries) is essential.

Adaptive management benefits from open and transparent management wherein the results of monitoring, assessment, and decision making are routinely and consistently documented and communicated. These are essential to the program's success; they ensure PDTs, managers, and senior leaders are making decisions based on the best available information, they convey intent to the entities involved in the program, and they ensure transparency with the public. It is important that these communications conform to USACE standards and policies. A district's Public Affairs Office can assist with needed messaging.

Documentation minimally takes the form of annual (or more frequent) reports of monitoring and assessment results, but might also include scientific journal publications, reports of studies, fact sheets and "report cards," and decision documents. Electronic media (e.g., a web site) may be a convenient, efficient, and economical means for communicating and providing electronic access to information for an adaptive management program. As an example, see the Coast-wide Reference Monitoring System (CRMS) supporting the LCA (see Appendix B and Figure E3).

Figure E3. Example of online monitoring and assessment results in a "report card" format (from the CRMS website).



E.3 Challenges to adaptive management

Although adaptive management has been applied to natural resource management for decades, implementation has not been easy. Obstacles include concerns that implementing, rigorously evaluating, and potentially adjusting management actions may be too costly, too risky, and/or contrary to values of some stakeholders, as well as perceptions that a shift to adaptive management threatens existing management, research, and monitoring programs.

Challenges have emerged in previous applications to adaptive management, especially active adaptive management. Plans should be developed in anticipation of these potential pitfalls in effectively executing adaptive management. Walters (1997) identified challenges to putting an adaptive management process into practice, and these have proven prescient based on a number of recent reviews of adaptive management practice:

- Modeling in support of adaptive management is often replaced by never-ending model development and modeling exercises with the presumption that detailed modeling can replace field experiments in defining best management practices. There are also technical issues (e.g., accuracy, reliability) associated with the development and use of models in adaptive management. For ecosystem restoration, the most difficult technical issue may be the cross-scale linkages between hydrodynamic, water quality, and ecological models that are necessary in using the models to design and evaluate management alternatives.

- Using active adaptive management (i.e., system manipulations as large-scale experiments) has been often viewed as excessively expensive or ecologically risky compared to traditional management approaches. Costly modeling studies may be needed to design the management manipulation. Follow-on monitoring programs add to the costs of active adaptive management. Manipulations may result in economic losses (e.g., lost revenues from reduced navigation). The management manipulation might result in unanticipated effects on non-target populations or resources, with unacceptable consequences.
- Those in management positions often oppose experimental management policies (e.g., adaptive management). Complex institutional settings involving multiple agencies with sometimes-overlapping responsibilities and legal mandates can lead to interference in operations and generate resistance to proposed changes in management policy.

With adaptive management as a tool, identification of a “best” plan based primarily on economic or cost-effective criteria may also consider other factors, wherein the adaptability of the plan, its ability to address risk and uncertainty, and the capability to respond to changing conditions may represent critical selection criteria because they ultimately affect likelihood of achieving success and, consequently, the projected benefits.

However, adaptive management has associated costs (for monitoring and subsequent adaptive actions) that need to be considered relative to the benefits in order to make an informed decision about the best plan. There is nothing prescriptive regarding the length of time required to recognize substantive improvements in understanding and management. Expectations about the pace of learning can be problematic, particularly if there are budget constraints or a perceived urgency to achieve specific goals. Several conditions can influence the rate of learning, including the size and complexity of the managed system, the number and complexity of management alternatives, and the sources and implications of uncertainty (Table E4).

Table E4. Factors affecting adaptive management success adapted from a summary compiled by Marmorek et al. 2006.

Factors related to attitude/philosophy	
Historical context	Context can cause AM to develop in very different ways. Its proper consideration will help ensure that AM is applied in the appropriate historic and local context. Context can strongly influence in positive and negative ways the institutional drivers motivating the need for AM and the relationships among individuals/organizations involved.
Trust and commitment	Trust and commitment relate to the strength of the relationships among individuals and organizations and affect their ability to participate, interact, and engage in the AM process.
Mindset (around uncertainty, risk, and AM)	There can be aversions to acknowledging or dealing with uncertainties in decision making that relate to the risk tolerance of stakeholders and willingness of decision makers to invest in management actions that may be seen as surprises. Embracing uncertainty and learning from mistakes can enable success.
Factors related to process	
Problem definition	Ensures there is agreement among parties and focus on the correct problem, which includes how the problem is expressed. Problem definition needs to be durable and capture the larger context; otherwise, the focus can be lost or lead to crisis management.
Executive direction/ support	A clear and strong commitment from executives is required, backed up by regulatory authority to do AM, to ensure success.
Leadership and vision	Leadership is essential, but not sufficient for success. This attribute involves effective communication to gain broad support regardless of the level at which leadership is rooted, though local-level leadership may be important in some cases where top-down leadership will not work.
Planning	AM actions are inevitably implemented within existing planning processes. The dominant planning paradigm can inhibit success if too restrictive or enable it if sufficiently flexible.
Communication and organizational structure	Effective, broad-based, and two-way communication is necessary within and outside the organizational structure governing AM. This attribute includes a consideration of the choice of language, world view being represented, and venues for communication. There is also a need to maintain flexibility in organizational structure to respond to unexpected events.
Community involvement	The need for community involvement depends on context, which affects the decision about whether to involve the community, who to involve, and how to do it. For public/shared resources, a participatory approach that involves varied stakeholders in knowledge generation, deliberation, and decision making can enable success. The most effective AM programs have a small number of stakeholders who trust each other and can make decisions in an agile manner.
Facilitation, bridging, and team building	To enable trust and learning, it is important that those individuals involved are supported through neutral facilitation, team building, and a bridging organization that seeks to bring disparate interests together to explore preferences, interpret information, and make decisions.
Knowledge generation and flow	Decision making and participation should be based on a strong foundation of rigorous science in the formulation and evaluation of management actions, which can also include local and/or traditional knowledge. Knowledge should flow through the governance network in a transparent way that can be important for building mutual trust.

Knowledge interpretation and sense- making	It is important to have a transparent and inclusive process for interpreting the information generated through AM, translating the science into a form that facilitates decision making.
Integration of AM	It important that the administrative/logistical aspects of AM are embedded into existing management structures and processes rather than in their own isolated institutional structure. People working within institutions should be rewarded for activities that advance AM.
Factors Related to Resources	
Funding/ management resources	AM requires sufficient funding and management resources to be successful. Level of funding can be an indicator of the presence, or lack, of executive support.
Staff training	In some cases there may be a need for staff/those involved to receive AM training to learn new skills that facilitate successful implementation. Key areas include training around basic concepts of AM, details of the AM program, and the knowledge gained to inform future actions/decisions.
Capacity	Implementation of AM requires sufficient capacity across all entities involved. Governance structures should be realistic in reflecting the available and projected capacity of participating entities.
Legislation	A strong legislative driver is an important enabling condition to initiate and sustain AM.

E.3.1 Institutional reluctance to change

For adaptive management to be accepted on an institutional level, refinements in existing approaches to management and restoration may be needed. The targets of resource management are rapidly becoming more inclusive. For example, ecosystem management has traditionally been approached by targeting only one or a few system attributes, failing to account for the broader resource context and its implications for resource management. Adaptive management allows the resource problem to be framed in a more comprehensive context that includes issues such as system viability and sustainability. Lack of institutional recognition of this and other benefits to the adaptive management approach may persist, despite updates in policy or missions, as new guidance and practices take time to become incorporated and routine while former practices become obsolete. Notable differences in institutional characteristics that encourage or discourage changes in practices comprise important sets of obstacles to progress or openings for dialogue (Table E5).

Table E5. Summary of factors that have been identified to enable or inhibit effective governance of adaptive management programs (adapted from the science and adaptive management plan for the MRRP[1]).

Factors Enabling Good Governance	Factors Inhibiting Good Governance
Collaborative, interdisciplinary working environment with free-flowing communication and easy access to well-synthesized information.	Communication among components/departments hindered by different mandates or between disciplinary specialists (i.e, stovepiping). Difficult to access required information.
Frequent re-examination of management and restructuring as needed.	Management done the same way for a very long period of time.
Leaders deliberately challenge themselves and staff to recognize change, innovatively adapt to challenges, and take calculated risks.	Leaders resist change, discourage risk and innovation, and create organizational culture of status quo.
Collaborative inputs to decision making over sustained period, generating buy-in and trust, allowing stakeholders to move from positions to interests, clarifying areas of agreement and disagreement.	Institutions isolated from public/stakeholders; very limited and inconsistent consultation. “Inform” rather than listen.
Recognize critical uncertainties and plan experiments to test alternative hypotheses/actions.	Plan based on past experience, practices, procedures established by senior staff.
Stress high-quality science at appropriate scales, with independent review panels. Data made available; different interpretations of data welcomed, used to postulate alternative hypotheses and design management experiments. Wide publishing of scientific findings.	Science discouraged or use of “advocacy science” to support agency’s position. Data kept internal; selective evidence used; insist on single, dogmatic agency position regarding data analysis.

Time itself is a challenge in implementing adaptive management. In many cases, the overall costs associated with adaptive management are tied as much to the timeframe of the project as they are to its complexity. Some adaptive management plans require extensive monitoring over long time periods (e.g., floodplain forest restoration) to measure the results of an initial action. Of course, models that forecast some future endpoint as a consequence of a decision or series of decisions should also be able to predict the resource status at various intervals prior to that endpoint, allowing management assessments to be performed on the predicted status over an abbreviated interval. The problem of time lags is further complicated by the fact that individual decision makers and/or managers may not remain in the same position over the needed timeframes,

[1] Fischenich, J. C., K. E. Buenau, J. L. Bonneau, C. A. Fleming, D. R. Marmorek, M. A. Nelitz, C. L. Murphy, G. Long, and C. J. Schwarz. 2018. *Missouri River recovery program science and adaptive management plan*. ERDC-EL TR (in preparation). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

emphasizing the need for an adaptive management plan and governance process that outlasts career moves, and a data management, reporting, and communications strategy that ensures new managers can access important historical information.

E.3.2 Surmounting challenges to adaptive management

Implementation of adaptive management can often require a shift in focus toward resource sustainability as a strategic target, with resource planning and design, decision-based monitoring, and assumption-driven research as central activities. Institutional support, described above, is instrumental in moving the state of the science forward.

Managers must carefully assess the costs of the monitoring and assessment that inform decision making in an adaptive management process. The costs of timely monitoring and assessment over extended time scales can be substantial and often appear to be high at the outset of a project. The USACE and partnering agencies must be willing to cover the costs of monitoring and evaluation over the life of an adaptive management project.

During design phases, the cost and details of adaptive management plan contingency options need to be identified in detail and included in the cost ledger of the project implementation report as an 06 feature code. Congressional authorization of these costs ensure that the 902 limit has enough room for the options to be budgeted, implemented, and cost-shared without breaking that limit.

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14. ABSTRACT

Implementation guidance for Sections 2036 and 2039 of WRDA 2007 and Section 1161 of WRDA 2016 requires that ecosystem restoration projects either include appropriately scoped monitoring and adaptive management plans or provide sound justifications for why adaptive management is not warranted. Under adaptive management, decisions are based on the best available (yet often incomplete and imperfect) scientific data, information, and understanding, recognizing uncertainties that introduce risks to the achievement of goals and objectives. Revision to management actions based upon information derived from ongoing monitoring and evaluation is possible. This guide provides an overview of adaptive management practice, emphasizing underpinning principles. An approach to determine the need for and development of adaptive management plans is presented, and the implementation of ecosystem restoration projects under adaptive management is presented.

15. SUBJECT TERMS

Adaptive management	Monitoring	Risk-management
Ecosystem restoration	Mitigation	Decision-making
	Ecosystem management	SMART planning

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Subject: Concerns regarding NorthMet Mining Project Flotation Tailings Basin Containment System

Dear Ms. Cohen:

In accordance with your request on December 21, 2021, I am writing to summarize issues that I have identified with the viability of the proposed NorthMet Project Flotation Tailings Basin (FTB) Seepage Containment System for controlling the release of contamination from the FTB.

I am currently a Professor and Chair of the Department of Civil and Environmental Engineering at Bucknell University (Lewisburg, PA), where I have been teaching and performing research in the areas of geotechnical and geoenvironmental engineering since 2005. My primary research activities and publications over the past 25 years have been focused on the design and performance of engineered soil and geosynthetic barriers for waste containment, most notably bentonite-based barriers such as geosynthetic clay liners and soil-bentonite cutoff walls. Over the past 12 years, in particular, my research has focused almost entirely on soil-bentonite cutoff walls, including field research on a large-scale (~500-ft long, ~22-ft deep) soil-bentonite cutoff wall constructed near the Bucknell University campus with support from the National Science Foundation (the first and only field research facility for SB cutoff walls constructed in the US). Prior to my academic career, I worked in environmental consulting as a Senior Engineer for GeoTrans, Inc. (Westminster, CO) and as a Principal Engineer for Sentinel Consulting Services, LLC (Highlands Ranch, CO). In both of these positions, a majority of my project work involved review and oversight of the design and construction of several large-scale waste containment and remediation projects as part of the $2B cleanup effort at the Rocky Mountain Arsenal site, which included two on-site hazardous waste landfills, over 400 acres of earthen cover systems, and soil-bentonite cutoff walls for in-situ waste containment. I am an actively licensed Professional Engineer in the State of Colorado (#37734).

As you know, I have been consulting with MCEA on the NorthMet project since 2014. My work began with an expert assessment of the technical viability of the various containment systems proposed for the NorthMet project based on my review of the Supplemental Draft Environmental Impact Statement (SDEIS) and related project documents. I provided a similar assessment on the Final Environmental Impact Statement (FEIS) in 2015, and subsequently provided expert review and commentary on the Draft Dam Safety Permit in 2017 and the revised Permit to Mine Application in 2018. In these various assessment reports, I expressed concerns regarding the viability of the FTB containment system for long-term, *in-situ* geoenvironmental containment. My commentary, presented below, addresses issues that I highlighted in my past reports, as well as additional issues I have identified based on new details I have learned since my prior reports were completed.

1. **The proposed FTB containment system represents an unprecedented and inappropriate use of a remediation technology**.

   The proposed FTB Containment System is comprised of two primary components: (1) a 23,740-ft-long (4.5-mile-long), soil-bentonite (SB) cutoff wall that will surround the west, north, and east sides of the FTB; and (2) a passive seepage collection system of similar length that will consist of a collection trench and drain pipe to maintain an inward hydraulic gradient along the wall. Over the past 40-50 years, cutoff walls installed at contaminated sites (with or without active hydraulic controls such as a seepage collection trench) have been employed exclusively as a remedial action to prevent the spread of existing subsurface contamination resulting from past releases (e.g., due to spills, prior uncontrolled waste disposal, etc.) until other *in-situ* or *ex-situ* remediation technologies are applied to address the source contamination (e.g., Sharma and Reddy 2004). Although cutoff walls may be considered a permanent remedial solution at some contaminated sites (i.e., in the event that other types of remedial technologies are cost-prohibitive or impractical), the cutoff wall system in this case is being proposed as a *permanent substitute for an engineered liner system to contain future tailings*. In essence, PolyMet is acknowledging that future releases of contamination associated with newly placed tailings from the FTB will occur, and is proposing to pre-install a remedial solution for the site rather than construct an engineered barrier to prevent such releases in the first place. The use of a remediation technology as a substitute for an engineered liner system for newly disposed waste is unprecedented and inappropriate. Construction of a proper liner system to contain the newly placed tailings would be more consistent with modern standards of practice for waste containment and would be more protective than a 4.5-mile-long cutoff wall system constructed in a highly variable subsurface environment with difficult soil and geologic conditions (see further comments below). If necessary, the cutoff wall system could be installed as a remedial action to contain existing or new contamination below the FTB.

2. **The subsurface conditions along the length of the proposed cutoff wall alignment have not been adequately characterized.**

   Proper cutoff wall design requires sufficient investigation along the wall alignment to adequately define the continuity and elevation of the lower confining unit (bedrock, in this case), determine groundwater elevations, identify artesian conditions, and characterize the soils. Soil borings typically are drilled at 100- to 200-ft intervals along the alignment so that variations in the subsurface conditions can be delineated in adequate detail (EPA 1998). At the NorthMet site, a total of 33 borings are shown in the Permit Application Support Drawings (Appendix C) for the FTB containment system. This represents an average spatial distribution of *one boring for every 720 ft* (given a total wall length of 23,740 ft). In addition, there are several sections along the wall alignment in which the distance between adjacent borings spans over 1,000 ft. Finally, only 18 of the 33 borings were drilled within 40 feet of the proposed alignment (i.e., one boring for every 1,320 ft). This level of characterization does not meet the standard of practice for cutoff wall design in waste containment applications and does not adequately define the depth to bedrock. As shown in the Permit Application Support Drawings, the bedrock elevation is interpolated between borings with straight lines. However, there are several locations along the alignment where borings are more closely spaced, and these borings clearly reveal significant variability in the bedrock elevation. Without better delineation of the bedrock, the likelihood of making intimate contact with the bedrock along the entire bottom of the cutoff wall is low, especially if trenchless construction is used (i.e., trenchless methods do not allow for the bedrock elevation or key penetration to be confirmed during construction). Also, boulders may be more prevalent in the till than identified in the drawings, which would be problematic for trenchless construction. The additional characterization should be completed, and the results assessed, before the project mores forward.

3. **The proposed monitoring system is inadequate, and the permit requirement allowing any non-zero value of inward hydraulic gradient may not be sufficient to prevent releases of contamination.**

According to the December 2018 NPDES permit for the FTB, the monitoring scheme for the FTB containment system will include only seven pairs of piezometers and six pairs of monitoring wells along the entire wall alignment. Thus, there will be, on average, only one piezometer/well pair for inward gradient monitoring for every 1,828 linear feet of wall, and one well pair for water quality monitoring for every 3,960 linear feet of wall. These average spacings are much greater than the average spacing of 760 feet for inward gradient monitoring and 500 feet for groundwater quality monitoring observed in the EPA (1998) evaluation of vertical barriers in the US. A more robust monitoring system should be required as a condition of the permit.

Also, the NPDES permit requires only that a non-zero inward hydraulic gradient be maintained across the wall. This requirement fails to consider diffusion as a significant transport mechanism for contaminants in the tailings to migrate through the wall. A more stringent performance standard needs to be established for this aspect of the containment system before the project moves forward, to ensure that spreading of contamination beyond the cutoff wall will not occur.

4. **The proposed construction method is unsuitable for the soil conditions.**

My current understanding is that the proposed SB cutoff wall will be constructed using a trenchless construction technique such as the DeWind One-Pass technique or the trench cutting and remixing deep wall (TRD) method (https://www.keller-na.com/expertise/techniques/trd-soil-mix-walls). A disadvantage of this type of cutoff wall construction is that all of the native soils (including unsuitable layers) are incorporated into the finished wall. My recent review of the Permit Application Support Drawings indicates that large amounts of organic/peaty soil are present in the subsurface along significant portions of the wall alignment, most notably in the 3000-ft stretch of wall between stations 155+00 and 185+00 where the organic layer thickness approaches 20 feet. Deleterious materials, such as organic matter, can compromise the hydraulic performance and should not be incorporated into the wall (EPA 1984, Evans et al. 2021). Also, as mentioned previously, boulder deposits within the till will make construction difficult at best. Additional characterization is needed to better determine the prevalence of boulders. During my prior work on this project, I was not aware of the extent of the organic soil, the planned use of trenchless construction (I had assumed that slurry trench construction would be employed), or the sparse distribution of borings along the wall alignment. The implications of these poor soil conditions on the constructability and performance of the wall should be fully investigated and assessed prior to approval to mine.

5. Establishing an adequate key for the cutoff wall in the fractured granite bedrock likely will not be feasible.

In my previous reports on this project, I had expressed the concern that a minimum depth of key for the cutoff wall into the underlying bedrock needs to be specified. Cutoff wall failures are often due to unexpectedly high underseepage caused by an inadequate key, as indicated by the results of the aforementioned EPA (1998) study. In fractured bedrock, in particular, an adequate key is important for minimizing seepage through the fractures. However, in the case of hard (granite) bedrock, a typical minimum key (e.g., two feet or more) will be difficult, if not impossible, to achieve (especially with trench cutting methods) and could cause further damage to the rock, creating more fractures (Ryan and Day 2003). Underseepage will make the maintenance of a sufficient inward gradient more difficult. If an adequate key cannot be established, then a grout curtain should be installed at and below the bottom of the wall to seal the fractures and mitigate underseepage.

References

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If you have any questions regarding this letter, please do not hesitate to contact me at 570-412-2069 or michael.malusis@bucknell.edu.

Sincerely,

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Report on
Groundwater and Surface Water Contamination
at the Flambeau Mine

David M Chambers, Ph.D.
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Center for Science in Public Participation

June 5, 2009

The Center for Science in Public Participation provides technical advice to public interest groups, non-governmental organizations, regulatory agencies, mining companies, and indigenous communities on the environmental impacts of mining. CSP2 specializes in mining, especially with those issues related to water quality impacts and reclamation bonding.

SURFACE WATER

The Flambeau Mine, an open-pit copper-gold-silver mine located near Ladysmith, Wisconsin was permitted in January 1991 and began production in 1993. The ore body, characterized as a "Precambrian supergene enriched massive sulfide deposit," [1] yielded 181,000 tons of copper, 334,000 ounces of gold and 3.3 million ounces of silver over the mine's brief four-year lifespan.[2] Approximately 4.5 million tons of waste rock characterized as "high sulfur" and 4 million tons of "low sulfur" waste were generated and stockpiled on site for eventual return to the pit.[3]

When mine operations ceased in 1997, the open pit was 220 feet deep, a half mile long and 32 acres in size. Backfill operations commenced promptly, and over 30,000 tons of limestone was blended into the sulfide-bearing waste rock on relocation.[4] In addition, a layer of non-acid generating waste was placed on top of the acid-generating waste backfilled into the pit. Although groundwater has infiltrated the backfilled pit, the combination of neutralizing limestone and submergence of the acid-generating material in water, which limits the availability of oxygen, is meant to slow the generation of acid and dissolution of metals in this material to an acceptable amount.

Backfill operations were completed by early 1998, at which time surface reclamation began. This entailed recontouring the surface, spreading topsoil and establishing plant communities. In late 2001 a Notice of Completion for reclamation activities was submitted to the state regulatory agency, followed by a mandatory four-year monitoring period.

A partial Certificate of Completion for reclamation activities was granted in May 2007 subsequent to an agreement negotiated between opposing parties at a contested case hearing. Groundwater contamination within the backfilled pit, exceedances of applicable groundwater standards at the mine's legally-

[1] "Flambeau – A Precambrian Supergene Enriched Massive Sulfide Deposit," *Geoscience Wisconsin*, July 1977
[2] Flambeau Mining Company, 2007 Annual Report, January 2008, pg 3
[3] Flambeau Mining Company, 1997 Backfilling Plan for Stockpiled Type II Material, March 1997, pg ii-iii
[4] Flambeau Mining Company, 2007 Annual Report, January 2008, pg 3

established intervention boundary, and data related to potential impacts of the mine on macroinvertebrates, sediment, crayfish, and walleye in the Flambeau River were not assessed as part of the certification process and therefore did not factor into the decision. Rather, partial certification for the site was based upon completion of backfill operations according to plan and successful revegetation of the surface. Due to ongoing problems with surface water pollution in a small creek that receives runoff from the mine site, certification was withheld for a 32-acre section of the mine site known as the Industrial Outlot. The Industrial Outlot includes the area where the mine's rail spur, runoff and surge ponds, water treatment plant and administrative building were located during the mining years, as well as a portion of the high sulfur waste rock stockpile**.**

During mining, water was pumped from the pit to keep it relatively dry. This pumping caused a groundwater cone of depression to form around the pit, directing all groundwater flow during mining toward the pit. At mine closure the pumping ceased and natural groundwater flow patterns were restored. The southwestern edge of the pit is 140 feet from the Flambeau River. The pit is separated from the Flambeau River by a slurry cutoff wall designed to limit groundwater flow to/from the river both during and after mining. The post-mining groundwater hydrology is described as flow from the pit towards the Flambeau River (see Figure A and Figure B).

Ore from the mine received only minimal processing at the mine site. An ore crusher was positioned close to a mine site rail terminal, and from there the ore was shipped to Canada for further processing. During mining, water pumped from the pit that came in contact with acid-generating rock and contaminated water from the mine's high sulfur waste rock stockpile was routed to a surge pond and from there to an onsite water treatment plant. After mining ceased, the reclamation plan was modified to allow the surge pond to stay in place, and the pond was modified to facilitate its use as a biofilter for treating water collected from the southeast corner of the mine site where the Industrial Outlot is located (see Figure C). This wetland, the "Outlot (0.9 acre) Biofilter," now discharges into Stream C, which flows into the Flambeau River (See Figure D).

There are presently two areas of concern with regard to contamination of water coming from the reclaimed mine site.

First: Water discharged from the Outlot Biofilter wetland into Stream C does not meet Wisconsin surface water quality standards. This water flows into the Flambeau River.

Second: Groundwater in a monitoring well between the pit and the Flambeau River (on the Flambeau River side of the slurry wall separating the pit from the river) does not meet Wisconsin groundwater quality standards.

Stream C

Stream C originates in an area just northeast of where the rail spur was located during mining, and then flows through the eastern portion of the Industrial Outlot where the discharge from the Outlot Biofilter joins it. Stream C flows southwest for approximately one half mile and discharges directly into the Flambeau River. Today the stream is relatively small and has little aquatic life. The pre-mining data is insufficient to document the flow or extent of aquatic life.

Stream C is classified as "navigable" and "intermittent." Presence of aquatic life in Stream C has been documented when it is flowing, and observation of unimpacted streams in the vicinity suggests that aquatic life was probably present before mining. Flow in Stream C is not likely to have been increased by mining activity and reclamation, since the backfilled pit constitutes a preferential flow path away from Stream C, and the industrial activities at the present site (roads, parking lots, buildings, etc.) would enhance stormwater runoff and lessen stream base flow related to groundwater recharge.

Stream C Water Quality

There appears to be no quantitative or qualitative pre-mining water quality data for Stream C, but there is nothing to indicate that the pre-mining background levels of copper in Stream C were at the levels measured post-mining. All indications appear to be that Stream C was much like other streams in this area – relatively clean water with low copper content. It is interesting to note that the discharge from the wetland/biofilter is a direct point discharge into a water of the State/US, hence could or should be governed by the discharge permit requirements of the Clean Water Act.

Water quality data for Stream C has been recorded only sporadically. In 2004-2005 Foth & Van Dyke of Green Bay, Wisconsin, recorded data from multiple Stream C locations on four different days. Although this may not be a true synoptic sample, it is probably as close as can be had to synoptic data for this site. Of the analytes recorded in the data for Stream C it appears that copper is a contaminant of significant concern. This is potentially significant since aquatic organisms are not only very sensitive to copper,[5] but also sensitive to changes in copper over background levels.[6]

At the present time the levels of copper in the discharge from the wetland/biofilter, and from Stream C into the Flambeau River, both exceed Wisconsin water quality standards.

The data in Table 1 is taken from the report "Stream C - 2005 Analysis of Collected Data," Foth & Van Dyke, October 10, 2005, Figure 2; and, "2008 Monitoring Results and Copper Park Lane Work Plan," Foth Infrastructure & Environment, Table 1 – 2008 Monitoring Results. The full Foth & Van Dyke Figure 2, which contains most of the reported surface water data from Stream C, is attached as Figure E. The data for two of these sites is presented in Table 1 – station BFSW-C2, the outlet from the wetland/biofilter, and station SW-C6, Stream C just before it flows into the Flambeau River.

Table 1: Stream C Water Quality Data

	Date						
***from WAC NR 105.06 (Nov08)**	**15Sep04**	**23Oct04**	**26Apr05**	**09Jun05**	**25Apr08**	**8Jun08**	**27Oct08**
Biofilter Outlet BFSW-C2							
Copper (Cu) (µg/L)	67	28	27	46	22	8.8	16
Hardness (mg/L)	24	24	29	32	27	19	17
pH, Lab (s.u.)	6.37	6.64	6.82	6.85	7.63	7.31	6.83
Chronic Copper Water Quality Standard based on Hardness (µg/L)*	3.1	3.1	3.6	3.9	3.4	2.5	2.3
Acute Copper Water Quality Standard based on Hardness (µg/L)*	4.0	4.0	4.8	5.3	4.5	3.2	2.9
Stream C Outlet SW-C6							
Copper (Cu) (µg/L)	34	15	14	36	no data	no data	no data
Hardness (mg/L)	35	82	39	31	no data	no data	no data
pH, Lab (s.u.)	6.20	6.52	7.19	6.67	no data	no data	no data
Chronic Copper Water Quality Standard based on Hardness (µg/L)*	4.2	8.7	4.6	3.8	no data	no data	no data
Acute Copper Water Quality Standard based on Hardness (µg/L)*	5.8	12.9	6.4	5.1	no data	no data	no data

[5] Hall et al. 1988, Eisler 2000, Baldwin et al. 2003
[6] Baldwin et al. 2003

It can be seen that the copper level in the water entering Stream C from the wetland/biofilter is approximately a factor of two higher than the copper level in the discharge from Stream C as it entered the Flambeau River. It would be expected that some dilution would occur as water in Stream C gets closer to the Flambeau River because of the diluting effect of the unnamed stream that enters Stream C approximately half way between the wetland/biofilter discharge point to Stream C and where Stream C enters the Flambeau River. It is also probable that there is some groundwater recharge to Stream C.

It should be noted that copper in Stream C, as shown in Table 1, exceeds Wisconsin water quality standards both at the discharge from the wetland/biofilter and from Stream C as it flows into the Flambeau River.

The water quality standard for copper is a function of the hardness of the water. Since hardness data was available, the calculated hardness-dependent values for the chronic and acute copper standard are also listed in Table 1. As can be seen from this table, both the chronic and acute standard for copper was exceeded on each day for which data was recorded.

In the 2008 Foth report a proposal to remove and replace soil from the Copper Park Lane drainage ditch is discussed. It is clear from the monitoring data that copper is coming from the drainage ditch and is loading Stream C downstream of the biofilter. The removal of the surface material in the Copper Park Lane drainage ditch should help lower the level of copper in Stream C. However, it is also clear that the level of copper coming from the biofilter itself is still enough to cause an exceedance of Wisconsin water quality standards at Stream C at the mine boundary.

It was noted in the Foth & Van Dyke report:

> "The stream appears to be very limited in biota in all aspects including aquatic vegetation, macroinvertebrate populations, and fish."[7]

A slight increase in the level of copper can form a barrier to the migration of fish.[8] Stream C flows into the Flambeau River immediately upstream of Meadowbrook Creek. Copper could potentially impact the migration of fish into and out of Meadowbrook Creek.

With copper levels significantly exceeding both chronic and acute water quality criteria, it is likely that these high metal levels are contributing to the lack of aquatic life in Stream C. These levels also suggest that better monitoring of Stream C and the Flambeau River below Stream C should be done.

The discharge from the outlet of the wetland treatment system should meet Wisconsin water quality standards at that point. There is not enough dilution in Stream C to effectively dilute contaminants, so any contaminant will impact aquatic organisms along most or all of the length of Stream C. Because of this fact, Stream C is being presently used as a conduit for contaminated water from the mine site to the Flambeau River, where dilution by the large volume of water in the river occurs.

Surface water data from 2008 shows that at SW-C5 (below the biofilter discharge to Stream C, but above the contribution from the Copper Park Lane ditch) the copper level is approximately 10 times the hardness-based acute water quality standard, and the zinc level is approximately twice the hardness-based acute water quality standard.[9] Copper and zinc are synergistic metals, so their combined impact on aquatic organisms is greater than that of either by itself.

[7] Foth & Van Dyke, 2005, p.4
[8] Baldwin et al. 2003, van Aardt et al. 2007
[9] Foth Infrastructure & Environment, 2008, Table 1 – 2008 Monitoring Results

Surface water data has been simultaneously sampled only three times at SW-2 (Flambeau River below the mine site) and SW-3 (Flambeau River just below Stream C, and below SW-2). On all three sampling dates the copper level is greater at SW-3, below the outlet of Stream C, than at SW-2. On April 25, 2008, the sample data for SW-3 show the copper level is approximately double the Wisconsin chronic water quality standard, while the copper level at SW-2 is below the standard.[10] The measured level for copper at SW-3 in the Flambeau River was 5.6 ug/L, while the hardness-based copper water quality standard is 3.2 µg/L for chronic effects, and 4.2 µg/L for acute effects. The copper level measured exceeds both the chronic and acute standards. If the copper is coming from Stream C, as would be likely, then it is probably being diluted to below the water quality standard as it enters the Flambeau River just above SW-3. Dilution of water from Stream C would constitute a "mixing zone" under a discharge permit which would extend below SW-3. At present no permit or authorized mixing zone exist.

Table 2: Flambeau River Water Quality Data

	Date		
***from WAC NR 105.06 (Nov08)**	**21Sep07**	**25Apr08**	**27Oct08**
SW-2 (Flambeau River at Mine Boundary)			
Copper (Cu) (µg/L)	<1.3	2.8	1.8
Hardness (mg/L)	60	27	57
pH, Lab (s.u.)	7.94	7.54	8.26
Chronic Copper Water Quality Standard based on Hardness (µg/L)*	6.7	3.4	6.4
Acute Copper Water Quality Standard based on Hardness (µg/L)*	9.6	4.5	9.1
SW-3 (Flambeau River below Stream C)			
Copper (Cu) (µg/L)	4.2	5.6	2.7
Hardness (mg/L)	53	25	56
pH, Lab (s.u.)	7.83	7.46	8.25
Chronic Copper Water Quality Standard based on Hardness (µg/L)*	6.0	3.2	6.3
Acute Copper Water Quality Standard based on Hardness (µg/L)*	8.5	4.2	9.0

In order to address the question of whether the increase in copper at SW-3 is coming from Stream C, water quality samples should be taken in Stream C just prior to its discharge point into the Flambeau River. This could be easily accomplished by reactivating sampling station SW-C6, which was sampled from September, 2004 to June, 2005.

At the present time the levels of copper in the discharge from the wetland/biofilter, and from Stream C into the Flambeau River, both exceed Wisconsin water quality standards. This discharge of copper appears to be impacting the water in the Flambeau River, as measured at SW-3 just downstream of the junction of Stream C with the river.

Recommendation:* *In order to address the question of the amount of copper contamination entering the Flambeau River from Stream C, and the increase in copper at SW-3, water quality samples should be taken in Stream C just prior to its discharge point into the Flambeau River. This should be done by reactivating sampling station SW-C6, which was sampled from September, 2004 to June, 2005.

[10] Foth Infrastructure & Environment, 2008, Table 1 – 2008 Monitoring Results

An increase in monitoring frequency would better establish the risk presently being posed to aquatic organisms in the Flambeau River. Presently surface water sampling is being done twice per year.

Recommendation: Until it can be demonstrated that the water quality in Stream C, and in the Flambeau River below Stream C, is not being impacted by mine-related contamination, sampling in Stream C and at SW-3 in the Flambeau River, and at SW-1 and SW-2 in order to provide background water quality information, should be done at least quarterly. This frequency should be maintained for at least 5 years after water quality exceedances cease.

Copper is demonstrably the contaminant of concern. The monitoring recommendation above is the minimum necessary to adequately monitor water quality to determine the presence/absence of copper contamination. A more thorough monitoring program would also look for the presence of other potential contaminants, since it is rare that only one metal is present at elevated levels.

Recommendation: It is also recommended that once per year, in the spring sampling event, a full suite of metals and their associated indicator parameters be sampled, until water quality exceedances cease. These parameters should include Conductivity (field), pH (field), Total Suspended Solids, Total Dissolved Solids, Aluminum, Arsenic, Cadmium, Chromium, Cobalt, Copper, Lead, Mercury, Nickel, Selenium, Silver, Uranium/Radioactivity, Zinc, Hardness, Iron, Manganese, and Sulfate.

Potential Mitigation Measures for Stream C

In reviewing the Foth & Van Dyke data for Stream C it is also evident that the portion of Stream C above the junction with the wetland/biofilter also carries significant copper, and possibly some zinc contamination (See Figure E, station SW-C8). In general the data also indicates the pH is normal, with some fluctuations, and the sulfate level is low. These would all suggest that metals are being sequestered in the wetland/biofilter, but that copper may be attached to suspended sediment or organic particles flowing from the wetland/biofilter. It could also be that there is just too much copper to be effectively filtered by the existing wetland. There is little data available on total suspended solids to correlate with the available water quality data.

In either case an expanded wetland/biofilter could be constructed to give more residence/treatment time to remove copper not only from the mine site drainage, but also to include water from the upper portion of Stream C above the Lot, which also shows indications of contamination.

GROUNDWATER

The long term closure plans of the Flambeau Mining Company included backfilling the open pit with waste rock, sludge, and limestone and allowing the pit to fill with groundwater. This will submerge the rock to limit oxygen and oxidative reactions. However, this placement of reactive rock surfaces in contact with water will result in long term reactions within the pit that are unlikely to stabilize in the near future. Rock surfaces are reactive in terms of redox chemistry and solubility, resulting in localized reactions that form acid, dissolved metals, and secondary mineral oxides. To date it appears that backfilling has not resulted in additional acid production, but metal leaching is occurring and complex pit chemistry is difficult to predict over the long term. Some current and future issues include

- Solubility/precipitation reactions within the pit
- Depletion/passivation of limestone
- Dissolution and flushing of material out of the pit

Reactions within pit

To monitor pit chemistry, two pit monitoring well nests (MW-1013 and MW-1014) were constructed in September 1998 after the backfill had roughly a year to settle (see Figure F for well positions in pit). Wells were nested in order to sample water at different depths (24', 47', 86', 202' for MW-1013; 34', 64', 105', and 157' for MW-1014).

Groundwater only fully rebounded in pit wells (MW-1013, MW-1013A, MW-1014) in 2005, therefore some wells have only three years worth of water quality data. It has been recognized by FMC that pit reactions have not stabilized,[11] and that reactions (dissolution and precipitation of metals and ions) are controlled by pH and redox.[12] The long term stable condition of the pit will not be determined until redox and pH are stable. Redox continues to fluctuate in pit wells, particularly in the more shallow screens.[13] The pH is controlled by dissolution of limestone intentionally mixed with waste rock to control acid. It may take hundreds of years for the limestone to completely dissolve as FMC states,[14] but limestone could become ineffective much sooner if secondary minerals (hydroxides and carbonates) precipitate and coat limestone. If/when limestone stops going into solution, pH may drop and significantly affect the concentrations of minerals in solution.

Pit Chemistry

Sampling has indicated and continues to indicate that pit chemistry reactions have not stabilized. Manganese, copper, iron, zinc and redox remain in flux within the pit wells. This is likely due in part to localized oxidation reactions between waste rock and sludge: ferric iron (Fe^{3+}) that precipitated during mine-water treatment remains in sludge, and is available to oxidize the pyrite present in waste rock. This results in the release of ferrous iron (Fe^{2+}) and acid in localized pockets even under anoxic conditions:

$$FeS_2 + 8\ H_2O + 14\ Fe^{3+} \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$$

Where acid (H^+) is generated, dissolution of minerals – particularly of copper and manganese from sulfidic waste rock – will occur. To date, reactions continue to occur within the pit, as demonstrated by

- Increase of copper in MW-1013B
- Increases in manganese and iron in MW-1013C

[11] Flambeau Mining Company. 2007 Annual Report.
[12] Foth and Van Dyke/SRK Consulting memorandum. Oct 12 2000. In Flambeau Mining Company 2000 Annual Report.
[13] SRK Consulting memorandum Jan 25 2008 in Flambeau Mining Company 2007 Annual Report, Figures 14-15.
[14] Flambeau Mining Company 2000 Annual Report

- Manganese decreases in MW-1014A and MW-1014B
- Iron decreases and loss of gypsum in MW-1014C
- Increasing redox in MW-1014A and decreasing redox in MW-1013A

Because the mixture within the pit is not homogenous, different reactions can be expected to occur and at different rates, making it quite difficult to develop accurate models.[15] Models for the Flambeau mine pit groundwater were generated in 1989, when the Mining Permit Application was submitted to the state regulatory agency for review. Specifically, the application included a data table entitled "Predicted Parameter Concentrations of Contact Groundwater Leaving the Backfilled Pit"[16] that is reproduced here for review (see Table 3). The table has utility from two viewpoints: (1) it summarizes projected water quality for pit water; and (2) per the terms of the Flambeau Mine Permit, it defines the applicable groundwater enforcement standards for monitoring wells MW-1000 and MW-1010 located between the backfilled pit and the Flambeau River.[17]

Table 3: Predicted Concentrations of Groundwater Contaminants[18]

TABLE NO. 2-5

Predicted Parameter Concentrations of Contact Groundwater Leaving the Backfilled Pit

Parameter	Concentration, mg/L	Years
Sulfate	1,360	0-8.42
	1,100	8.42-132
	832	132-2,850
	317	2,850-3,010
	9.9	3,010+
Manganese	0.550	0-3,920
	0.445	3,920-4,000
	0.350	4,000+
Iron	0.320	>4,000
Copper	0.014	>4,000

[15] Kuipers et al 2006
[16] Foth and Van Dyke, 1989
[17] Decision, Findings of Fact, Conclusions of Law and Permits [for the Flambeau Mine], State of Wisconsin Division of Hearings and Appeals, 1991, pp. 87-93.
[18] Table 2-5 from Appendix L of Flambeau Mine Permit Application, 1989

Column testing by the Flambeau Mining Company in 1997 was not able to produce the manganese concentrations predicted, but it was thought that "with an extended time manganese levels would decrease to those predicted in Table 4-23"[19]; i.e. 2 mg/L (2,000 µg/L) at 1% carbon dioxide.[20] However, ten years after backfilling, manganese concentrations in pit pore water remain underestimated by more than an order of magnitude in four of the eight pit monitoring wells (MW-1013, 1013B, 1013C, and 1014B), and fluctuate strongly in three of the remaining four (MW-1013A, 1014, 1014A) (Table 4 and Figure G).

Gypsum and metal hydroxides present in buried water treatment sludge can be expected to dissolve over time and flush down-gradient, making their way into or under the Flambeau River. Metals and mineral oxides that dissolve as a result of localized oxidation reactions within backfill can also be expected to flush down-gradient. Flushing will remain a concern for decades to come.

The most likely fate of manganese will be to flush out of the pit. It is unlikely to precipitate at neutral pH in the presence of iron. Dissolution reactions, in addition to influx of groundwater high in manganese, have likely contributed to the high manganese concentrations observed in the pit that were not predicted by modeling.

The fate of copper in the pore water within the backfilled mine pit depends on ion concentrations, pH, and redox conditions.

Copper may

- flush in the dissolved form
- precipitate as an oxide/carbonate
- sorb to surfaces

To date copper concentrations in pit pore water have generally reached concentrations expected from company modeling, but exceed expected concentrations by more than an order of magnitude at pit wells MW-1013B (86') and MW-1014B (105'), with no apparent trends (Table 5).

Similarly, iron levels reached expected concentrations in pit pore water measured at MW-1013A, 1013B, 1014, 1014A and 1014B, but were underestimated by more than an order of magnitude in pit wells MW-1013, 1013C, and 1014C (Table 6). No trends in iron are evident; while MW-1014C has generally declined in iron concentrations, MW-1013 and MW-1013C fluctuate.

The unpredictability observed in copper, iron, and manganese concentrations indicates that important assumptions were missing in original modeling or that more time is needed for complex dissolution and precipitation reactions to stabilize.

Limestone performance

Limestone is being relied on to neutralize acidity present at the time of backfill as well as any acidity produced after backfilling by reactions between ferric iron and waste rock. Ferric iron oxidation reactions may continue for some time, and until they stop, limestone will be required to neutralize acidity and precipitate resulting metal dissolution. Precipitation products such as aluminum hydroxide can be expected to settle on the limestone surface, and may render it less effective. It is not known how limestone will perform over the long term. If the limestone loses effectiveness, intervention wells along with pit wells will be important in tracking potential changes in pit water quality.

[19] Flambeau Mining Company, 1997, pg 68
[20] Flambeau Mining Company, 1997, Table 4-23 and Table 4-24

Unexamined Contaminants

Consideration should also be given to expanding the groundwater monitoring program at the Flambeau mine site to include more parameters. The geology of the area and of ore samples suggests nickel,[21] cobalt, aluminum,[22] and uranium[23] could be elevated. Although testing was conducted for all in 1987-1988, no groundwater analysis for these elements have been conducted since then, with the exception that samples were analyzed for nickel in July 2005. Shallow wells not recovered from groundwater drawdown did not yet have water and were therefore not sampled for nickel.

Monitoring wells MW-1014B, MW-1014C, and MW-1013C in the pit all had significant levels of nickel for the one reported nickel measurement taken in 2005, with MW-1014B as high as 440 ug/L. MW-1000PR was also sampled for nickel in 2005 and a level of 94 µg/L recorded. Effluent limits for nickel were set in the WPDES permit at a maximum discharge of 3100 ug/L daily.[24] The most stringent standard listed in 1992 was 38 ug/L.[25] The EPA water quality standard for nickel is hardness-dependant. A typical hardness for the Flambeau River is 60 mg/L (2007). At a hardness of 60 mg/L, the water quality limit for nickel would be 34 µg/L. Therefore, if well water from MW-1000PR was entering the Flambeau River at the measured level of 94 µg/L, it is possible that the water quality standard is being violated.

Other parameters that should be added to the list include cobalt and aluminum, since both were identified in measurable quantities in pore water obtained from leach extraction tests performed by the company on waste rock samples in 1997.[26] It is also recommended that groundwater and stream sediment be tested for radioactivity, since Rusk County has been identified by the United States Department of Energy in 1980 as "favorable for uranium deposits"[27] and enforcement standards specific to radioactivity were included in the Flambeau Mine Permit. Adding nickel, cobalt, aluminum, uranium and radioactivity to the list of parameters will not have a significant impact to the collection or analytical monitoring costs.

Pit Monitoring Wells

Monitoring of pit wells and downgradient intervention wells should be continued until the pit chemistry has stabilized. Original modeling predicted concentrations of manganese, iron, and copper exiting the pit would be near background concentrations early on.[28] In the case of manganese, and occasionally iron and copper, this has not proved to be the case (Table 4 to 7). In addition, sulfate was expected to be, and is, high in concentration in the pit.

Since chemistry in pit wells, intervention wells, and at the compliance well has not stabilized, and since it is not known how limestone will perform over the long term, monitoring should continue. Also, a measure of confidence would be added if samples collected by FMC were available for independent analysis, if this is not already being done.

Recommendation: Monitoring should be continued in the pit until redox stabilizes.

[21] 2005 data for monitoring wells MW-1014B, MW-1014C, and MW-1013C
[22] Cobalt and aluminum identified in waste rock, Flambeau Mining Company 1997
[23] Cannon, WF and LG Woodruff. 2003. The Geochemical Landscape of Northwestern Wisconsin and adjacent parts of Northern Michigan and Minnesota (Geochemical Data Files). US Geological Survey Open File Report 03-259 http://pubs.usgs.gov/of/2003/of03-259/
[24] WDNR. 1992. An evaluation of endangered resources in the Flambeau River and a supplement to the Environmental Impact Statement for the Flambeau Mine project. Table 8.
[25] ibid Table 14.
[26] Flambeau Mining Company 1997
[27] Cannon, WF and LG Woodruff. 2003. The Geochemical Landscape of Northwestern Wisconsin and adjacent parts of Northern Michigan and Minnesota (Geochemical Data Files). US Geological Survey Open File Report 03-259 http://pubs.usgs.gov/of/2003/of03-259/
[28] Foth and Van Dyke, 1989, Appendix L

Recommendation: Add nickel, cobalt, aluminum, and uranium/radioactivity to parameters being measured.

Recommendation: Split groundwater samples with WDNR or the public, if requested.

Migration of Contaminants

Pit contaminants are moving out of the pit, as evidenced by concentrations of elements in the intervention boundary well MW1000PR, located on the Flambeau River side of the pit slurry wall. It is possible that contaminants may be moving around the ends of the slurry wall and/or under the bed of the Flambeau River. In addition, elevated copper has been consistently found in surface water near the Industrial Outlot, but there are no intervention or compliance wells between the Outlot and the western or southern compliance boundaries. Currently there is only one monitoring well (MW-1015) on the compliance boundary, which surrounds approximately 180 acres of the mine footprint.

If bedrock is permeable, then what occurs within the pit is relevant in that constituents move out of the pit. The bedrock forming the wall between the pit and the Flambeau River has been described as a "natural impermeable barrier"[29] but other statements referred to the river pillar of this area as "relatively highly permeable",[30] "fractured",[31] and that blasting during mining had the potential to increase fractures.[32]

The fractured bedrock forms a conduit from the pit to the River, allowing water movement in both directions. During operations, "water from the Flambeau River was drawn into the dewatered pit through fractured Precambrian bedrock that formed the western wall".[33] After closure, modeling in 1989 indicated that

> "groundwater flowing through the….pit will exit….through the Precambrian rock in the river pillar and flow directly into the bed of the Flambeau river…..Since there will be no dispersion, dilution or retardation in the river pillar, the concentrations of these constituents in the groundwater leaving the pit will be the same as the concentrations entering the river bed"[34]

Some of these constituents, as observed at MW-1000PR, fail to comply with Flambeau Mine groundwater enforcement standards.

Between the pit and the River, a bentonite slurry cutoff wall was built to limit water exiting from the pit. Whether pit water is moving around, under or through the slurry cutoff wall is not known. It is presumed that groundwater moves from the pit into the Flambeau River (see Figure A in this paper), but potentially groundwater could move under the river. MW-1000PR, which appears to be receiving groundwater from the pit, is located west of the slurry wall and below the bed of the Flambeau River.[35] It is not evident whether the bedrock itself under the river is impermeable, or contains fractures that could carry pit constituents to the west side of the river. The draft EIS refers to "groundwater movement to the

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[29] Preliminary Environmental Report, 1975, pg 29 and Figure 16 http://digital.library.wisc.edu/1711.dl/EcoNatRes.PreEnvRepAug75

[30] Foth and Van Dyke, 1989, Appendix L pg L4

[31] Foth and Van Dyke, 1989, Appendix L pg L32 says "…all of the groundwater flowing through the …reclaimed pit will exit through the Precambrian rock in the river pillar and flow directly into the bed of the Flambeau River….Since this flow path is very short and occurs entirely within fractured crystalline rock….". Also see Environmental Impact Report for the Kennecott Flambeau Project (Report Narrative), 1989, pg. 3.6-33 and Foth & Van Dyke Memorandum to Jana Murphy, Flambeau Mining Company, October 12, 2000, p.13-14

[32] Final Environmental Impact Statement 1990, pg 76 http://digital.library.wisc.edu/1711.dl/EcoNatRes.FinEnvImpMar90

[33] Foth & Van Dyke, 2000, p.13-14

[34] Foth and Van Dyke, 1989, Appendix L pg L29

[35] Well begins at land elevation 1100.5' and ends 57' down at 1043.5'. The river bed is at 1080' elevation.

southwest along the strike of the ore body"[36] and the ore body is shown to extend under the river to the west side[37] although mining stopped just short of the river.

Flambeau Mine Management

Wisconsin law requires the establishment of two different boundaries at mine sites for enforcement of groundwater quality standards. The first, known as the compliance boundary, is located 1,200 feet from the outer perimeter of the mining waste facility (NR 182.075). The term "compliance boundary" was changed to "design management zone" when the statute was amended in 1998; it is referred to in the present document as the "compliance boundary". In the case of the Flambeau Mine, the unlined backfilled pit constitutes the mining waste facility. See Figure A for the location of the Flambeau Mine compliance boundary.

The compliance boundary marks the point where groundwater quality must be in compliance with the state's groundwater protection law. In particular, drinking water standards established in Chapter NR 140 of the *Wisconsin Administrative Code* cannot be exceeded at or beyond the boundary. These standards, known as Maximum Contaminant Levels (MCLs), were specifically listed in the 1991 Flambeau Mine Permit as the applicable groundwater enforcement standards for the mine's compliance boundary, with the exception of manganese.[38] Since baseline manganese levels at the mine site already exceeded the NR 140 MCL of 50 µg/L, the Flambeau-specific enforcement standards were set at 90 µg/L (overburden), 360 µg/L (shallow Precambrian) and 230 µg /L (deep Precambrian).

In addition to the 1,200-foot compliance boundary, an intervention boundary was established for the Flambeau Mine between the mine pit and compliance boundary, as required by law (NR 182.075). Monitoring groundwater quality at the intervention boundary is designed to help identify emerging pollution problems before they have a chance to reach the compliance boundary. As such, the applicable groundwater enforcement standards, known as Preventive Action Limits (PALs) and listed in Chapter NR 140 of the *Wisconsin Administrative Code*, are typically 10-20% of the corresponding MCLs, with some as high as 50%.

Intervention Boundary Wells

Five different monitoring wells (MW-1000, 1002, 1004, 1005 and 1010) constitute the intervention boundary established for the Flambeau Mine site when permits were granted in January 1991 (Figure A). Per the terms of the permit, two different sets of enforcement standards for groundwater pollution apply to the wells: (1) MW-1002, 1004 and 1005 are subject to PAL standards; and (2) MW-1000 and 1010 are subject to the same, except in the case of copper, iron, manganese and sulfate, where enforcement standards are based upon water quality projections for the backfilled pit as set forth in Appendix L of the Mining Permit Application.[39]

Intervention well MW-1002 in the northwest quadrant of the mine site is nested (16', 52'), as is MW-1004 at the northwest edge of the pit (13', 30', 76') and MW-1005 east of the former high sulfide rock stockpile (19', 52', 92'). Pit water is not expected to move towards these wells. Water sampling indicates these wells are stable with regards to redox, contain low concentrations of iron and manganese, and constituents do not exceed the baseline measurements. However, monitoring well MW-1004, listed as an active well in the Wisconsin DNR Groundwater Environmental Monitoring System (GEMS) database, has not since

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[36] Draft Environmental Impact Statement, 1976, pg 35 http://digital.library.wisc.edu/1711.dl/EcoNatRes.DraftEnvImpSep89
[37] Schwenk 1977, Figure 14
[38] Decision, Findings of Fact, Conclusions of Law and Permits [for the Flambeau Mine], State of Wisconsin Division of Hearings and Appeals, 1991, pp. 87-93.
[39] Foth & Van Dyke 1989, pg L27-L31.

1989 had the yearly sampling that other intervention wells are subjected to for a wide range of elements (arsenic, barium, cadmium, chromium, lead, mercury, silver, selenium, and zinc).

Pit water is expected to move to the southwestern end of the pit, near the slurry wall. The monitoring well MW-1001 is located just south of the west end of the pit. It appears that water is not being collected from MW-1001 (nested at 33', 52', and 95'), although the wells are listed as "active" in the WDNR GEMS database.[40] If possible, data should be collected from this nest in order to assist in characterizing groundwater quality and flow.

Between the pit and the river is a slurry cutoff wall. Intervention boundary wells MW-1000PR, MW-1000R and MW-1010P sit about 125' from the Flambeau River, directly between the backfilled pit and river, on the west side of the slurry cutoff wall. They are well-situated to indicate the quality of groundwater entering the river.

It appears that water is not being collected from MW-1000R (24.5', not nested). It is noteworthy that this well has not had water testing since 1988 when baseline data was reported, although it appears to remain an active well. If the well is operational, water samples should be collected.

Water samples are collected from MW-1010P (115', not nested). Although this well is not generally exceeding mine permit water quality standards, redox is not stable, indicating that water chemistry has not stabilized, and it has exceeded the PAL for arsenic (5 ug/L) in 21 out of 28 samples taken between 1999 and June 2008, with one of the highest concentrations detected in June 2008 (23 ug/L). It also has not been tested for uranium, thorium, or other radioactive material.

The intervention monitoring well MW-1000PR (57', not nested) may be a good indicator of the water quality entering the Flambeau River, in that it is located

> "within a weathered and highly fractured schist …. (and) pore water has begun migrating through this fracture zone from the backfill toward the Flambeau River and MW-1000PR"[41]

Water quality at MW-1000PR consistently exceeds 1991 baseline measurements in sulfate, total dissolved solids (TDS), conductivity, manganese, zinc and calcium; baseline iron and copper levels have also been exceeded on occasion.

There have been consistent and statistically significant exceedances of 1991 Flambeau mine permit standards at MW-1000PR for manganese, calcium, conductance and TDS; manganese exceeds standards by nearly an order of magnitude. In addition, although the PAL standard of 2500 µg/L for zinc has not been exceeded in MW-1000PR, the well often contains 600-800 µg/L, significantly elevated above the <70 µg/L baseline. Similarly sulfate has not exceeded the 1100 mg/L site-specific permit application standard, but has consistently been at or above 300 mg/L, greatly elevated above the baseline of <31 µg/L, and would exceed the NR 140 PAL of 125 µg/L had that standard been specified in the mine permit (Table 7).

It is possible that pit water could be moving around the ends of the slurry wall. Inspection of the projected groundwater flow directions in Figure A and the groundwater potentiometric surface lines in Figure B both support this hypothesis. It appears that both MW-1000PR[42] and MW-1010P are screened in bedrock. Since it is apparent from the MW-1000PR data that groundwater contamination is exiting the pit toward the river, two nested wells should be placed at the northwest and southeast ends of the slurry wall separating the pit from the Flambeau River. These wells would either confirm that no groundwater

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[40] http://prodoasext.dnr.wi.gov/inter1/gemsfac$points.startup?P_LIC_NUMBER=3180&P_0=3180&Z_CHK=57753
[41] Foth & Van Dyke, 2000, p.13
[42] Foth & Van Dyke Memorandum to Jana Murphy, Flambeau Mining Company, October 12, 2000, p.13

leakage is going around the slurry wall, or would provide a means to measure the amount and water quality of this leakage.

Recommendation:* *Place nested wells at either end of the slurry wall; if MW-1000R (25' deep) is active, this could serve as one of the new monitoring wells; a deeper well should be constructed next to it. In addition, samples should be taken from MW-1001 which, although not located at the slurry wall, is nested (33', 52', 95') and located just to the southeast of the wall and would aid in determining groundwater flow direction. A monitoring well on the southern compliance boundary would ensure no contaminants are moving in that direction.

Recommendation:* *Site a monitoring well for "background" groundwater samples away from the mine site, Industrial Outlot, and roads.

Compliance Boundary Well

Only one well is currently sited at a compliance boundary. This well, MW-1015A/B (64', 148') is located northwest of the former pit and about 320 feet from the Flambeau River. It was drilled in January 2001, three years after the mine pit was backfilled, so no pre-mine baseline water quality data exists.

The company's groundwater modeling suggests that MW-1015 is not likely to receive a substantial influx of groundwater from the backfilled pit.[43] However, the well remains unstable with regards to redox, and MW-1015B has shown exceedances of the applicable groundwater enforcement standard for manganese (2002-2004) and had an exceedance of the 1991 permit standard for iron in at least one sample in every year from 2002-2007[44] (Table 8).

Given that exceedances have occurred in the one compliance well, and given the movement of contaminants out of the pit towards MW-1000PR, and since it is theoretically possible that contaminated groundwater could move under the Flambeau River toward the compliance boundary located west of the mine site, it would be prudent to provide a nested monitoring well at the compliance boundary to the west of the Flambeau River to ensure that any residential or agricultural well water quality is not being impacted, and to provide a point of measurement for ensuring groundwater meets Wisconsin drinking water standards.

Recommendation:* *Place a nested well on the compliance boundary on the western side of the Flambeau River to determine if contaminated groundwater is moving under the River.

[43] Final Environmental Impact Statement. 1990. Figure 3-7
[44] Flambeau Mining Company 2007 Annual Report, Appendix B, Attachment 1 "Historical Groundwater Results"

Monitoring Mine Management Wells

Long term monitoring will determine whether permit violations continue to occur at the Flambeau Mine intervention boundary (MW-1000PR and MW-1010) and compliance boundary (MW-1015). Since 1999, measured concentrations of manganese and iron in MW-1000PR (125' from the Flambeau River) have repeatedly been greater than the enforcement standards cited in the 1991 mine permit, and manganese significantly greater. MW-1015, 320' from the Flambeau River exceeded 1991 groundwater enforcement standards for iron at least once every year between 2002 and 2007, and remains unstable in redox, warranting continued monitoring.

A measure of confidence would be added if samples collected by FMC were available for independent analysis.

Recommendation: Monitoring should be continued at intervention and compliance wells until metal concentrations consistently remain below Wisconsin water quality standards and redox stabilizes.

Recommendation: Split groundwater samples with WDNR or the public, if requested.

MONITORING FLAMBEAU RIVER BIOTA

In 1991, Flambeau Mining Company initiated monitoring programs in the Flambeau River to assess potential accumulation of heavy metals in crayfish, walleye and sediment downstream from the mine site. Macroinvertebrate studies were also initiated to assess potential impacts of the mine on river health. Studies were performed on an annual basis through 1998 (macroinvertebrates), 2000 (walleye and sediment) and 2001 (crayfish). Additional studies were conducted in 2004 (crayfish and macroinvertebrates), 2005 (walleye), 2006 (crayfish, walleye, sediment and macroinvertebrates) and 2007 - 2008 (crayfish, walleye, and sediment). Additional crayfish and walleye studies are scheduled to be conducted on an annual basis through 2011.

Despite the assemblage of data, it is unclear how the monitoring programs for crayfish and walleye will provide statistically significant data regarding mine impacts to the Flambeau River and biota, or lack thereof. As discussed below, flaws may exist in the study design, methods, and/or presentation of information. This makes it difficult for the public to ascertain whether contaminants are moving into biota and sediment, or whether natural macroinvertebrate populations have been impacted downstream from the mine site.

Crayfish and Walleye

The current monitoring program for crayfish does not outline a determinate number of specimens to be collected at each sample site to ensure consistency, nor how a determination would provide statistically relevant information. Moreover, even though the walleye monitoring plan calls for sampling a set number of fish at each of two sampling sites in the river, the sample sizes are quite small – one to three fish each of 5 different sizes. The plan does not explain how the collected data of such a small sample set will be statistically relevant.

Monitoring plans do not provide information regarding the natural ranging and foraging habits of crayfish and walleye to determine if these species are likely to provide information on contaminant movement specifically from the mine site. Possibly shellfish located near mine site discharges would be better indicators, if shellfish are present. The choice of species lies primarily in what question is being answered. Is the question "Are bioavailable contaminants moving out of the mine area?" or is the question "Is aquatic life safe to eat?" It would be helpful for the Stipulation Monitoring Plan to state the question they want answered.

Macroinvertebrates

A common method for assessing stream health is bioassessment using macroinvertebrates. Bioassessments were conducted 1991-1998, 2004 and 2006. Although the full data is presented, it is not clear what the data indicates. Abundance of taxa, which is presented, does not necessarily imply stream health. Rather, it is the ratio of taxa that are sensitive to pollution (generally species within Ephemeroptera, Plecoptera, Trichoptera, or EPT) and those that are tolerant to pollution (such as Diptera) that provides information. Presentation of ratios and trends in ratios over time would allow the public to better understand impacts to aquatic life in the Flambeau River.

While it is essential and useful to provide raw numbers of species in order to allow independent experts the ability to analyze the data, the utility of the macroinvertebrate data would be enhanced by reporting summary information such as percent EPT of total abundance; richness of each of Ephemeroptera, Plecoptera, Trichoptera, and Diptera; percent taxa intolerant to pollution and percent taxa tolerant to pollution in a manner that allows the general public to understand trends.

CONCLUSIONS

Copper contamination in excess of Wisconsin water quality standards is reaching the Flambeau River from the Flambeau mine site and the Flambeau pit is leaching contaminants that exceed Wisconsin groundwater quality standards to beyond the slurry wall designed to separate pit water from the Flambeau River. It appears that the state is allowing these unpermitted discharges to continue under the assumptions that (1) dilution in the Flambeau River is such that no impact is occurring, and that (2) no contaminated groundwater from the pit is flowing under the Flambeau River toward the groundwater compliance boundary.

If all, or part of the groundwater contamination is not entering the Flambeau River, as is presently assumed, then it is going under the river towards the 1200 foot compliance boundary. There appears to be insufficient monitoring to determine either the quantity of groundwater movement, the quantity of contamination entering the Flambeau River, and/or the groundwater contamination migrating toward the southwest groundwater compliance boundary.

As discussed in this report, it is not clear from the monitoring data that there is no impact from the surface water discharge both into Stream C, and from Stream C into the Flambeau River, as it crosses Meadowbrook Creek. Since this is an ongoing discharge from an industrial facility, the discharge should be more carefully monitored, and should either be cleaned up before it leaves the mine site, or the discharge should be regulated under a Clean Water Act discharge permit which would place limits on the amount of contamination discharged, and the “mixing zone” which is currently being utilized in the Flambeau River.

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Figure A: Plan View Groundwater Flow

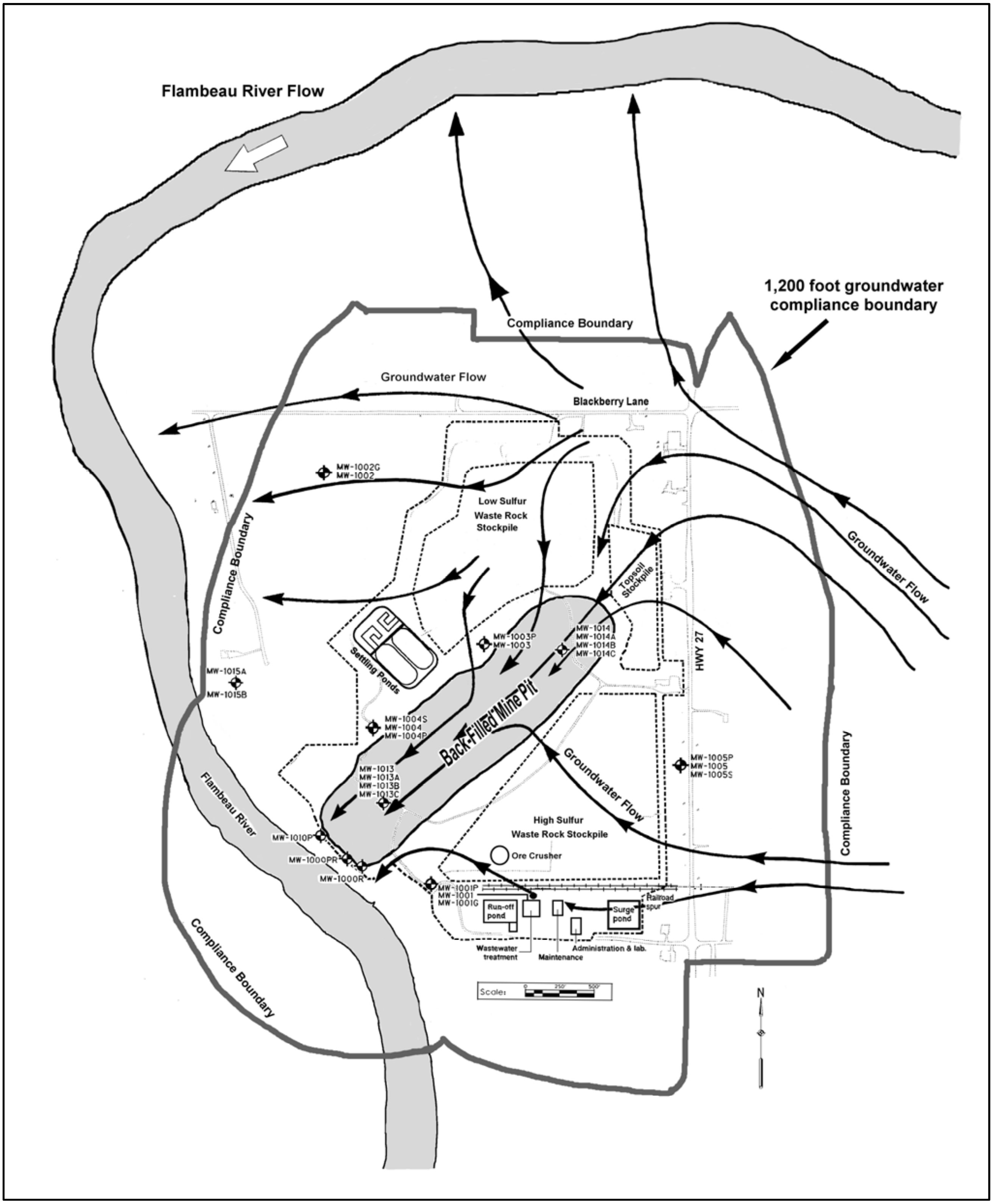


Figure B: Groundwater Potentiometric Surface

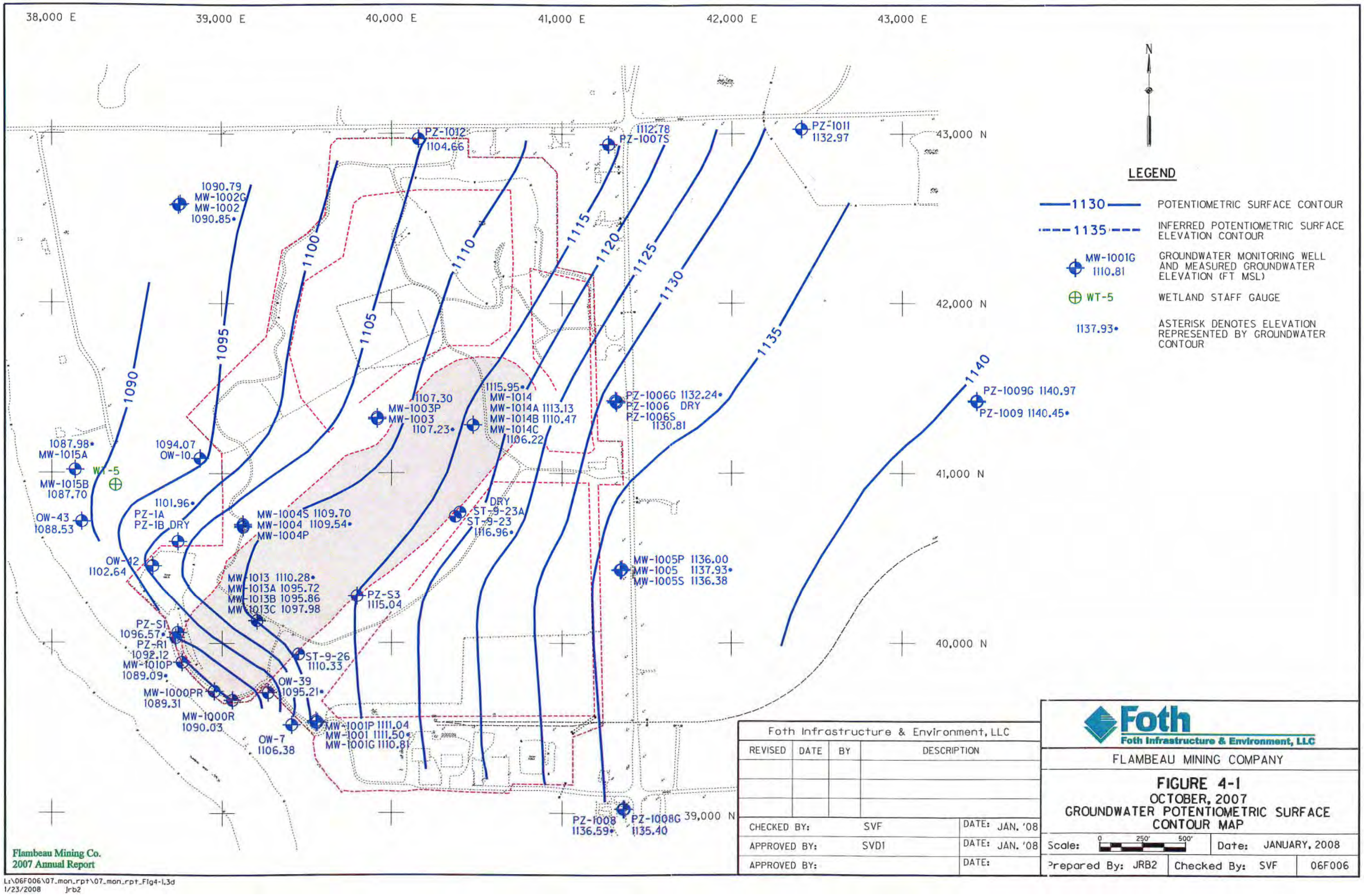


Figure C: Outlot Biofilter Drainage Area

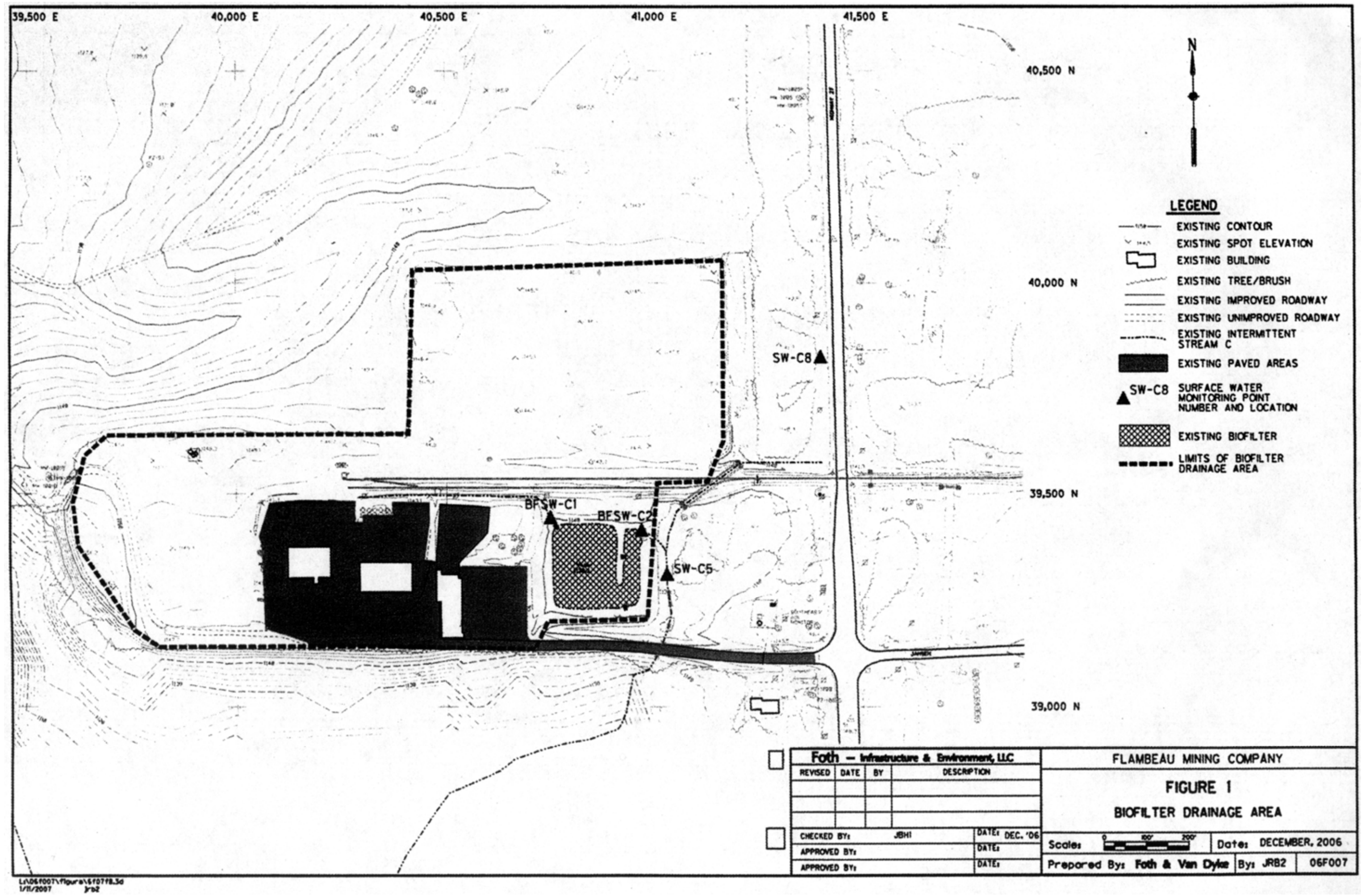
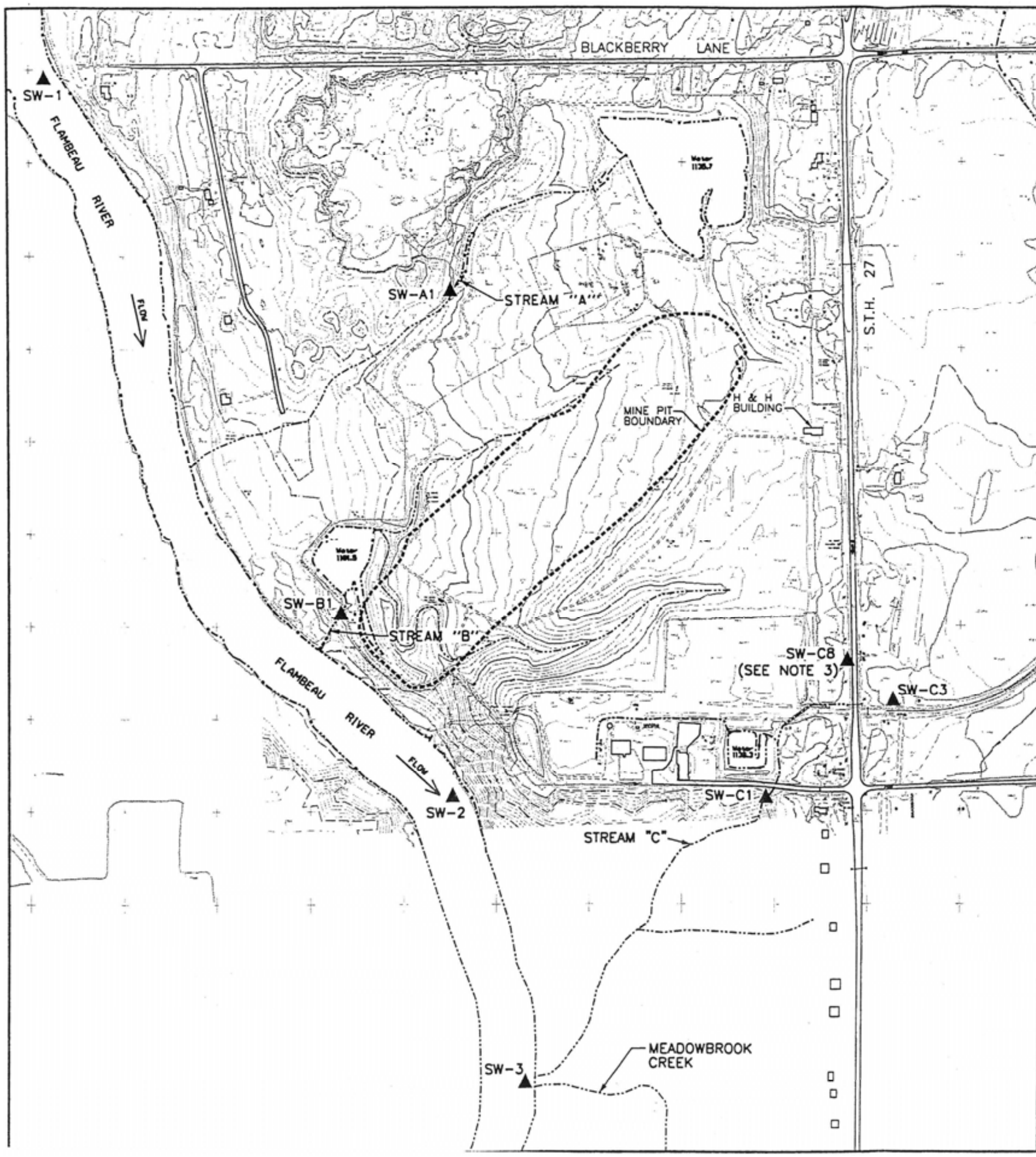


Figure D: Active Surface Water Monitoring Locations



	Location	ug/L Copper.tot	mg/L Iron.tot	ug/L Mn	mg/L Sulfate	ug/L Zinc
(SEE NOTE 3) →	SW-C8	86	2.5	140	5.3	41
	SW-A1	[3.1]	0.37	61	<2.5	10
	SW-B1	[2.7]	0.44	13	<2.5	[7.8]
	SW-B1(DUP)	[2.9]	0.45	13	<2.5	[7.1]
	SW-C1	47	1.3	23	5.8	52
	SW-1	<1.3	0.57	130	10	[6.0]
	SW-2	<1.3	0.50	130	11	[5.4]
	SW-3	4.2	0.60	100	10	[8.6]

NOTES:
- < NOT DETECTED ABOVE THE LOD
- [ ] RESULTS ≥ THE LOD BUT < THE LOQ AND ARE WITHIN A REGION OF "LESS-CERTAIN QUANTITATION"
- LOD LIMIT OF DETECTION
- LOQ LIMIT OF QUANTITATION
- DUP DUPLICATE
- ug/L MICROGRAMS/LITER
- mg/L MILLIGRAMS/LITER

N

LEGEND
- SW-A1 ▲ SURFACE WATER SAMPLE NUMBER AND LOCATION
- EXISTING CONTOUR
- EXISTING SPOT ELEVATION
- EXISTING BUILDING
- EXISTING TREE/BRUSH
- EXISTING IMPROVED ROADWAY
- EXISTING UNIMPROVED ROADWAY

NOTES:
1. RESULTS POSTED FROM SEPTEMBER 2007.
2. SW-C3 WAS ADDED TO THE SAMPLING PLAN IN NOVEMBER 2007 AND WAS NOT SAMPLED IN SEPTEMBER 2007.
3. SW-C8 COC AND DATA SHEET SUBMITTED WITH THE BIOFILTER SUBMITTAL DATED 9/27/07

Foth – Infrastructure & Environment, LLC

REVISED	DATE	BY	DESCRIPTION

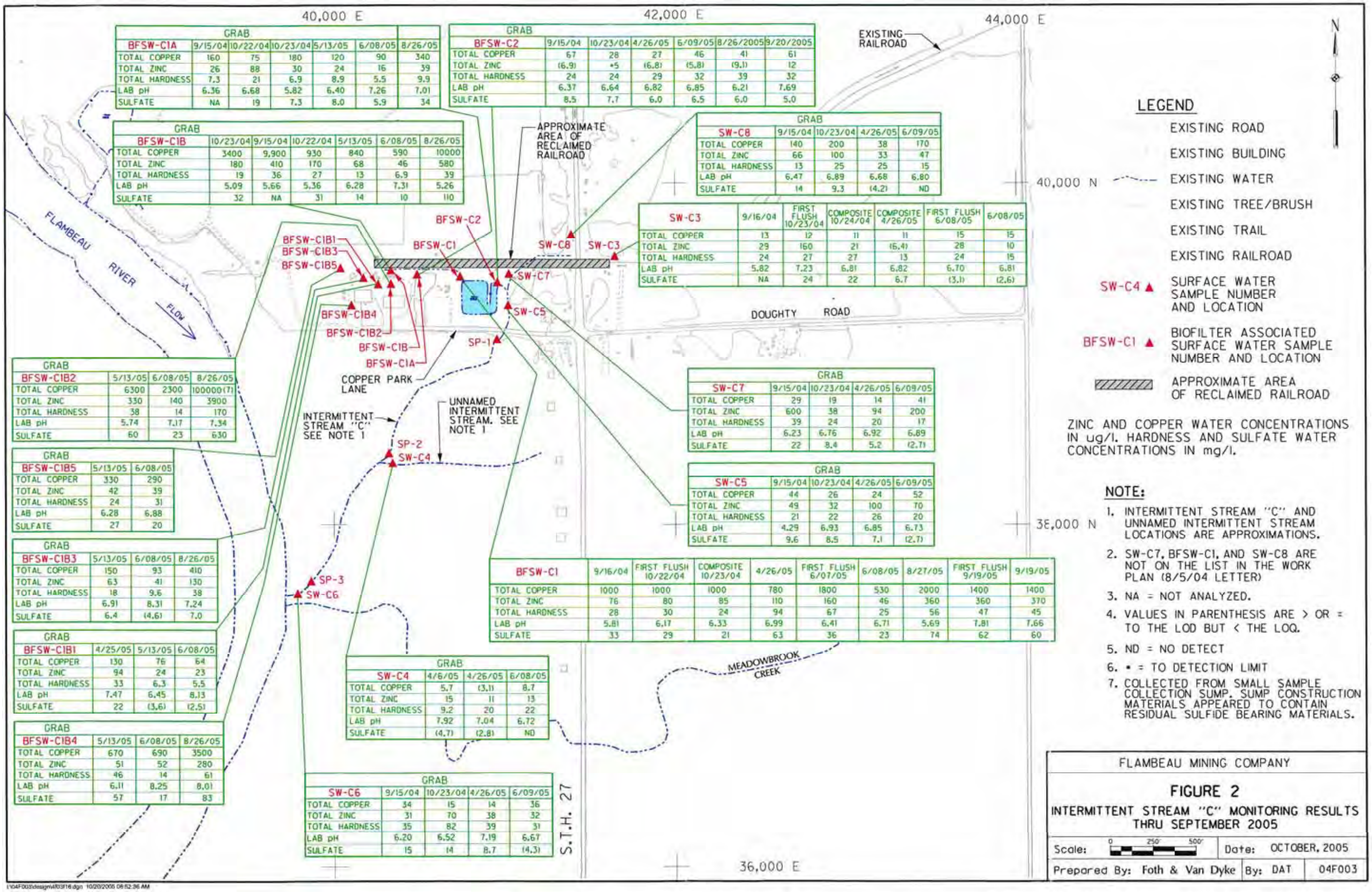
CHECKED BY: DATE:
APPROVED BY: DATE:
APPROVED BY: DATE:

FLAMBEAU MINING COMPANY

FIGURE 1
STIPULATED MONITORING
SURFACE WATER SAMPLE LOCATIONS
AND SEPTEMBER 2007 RESULTS

Scale: 0 300' 600' | Date: DECEMBER, 2007
Prepared By: BLK | Checked By: SVF | 06F006

Figure E: Stream C Water Quality Data



BFSW-C1A (GRAB)	9/15/04	10/22/04	10/23/04	5/13/05	6/08/05	8/26/05
TOTAL COPPER	160	75	180	120	90	340
TOTAL ZINC	26	88	30	24	16	39
TOTAL HARDNESS	7.3	21	6.9	8.9	5.5	9.9
LAB pH	6.36	6.68	5.82	6.40	7.26	7.01
SULFATE	NA	19	7.3	8.0	5.9	34

BFSW-C1B (GRAB)	10/23/04	9/15/04	10/22/04	5/13/05	6/08/05	8/26/05
TOTAL COPPER	3400	9,900	930	840	590	10000
TOTAL ZINC	180	410	170	68	46	580
TOTAL HARDNESS	19	36	27	13	6.9	39
LAB pH	5.09	5.66	5.36	6.28	7.31	5.26
SULFATE	32	NA	31	14	10	110

BFSW-C2 (GRAB)	9/15/04	10/23/04	4/26/05	6/09/05	8/26/2005	9/20/2005
TOTAL COPPER	67	28	27	46	41	61
TOTAL ZINC	(6.9)	*5	(6.8)	(5.8)	(9.1)	12
TOTAL HARDNESS	24	24	29	32	39	32
LAB pH	6.37	6.64	6.82	6.85	6.21	7.69
SULFATE	8.5	7.7	6.0	6.5	6.0	5.0

SW-C8 (GRAB)	9/15/04	10/23/04	4/26/05	6/09/05
TOTAL COPPER	140	200	38	170
TOTAL ZINC	66	100	33	47
TOTAL HARDNESS	13	25	25	15
LAB pH	6.47	6.89	6.68	6.80
SULFATE	14	9.3	(4.2)	ND

SW-C3	9/16/04	FIRST FLUSH 10/23/04	COMPOSITE 10/24/04	COMPOSITE 4/26/05	FIRST FLUSH 6/08/05	6/08/05
TOTAL COPPER	13	12	11	11	15	15
TOTAL ZINC	29	160	21	(6.4)	28	10
TOTAL HARDNESS	24	27	27	13	24	15
LAB pH	5.82	7.23	6.81	6.82	6.70	6.81
SULFATE	NA	24	22	6.7	(3.1)	(2.6)

BFSW-C1B2 (GRAB)	5/13/05	6/08/05	8/26/05
TOTAL COPPER	6300	2300	100000(7)
TOTAL ZINC	330	140	3900
TOTAL HARDNESS	38	14	170
LAB pH	5.74	7.17	7.34
SULFATE	60	23	630

BFSW-C1B5 (GRAB)	5/13/05	6/08/05
TOTAL COPPER	330	290
TOTAL ZINC	42	39
TOTAL HARDNESS	24	31
LAB pH	6.28	6.88
SULFATE	27	20

BFSW-C1B3 (GRAB)	5/13/05	6/08/05	8/26/05
TOTAL COPPER	150	93	410
TOTAL ZINC	63	41	130
TOTAL HARDNESS	18	9.6	38
LAB pH	6.91	8.31	7.24
SULFATE	6.4	(4.6)	7.0

BFSW-C1B1 (GRAB)	4/25/05	5/13/05	6/08/05
TOTAL COPPER	130	76	64
TOTAL ZINC	94	24	23
TOTAL HARDNESS	33	6.3	5.5
LAB pH	7.47	6.45	8.13
SULFATE	22	(3.6)	(2.5)

BFSW-C1B4 (GRAB)	5/13/05	6/08/05	8/26/05
TOTAL COPPER	670	690	3500
TOTAL ZINC	51	52	280
TOTAL HARDNESS	46	14	61
LAB pH	6.11	8.25	8.01
SULFATE	57	17	83

SW-C7 (GRAB)	9/15/04	10/23/04	4/26/05	6/09/05
TOTAL COPPER	29	19	14	41
TOTAL ZINC	600	38	94	200
TOTAL HARDNESS	39	24	20	17
LAB pH	6.23	6.76	6.92	6.89
SULFATE	22	8.4	5.2	(2.7)

SW-C5 (GRAB)	9/15/04	10/23/04	4/26/05	6/09/05
TOTAL COPPER	44	26	24	52
TOTAL ZINC	49	32	100	70
TOTAL HARDNESS	21	22	26	20
LAB pH	4.29	6.93	6.85	6.73
SULFATE	9.6	8.5	7.1	(2.7)

BFSW-C1	9/16/04	FIRST FLUSH 10/22/04	COMPOSITE 10/23/04	4/26/05	FIRST FLUSH 6/07/05	6/08/05	8/27/05	FIRST FLUSH 9/19/05	9/19/05
TOTAL COPPER	1000	1000	1000	780	1800	530	2000	1400	1400
TOTAL ZINC	76	80	85	110	160	46	360	360	370
TOTAL HARDNESS	28	30	24	94	67	25	56	47	45
LAB pH	5.81	6.17	6.33	6.99	6.41	6.71	5.69	7.81	7.66
SULFATE	33	29	21	63	36	23	74	62	60

SW-C4 (GRAB)	4/6/05	4/26/05	6/08/05
TOTAL COPPER	5.7	(3.1)	8.7
TOTAL ZINC	15	11	13
TOTAL HARDNESS	9.2	20	22
LAB pH	7.92	7.04	6.72
SULFATE	(4.7)	(2.8)	ND

SW-C6 (GRAB)	9/15/04	10/23/04	4/26/05	6/09/05
TOTAL COPPER	34	15	14	36
TOTAL ZINC	31	70	38	32
TOTAL HARDNESS	35	82	39	31
LAB pH	6.20	6.52	7.19	6.67
SULFATE	15	14	8.7	(4.3)

Figure F: Location of pit monitoring wells (Flambeau Mine Company Annual Report 2007)

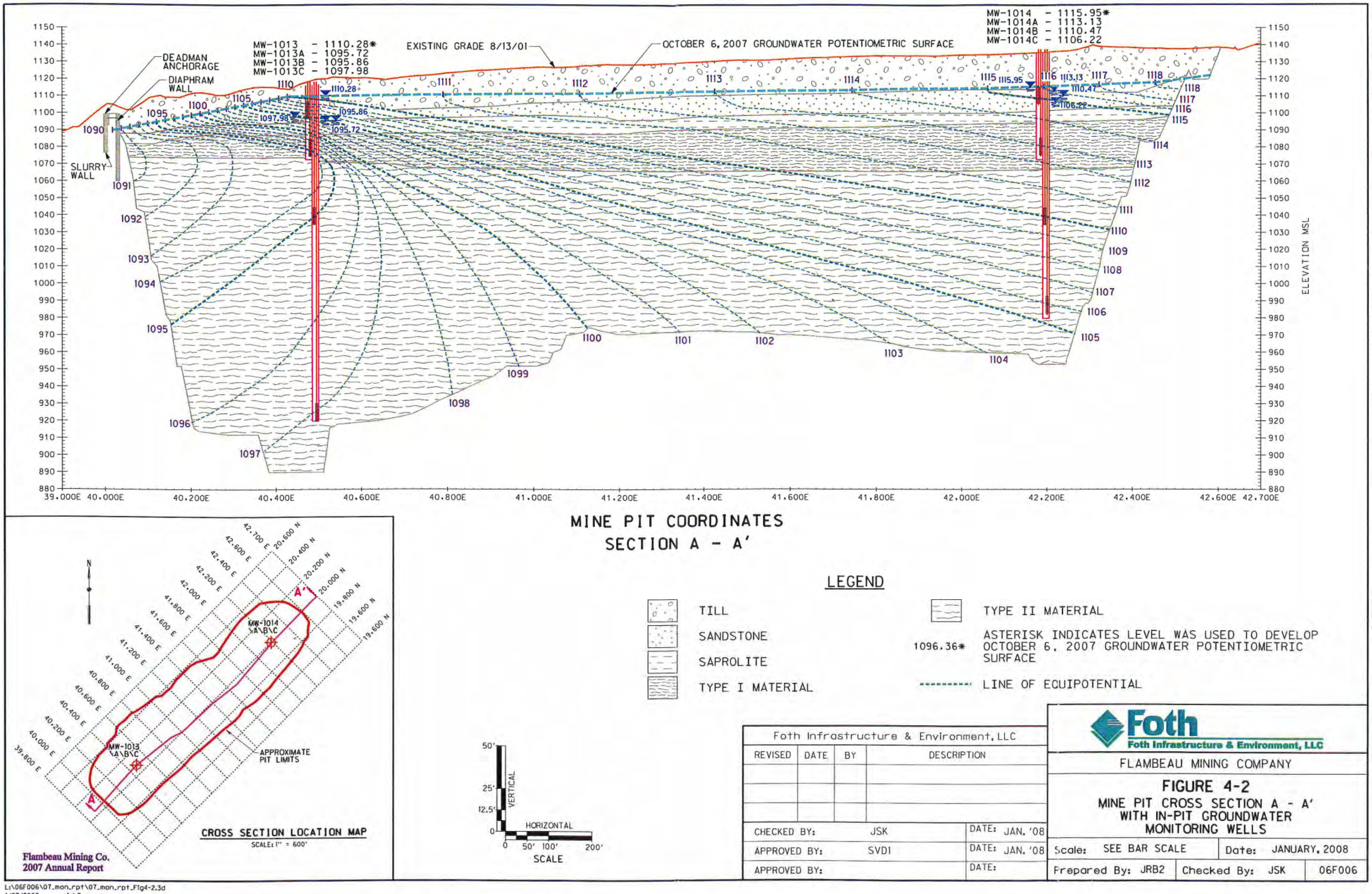


Figure G: Manganese Levels in Monitoring Well 1013-B at Reclaimed Flambeau Mine Site (1999-2007) (raw data obtained from Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trend and Flambeau Mining Company, Environmental Monitoring Results (Groundwater), First Quarter 2008, Second Quarter 2008, and Third Quarter 2008 reports)

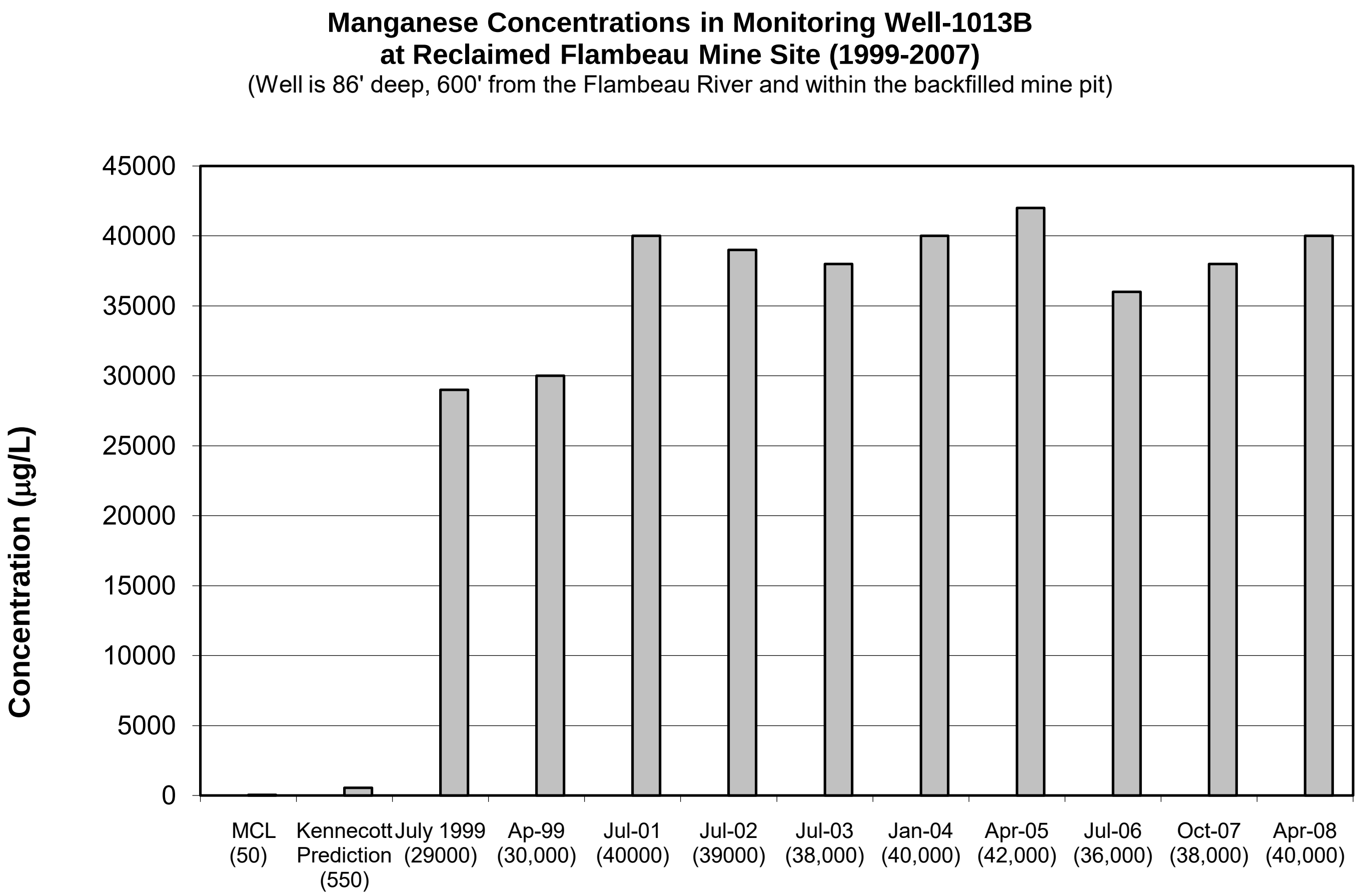


Table 4. Manganese Levels in Pore Water within Backfilled Flambeau Mine Pit Reported by Flambeau Mining Company (FMC) to the Wisconsin Department of Natural Resources (μg/L)[45]

	MW 1013	MW 1013A	MW 1013B	MW 1013C	MW 1014	MW 1014A	MW 1014B	MW 1014C
Depth	24'	47'	86'	202'	34'	64'	105'	157'
FMC Prediction [46]	550	550	550	550	550	550	550	550
Feb 99	Dry	Dry	25,000	7,200	Dry	Dry	23,000	4,300
Apr 99	Dry	Dry	30,000	7,700	Dry	Dry	23,000	4,500
Jul 99	Dry	Dry	29,000	7,300	Dry	Dry	23,000	4,000
Apr 00	Dry	Dry	32,000	7,800	Dry	7,200	22,000	3,600
Oct 00	Dry	Dry	35,000	8,200	Dry	6,700	21,000	3,200
Jul 01	Dry	Dry	40,000	9,000	Dry	6,500	20,000	3,000
Oct 01	Dry	Dry	34,000	8,500	Dry	6,000	18,000	2,900
Jul 02	Dry	Dry	39,000	10,000	Dry	6,100	19,000	2,700
Jan 03	Dry	Dry	33,000	9,500	Dry	5,300	17,000	2,400
Jul 03	Dry	Dry	38,000	9,600	Dry	4,200	16,000	2,500
Oct 03	Dry	Dry	37,000	9,800	Dry	3,000	19,000	2,400
Jan 04	Dry	Dry	40,000	9,100	Dry	3,100	17,000	2,300
Apr 04	Dry	Dry	32,000	9,700	Dry	3,100	14,000	2,300
Oct 04	Dry	Dry	34,000	9,800	Dry	2,000	17,000	2,100
Jan 05	Dry	Dry	24,000	9,500	Dry	2,000	16,000	2,000
Apr 05	Dry	Dry	42,000	10,000	Dry	2,000	16,000	2,300
Jul 05	Dry	Dry	39,000	11,000	Dry	1,400	17,000	2,200
Oct 05	25,000	4,500	30,000	11,000	1,300	1,500	15,000	2,200
Apr 06	21,000	3,900	25,000	11,000	1,200	2,100	14,000	2,100
Jul 06	20,000	1,700	36,000	9,800	940	1,400	12,000	1,900
Oct 06	24,000	2,400	23,000	11,000	880	820	13,000	2,000
Jan 07	24,000	1,700	24,000	11,000	1,300	780	15,000	1,900
Apr 07	24,000	1,700	23,000	11,000	610	920	14,000	2,000
Oct 07	24,000	2,600	38,000	11,000	580	890	13,000	2,000
Jan 08	24,000	2,100	31,000	10,000	800	940	14,000	1,800
Apr 08	23,000	2,800	40,000	11,000	260	1,100	14,000	1,900
Jun 08	22,000	3,500	21,000	10,000	830	410	14,000	1,800

[45] Unless otherwise indicated, data was obtained from: (1) Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trends; or (2) Flambeau Mining Company, Environmental Monitoring Results (Groundwater), First Quarter 2008, Second Quarter 2008, and Third Quarter 2008 reports.

[46] Foth & Van Dyke, 1989, pg L27-L31.

Table 5. Copper Levels in Pore Water within Backfilled Flambeau Mine Pit Reported by Flambeau Mining Company (FMC) to Wisconsin Department of Natural Resources (µg/l)[a]

	MW 1013	MW 1013A	MW 1013B	MW 1013C	MW 1014	MW 1014A	MW 1014B	MW 1014C
Depth	24'	47'	86'	202'	34'	64'	105'	157'
FMC Prediction[b]	14	14	14	14	14	14	14	14
Feb 99	Dry	Dry	36	100	Dry	Dry	810	<4.7
Jul 99	Dry	Dry	33	50	Dry	Dry	520	16
Oct 00	Dry	Dry	<12	<12	Dry	<12	430	<12
Oct 01	Dry	Dry	69	<13	Dry	<13	490	<13
Jul 02	Dry	Dry	150	<13	Dry	<13	550	<13
Jan 03	Dry	Dry	92	<13	Dry	<13	590	<13
Jul 03	Dry	Dry	120	<13	Dry	<13	500	<13
Oct 03	Dry	Dry	110	<13	Dry	<13	640	<1.3
Apr 04	Dry	Dry	230	<13	Dry	<13	440	<13
Oct 04	Dry	Dry	380	<13	Dry	<13	550	<13
Jan 05	Dry	Dry	180	<13	Dry	<13	520	<13
Apr 05	Dry	Dry	450	<13	Dry	<13	460	<13
Jul 05	Dry	Dry	400	<13	Dry	<13	560	<13
Oct 05	<13	<13	230	<13	<13	<13	400	<13
Apr 06	23	17	280	<13	36	22	530	<13
Jul 06	24	16	470	14	26	31	510	16
Oct 06	<13	<13	200	<13	<13	<13	460	<13
Jan 07	<13	<13	290	<13	39	<13	600	<13
Apr 07	<13	<13	230	<13	17	<13	470	<13
Jun 07	<13	<13	240	<13	<13	<13	600	<13
Oct 07	<13	<13	500	<13	33	<13	490	<13
Jan 08	<13	<13	400	<13	<13	<13	500	<13
Apr 08	<13	<13	530	<13	<13	<13	570	<13
June 08	[22]	<13	270	<13	22	<13	580	<13

[a] Unless otherwise indicated, data was obtained from: (1) Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trends; (2) Flambeau Mining Company, Environmental Monitoring Results (Groundwater), First Quarter 2008, Second Quarter 2008, and Third Quarter 2008 reports.

[b] Foth & Van Dyke, 1989, pg L27-L31.

Table 6. Iron Levels in Pore Water within Backfilled Flambeau Mine Pit Reported by Flambeau Mining Company (FMC) to Wisconsin Department of Natural Resources (µg/l)[a]

	MW 1013	MW 1013A	MW 1013B	MW 1013C	MW 1014	MW 1014A	MW 1014B	MW 1014C
Depth	24'	47'	86'	202'	34'	64'	105'	157'
FMC Prediction[b]	320	320	320	320	320	320	320	320
Feb 99	Dry	Dry	45	920	Dry	Dry	62	14,000
Jul 99	Dry	Dry	760	1,300	Dry	Dry	72	14,000
Oct 00	Dry	Dry	840	1,600	Dry	960	<360	12,000
Oct 01	Dry	Dry	660	2,700	Dry	1,500	<150	9,600
Jul 02	Dry	Dry	700	4,100	Dry	380	<150	9,400
Jan 03	Dry	Dry	150	5,400	Dry	540	<150	8,300
Jul 03	Dry	Dry	610	4,200	Dry	320	<290	8,200
Oct 03	Dry	Dry	<290	6,200	Dry	1,000	<290	7,800
Apr 04	Dry	Dry	<330	7,800	Dry	130	<330	7,500
Oct 04	Dry	Dry	<330	7,000	Dry	<330	<330	6,600
Jan 05	Dry	Dry	<330	7,200	Dry	<330	<330	6,400
Apr 05	Dry	Dry	<330	8,200	Dry	<330	<330	7,000
Jul 05	Dry	Dry	<330	8,500	Dry	<330	<330	6,900
Oct 05	22,000	<330	<330	8,300	<330	<330	<330	7,000
Apr 06	2,200	<330	<220	8,900	<330	<330	<330	6,400
Jul 06	3,200	<330	<330	7,000	<330	<330	<330	5,900
Oct 06	11,000	<330	<330	9,100	<330	<660	<330	6,100
Jan 07	12,000	<330	<330	9,500	<330	<330	<330	6,000
Apr 07	3,300	<330	<330	9,300	<33	530	<330	6,100
Jun 07	9,600	<330	<330	11,000	<330	<330	<330	5,800
Oct 07	15,000	<330	<330	9,700	<330	<330	<330	5,800
Jan 08	14,000	<330	<330	9,100	<330	<330	<330	5,400
Apr 08	4,100	<330	<330	9,600	<330	<330	<330	5,600
Jun 08	3,600	<330	<330	10,000	<330	<330	<330	5,400

[a] Unless otherwise indicated, data was obtained from: (1) Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trends; or (2) (2) Flambeau Mining Company, Environmental Monitoring Results (Groundwater), First Quarter 2008, Second Quarter 2008, and Third Quarter 2008 reports.

[b] Foth & Van Dyke, 1989, pg L27-L31.

Table 7. Groundwater Quality in Intervention Boundary Well MW-1000PR[a]

	Parameter							
	Calcium (mg/L)	Conductance, field (μmhos/cm)	Copper (μg/L)	Iron (μg/L)	Manganese (μg/L)	Sulfate (mg/L)	Total Diss. Solids (mg/L)	Zinc (μg/L)
1987-88 EIS Baseline (Prior to mining) [b]	9-26	98-251	< 66	< 620	260-590	16-31	100-350	<110
Flambeau Mine Permit Standard [c]	25 over baseline	200 over baseline	14	320	550	1100	200 over baseline	2500
Jul 1991 (Repeat Baseline)	20[d]	225	<14	650	850	<10	190	Not Done
Apr 96 (Prior to backfilling)	11[d]	150	31	18	64	16	130	Not Done
Apr 97 (During backfilling)	12[d]	133	32	43	190	10	160	Not Done
Jul 98 (After backfilling)	130[d]	1097	66	76	1800	350	250	42[d]
Apr 99	Not Done	1319	55	1300	5300	340	1200	Not Done
Jul 99	220	1310	97	3200	5600	350	1300	880
Oct 99	210	1400	17	3600	5200	680	1100	730
Oct 00	200[d]	1189	<2.6	6600	4200	460	1100	900
Oct 01	160	1109	<13	2800	3300	450	940	440
Jul 02	170	1093	<13	6200	3600	380	1000	640
Jan 03	170	1080	<13	6700	3200	390	990	700
Jul 03	170	1027	<6.7	6600	3200	360	810	730
Apr 04	151	1025	<6.7	7000	2900	330	720	623
Jul 04	150	998	28	2300	2800	310	690	830
Jul 05	160	962	27	1500	2900	330	680	650
Oct 05	Not Done	955	25	730	2900	330	730	Not Done
Apr 06	150	926	30	460	2600	300	620	560
Jul 06	130	928	21	620	2400	310	660	500
Oct 06	Not Done	948	12	490	2700	290	600	Not Done
Jan 07	Not Done	959	29	260	2600	290	570	Not Done
Apr 07	Not Done	929	13	380	2600	300	630	Not Done
Jul 07	140	887	12	660	2600	300	660	490
Oct 07	Not Done	933	<2.7	4700	2800	300	650	Not Done
Jan 08	Not Done	921	13	310	2400	310	690	Not Done
Apr 08	Not Done	880	7.8	330	2500	280	710	Not Done
Jun 08	140	932	21	460	2500	240	640	450

a Unless otherwise indicated, data was obtained from: (1) Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trends; or (2) Flambeau Mining Company, 2008 Environmental Monitoring Results (Groundwater) First Quarter, Second Quarter, and Third Quarter reports
b Data on file with Wisconsin Department of Natural Resources, Madison, WI
c Decision, Findings of Fact, Conclusions of Law and Permits [for the Flambeau Mine], State of Wisconsin Division of Hearings and Appeals, 1991, pp. 87-93.
d Since FMC did not report test results for the parameter in question, the indicated value is from split sample test results reported by the Wisconsin Department of Natural Resources and on file at Department headquarters in Madison, WI.

Table 8. Iron and Manganese Concentrations in Compliance Boundary Well MW-1015B [a]

	Parameter	
	Iron (µg/L)	**Manganese (µg/L)**
Pre-Mine Baseline[b]	Not Done	Not Done
Flambeau Mine Enforcement Standard[c]	300	230
Apr 01	69	140
Jul 01	<5	19
Oct 01	<5	8.6
Jan 02	<5	25
Apr 02	<5	73
Jul 02	69	53
Oct 02	420	380
Jan 03	120	440
Apr 03	210	250
Jul 03	450	170
Oct 03	670	290
Jan 04	440	240
Apr 04	380	120
Jul 04	450	190
Oct 04	300	140
Jan 05	220	120
Apr 05	290	130
Jul 05	400	140
Oct 05	300	140
Jan 06	320	110
Apr 06	440	100
Jul 06	52	97
Oct 06	320	110
Jan 07	350	120
Apr 07	160	81
Jul 07	340	100
Oct 07	330	100
Jan 08	290	94
Apr 08	300	86
Jun 08	200	89

[a] Unless otherwise indicated, data was obtained from: (1) Flambeau Mining Company, 2007 Annual Report, Appendix B – Groundwater Quality & Elevation/Surface Water Quality Trends; or (2) Flambeau Mining Company, 2008 Environmental Monitoring Results (Groundwater) First Quarter, Second Quarter, and Third Quarter reports

[b] The MW-1015 nest was not drilled until January 2001. Since the mine operated from 1993-1997 and the pit was backfilled in 1997, this means there are no pre-mine baseline measurements. The MW-1015 nest was first sampled in April 2001.

[c] Decision, Findings of Fact, Conclusions of Law and Permits [for the Flambeau Mine], State of Wisconsin Division of Hearings and Appeals, 1991, pp. 87-93.

Technical Memorandum

Review of PolyMet Project NPDES/SDS Permit Application

Prepared for Minnesota Center for Environmental Advocacy

Prepared by Tom Myers, Ph.D., Hydrologic Consultant, Reno NV

February 19, 2018

TABLE OF CONTENTS

FIGURES

TABLES

Executive Summary

The NPDES/SDS permit application for the PolyMet Project is insufficient to protect surface and groundwater in the area around the project. This review considers the assumptions relied upon by PolyMet to complete their application.

This review also used a groundwater flow model to assess various problems with the permit. The groundwater model, originally developed in 2014 to assess impacts of the project as outlined in the environmental impact statement, was updated to improve mass balance and transport calculations near the sources, so the predictions herein should be considered more accurate and precise than those made previously.

The report outlines and details the following results:

- The nondegradation analysis relies on the assumption that the engineered seepage capture system, covers, and mine site will be 100% effective. Based on my analysis, the assumptions underlying the seepage capture system are questionable. Applying more realistic assumptions, this analysis assumes there will be some leaks from the system. Any leaks will result in a contaminant plume that would be very difficult to remediate. And any leaks will result in groundwater and surface water contamination.
- Dewatering rates will vary substantially, and will likely exceed the treatment facilities capacity to treat water. Increases in dewatering due to fracture flow will likely require dewatering techniques such as dedicated dewatering wells that will cause the mine to violate the zero-discharge standard.
- Dewatering creates a groundwater divide under the mine site, creating pathways for contaminants to go both north and south, to the headwaters of or to downstream reaches of the Partridge River.
- Backfilling the East Pit with highly reactive waste creates a high concentration water in the pit that will increase the concentrations in dewatering flow that is not considered in the application.
- Backfilling the East Pit with highly reactive waste and then filling it with water creates a situation where pit water will likely flow into surrounding groundwater, at least temporarily, and contaminate it.
- Rapid fill of the West Pit will cause pit water to flow into surrounding groundwater, thereby degrading the groundwater. The application does not consider this groundwater degradation.
- Leaks emanating from different portions of the plant or mine site will follow different pathways to the rivers. Plume maps produced in Appendix A show that contamination

from leaks will follow a specific pathway with dispersion causing contamination to expand horizontally and vertically.

- Waste water seeping from both the tailings impoundment and waste sites on the Mine Site will reach surface water, as shown by transport analysis. Contaminant plumes released from both mine site and plant site sources will reach long stretches of surface water. This includes waste from the tailings impoundment reaching the Embarrass River and from mine site sources reaching the Partridge River both to the north and south.
- Variable slopes in the cumulative load curve for the Embarrass River, both with and without the cutoff wall, show areas of differing load reaching the river. This shows the need for at least four surface water monitoring points along the river, at about mile point 6, 8, 10, and 13.
- Pathways from both sites show the need for substantially more surface water monitoring. Contaminants could reach the river along substantial reaches, and it is necessary to monitor at many locations to identify the source.
- Proposed groundwater monitoring is insufficient. Contaminant plumes would move between widely-spaced monitoring wells. This observation holds for monitoring between the mine site and Partridge River and between the tailings impoundment and the Embarrass River.
- Groundwater monitoring wells should be placed where contaminant plumes are most likely to pass. This requires an understanding of flow in the area, which requires a conceptual flow and transport model (CFTM), prepared a scale appropriate to the site. This would include identifying all potential sources and sinks, such as facilities on the mine site that could release contaminants. Sinks that could be damaged are downgradient wells, springs, or streams. Once identified, it is necessary to determine the potential flow path from the source to the sink.

The NPDES/SDS permit for the PolyMet mine proposal should not be awarded because the application is based on overly optimistic design assumptions, modeling that does not consider flow path details near either the mine site or tailings impoundment, inaccurate analysis of pathways for contaminants to reach the rivers, and grossly insufficient proposed monitoring.

Introduction

PolyMet applied for a NPDES/SDS (National Pollutant Discharge Elimination System/State Disposal System) for its proposed Northmet mine. The NPDES/SDS permit is for discharge to surface water and groundwater protection in the area. PolyMet applied for a NPDES permit only at the plant site at the water treatment plant which will discharge water into three small streams near the tailings impoundment. Other conditions in the permit are intended to protect groundwater under state standards.

The NPDES/SDS permit application includes seven volumes, including an introductory volume describing the general permit requirements and issues, one volume for the mine site and five volumes for plant site. The focus of this review is PolyMet's NPDES/SDS permit application as it applies to the mine site (Volume II), the tailings facility (tailings basin and beneficiation plant) (Volume V), the hydrometallurgical residue facility (Volume VI), and aspects of the waste water treatment system (WWTS) (Volume III). The review is primarily of the revised application issued in October 2017. References to the application are to Volume number.

Volume I introduced the project and provided the most detail regarding the proposed monitoring. This review memorandum focuses on contamination from the mine site and tailings impoundment. It does not focus on stormwater management, the transportation system, or the details of the wastewater treatment. The memorandum identifies pathways through which discharges to groundwater may reach surface, thereby being a surface water discharge. It does this by considering the conceptual and numerical flow models of Myers (2014) to analyze pathways for contaminant transport to surface water. It also assesses the monitoring plans set forth in the application.

Description of the Application

NPDES/SDS refers to separate state-administered programs regarding how the project discharges water. NPDES in this application is for a traditional point-source discharge to waters of the state and SDS for the protection or remediation of groundwater, a state program described under Minn. R. 7060.0100-.0900. The project requested an NPDES permit only for the WWTS, specifically described in Volume III, which discharges as point source into three streams.

PolyMet's application primarily pertains to the first 5 years of the mine's operation, although it sometimes describes the plan for 11 years (*see, e.g.*, Vol. I, p. 27) and through closure in some places. The application identifies eleven types of water:

- <u>Mine water</u>: water collected by the mine water management systems, which includes runoff and groundwater from the mine site. Ostensibly, this is only water that has contacted mine sources, such as pit wall, waste rock, or ore, and has been collected from the pit sumps or various collection systems on the mine site.
- <u>Treated mine water</u>: water routed from the mine site to the plant site, after collection and treatment at the mine site water treatment facility.
- <u>Process water</u>: water used in beneficiation or hydrometallurgical process.

- Sewage: water from sanitary facilities.
- Tailings basin water: water in the tailings basin pond or the pores of the tailings, which includes process water, treated mine water route to the tailings basin, tailings basin seepage, treated sewage, and precipitation on the tailings.
- Tailings basin seepage: tailings basin water that infiltrates through the tailings basin.
- Hydrometallurgical residue facility (HRF) water: water collected and stored within the HRF.
- Plant reservoir water: water stored in the plant reservoir, including makeup water from Colby Lake and precipitation on the plant reservoir.
- Industrial stormwater
- Construction stormwater
- Non-contact stormwater

Volume II describes water management at the mine site, which PolyMet claims just collects mine water from a variety of sources, treats it, and pumps it to the plant site (into the tailings impoundment). The application completes a groundwater nondegradation analysis to show how the facilities with various liners, ponds, stockpiles, and pit will not degrade groundwater quality. This will be considered in detail below because there are many possible ways the project will degrade groundwater and it is possible the project will create an effective discharge to surface water.

Volume III considers the water treatment system, including the facilities at the mine site which would treat mine water prior to pumping it to the plant site and the water treatment plant at the plant site. Some water would be discharged from the plant site treatment facility to surface water in three separate drainages as hydrologic mitigation to make up for water lost to the seepage containment system at the tailings impoundment. The focus of this review is on whether the plant can accommodate the expected water flow rates, not on treatment processes.

Volume V describes water management at the tailings impoundment and beneficiation plant. PolyMet describes the water management as collection and management of process water, tailings basin water, and tailings basin seepage (Vol. V, p. 11). The tailings impoundment would be constructed on top of an existing ferrous metal tailings impoundment that has substantial leakage, with at least six seeps around its base, and significant downgradient groundwater contamination. Current seepage collection points would be replaced with a seepage containment system. There are many ways in which operations at this facility could fail and become major sources of contamination and are considered below.

The structure of this review is as follows. First, I consider the mine site NPDES/SDS issues. Second, I consider the Plant Site NPDES/SDS issues. Third, I consider pathways for flow to the rivers and the adequacy of the monitoring plans for each using an updated version of the Myers (2014) groundwater model.

Mine Site NPDES/SDS Analysis

There are three primary problems concerning permitting at the mine site. These are:

1. Groundwater and surface water degradation is highly likely because the assumption that the seepage capture system, covers, and mine site will be 100% effective is improbable and fractures in the bedrock will lead to surface water contamination;
2. The monitoring plan is unlikely to detect contaminants once a leak at the mine site occurs;
3. The size of the WWTS is inadequate for the volume of dewatering water in the system.

This section, supported by the modeling in Appendix A, describes each of these inadequacies.

Groundwater and Surface Water Degradation

The first issue with the draft NPDES/SDS permit is that it is based on PolyMet's promise that it designed the "Project to comply with the State's groundwater nondegradation policy" (Vol. II, p. 45). For this claim to be accepted, it is necessary for numerous engineered barriers to be 100% effective, and for the analyst to ignore several pathways for mercury to escape the overburden laydown area. This section explains the high likelihood that barriers will not function perfectly and both groundwater and surface water degradation will occur as a result.

Sources of Groundwater and Surface Water Degradation

I simulate paths and potential plumes from facilities on the mine site and the plant site in Appendix A. The simulations include seepage distributed around each facility and from leaks that could occur within each facility. The simulations include plumes that are compared to monitoring well locations to assess whether the proposed monitor well network is sufficient. Modeling also demonstrates that the monitoring is insufficient to detect the leaks with certainty.

The mine site would not intentionally discharge directly to surface water, but waste rock stockpiles, mine ponds, and open pits are potential sources of contamination to groundwater, as the following subsections describe. There are also sources throughout the mine site. Runoff from stockpiles could contaminate shallow groundwater. Mine ponds are potential sources of contaminants to groundwater if they are not lined or if the liners leak. Each time they fill, groundwater seepage will cause a plume to enter groundwater. This includes stormwater ponds if runoff from dumps will enter stormwater ditches and flow to a pond.

There are many examples of how the mine site could be a source of groundwater and surface water degradation. For example, if water reaches the ditch on the north side of the Category 2/3 dump, it will reach the stormwater pond from which it could seep into groundwater. The pond on the NE corner of the Category 1 dump collects runoff from all along the NE and NW side of the dump, essentially half of the dump. Vol II Sheet SW-008 shows no liner on Pond A and sheet SW-017 shows no liner for the North Perimeter Stormwater Ditch. There is also no liner for the ditch on the north side of the Category 2/3 stockpile. The ditches would carry mine-impacted water and the pond would contain mine-impacted water at least until the dump is reclaimed. The ditch essentially overlies the cutoff ditch, so that seepage would be into the one-inch rock filling the cutoff trench. GCS-010 shows the cutoff trench and stormwater ditch do not coincide. On the north side, the stormwater ditch, unlined, lies outside of the perimeter of the dump and cutoff trench. On the south, there is no stormwater ditch and the cutoff is between the dump and the pit lake. The combination of unlined ditches, cutoffs, and ponds could lead to a significant contaminant source not prevented by the NPDES/SDS permit.

Waste Stockpiles

One major source of leaks into surface water is the waste stockpiles. Contrary to other permeations of the project, the Category 1 stockpile will not have an underdrain liner, but it does have a cutoff wall. For the first 11 years, the Category 1 stockpile will have no cover, so infiltration will occur as it would for bare soil and rock. If the cutoff is not 100% effective, contaminants will reach the upper part of the Partridge River and will begin to flow south toward the lower reaches of the Partridge River. The more reactive Category 2/3 and Category 4 waste rock would be stockpiled over a liner and cutoff trench, but only temporarily. Again, any leaks would have a short path to the river.

Overburden Storage and Laydown Area

The overburden storage and laydown area (OSLA) is another area where leaks into ground and surface waters could occur. The OSLA will not have a liner (Vol. II, p. 48), even though it could be a source of mercury pollution. The base would have low permeability and drainage, water not entering the soil would be collected in an unlined mine water pond. The OSLA would have no liner in spite of the fact that peat can release mercury when it decomposes (Vol. II, p. 49). PolyMet would rely on two physical processes to prevent mercury from reaching waters, volatilization and attenuation with organic and soil matter (Id.). PolyMet ignores the ways that each of these factors could fail to prevent mercury from reaching ground or surface waters.

Mercury does volatilize, a process which could lower the concentration within the OSLA. However, gaseous mercury may not travel far before it settles from the atmosphere. This is the process by which power plant and gold mine refinery mercury emissions pollute soils and waters downwind from the source. Mercury volatilized from the OSLA could settle on soils downwind, which could leach to shallow groundwater or transport during runoff events to the rivers. PolyMet has not analyzed the potential for this and the draft NPDES/SDS permit fails to address this important issue.

Mercury also does attenuate in organic and soil matter by adhering to small particles, primarily clay and silt. Erosion of the organic or soil matter could wash the particles with mercury directly into surface water, where it could dissolve into the water column increasing mercury concentration or settle into the sediments. PolyMet has not analyzed the potential for this and the draft NPDES/SDS permit fails to address the issue.

Mine Pits

The mine pits could also be a source of contaminants to surrounding groundwater, even though dewatering could generally maintain a gradient toward the pits (Vol. II, p. 50). PolyMet would complete mining the East Pit in 11 years, after which it would be backfilled with Category 2, 3, and 4 waste rock (Vol. II, p. 51). Because the waste is reactive, PolyMet would pump water into the backfilled pit to maintain a water level above the top of the backfilled waste. As PolyMet attempts to fully saturate the backfilled waste, water levels could be higher than the surrounding groundwater for substantial periods. If this occurs, water (and contaminants) will flow into the groundwater. Fracture zones that intersect the pit could allow contaminants to escape the hydraulic control of the pit. PolyMet has not considered this source of groundwater contamination nor provided monitoring to document whether it occurs.

Similar considerations apply to the West Pit, which would be pumped full within six months of closure. The lake water levels would at that point be higher than the surrounding groundwater and, therefore, could flow into the groundwater. Once the West Pit Lake level reaches a certain level, it becomes a source of flow into the groundwater. For natural refill, the West Pit would leak a range of 400 to 450 m^3/d to the south, with about half going to bedrock, and up to 150 m^3/d to the west, mostly to bedrock (Myers 2014, p. 3-27). PolyMet fails to consider this pathway. Modeling performed in Appendix A highlights the importance of this pathway.

PolyMet has not considered these pathways. Although closure is beyond the period of this permit, now is the time to consider it because the mine operating plan could be changed if the West Pit was found to be a significant contaminant source.

Travel Times

PolyMet does simulate minor leakage rates from the mine site sources, and shows their estimated arrival time for the plume reaching the Partridge River (Vol. II, Table 4-1). The times for seepage through waste range from 30 to 90 years, and for seepage through the East/Central Pit to reach the river within 100 years, simulations presented in Appendix A shows the plumes reaching the river far sooner. The Myers MT3DMS model is far more physically realistic and accurate than the Goldsim One-D simulation (Myers 2015).

Monitoring

PolyMet relies on monitoring to determine whether leaks have occurred. As discussed below in the following section and as simulated in Appendix A, the monitoring is insufficient. But even if monitoring does detect a plume moving to the river or otherwise degrading the groundwater, there is little PolyMet would be able to do to prevent the plume from reaching the river. Once the monitoring wells, especially those midway between the mine site and the Partridge River, detect contaminants, the plume would consist of a huge mass. There are no plans to remediate the groundwater, so the degradation would be ongoing. It would be almost impossible to fully remediate the groundwater and prevent a discharge to surface water. And PolyMet failed to present any plan that would attempt to prevent this discharge.

Monitoring

Conceptual flow model for monitor well placement

There is no simple, uniform boilerplate format or guideline for developing a groundwater monitoring plan. However, groundwater monitoring wells should be placed where contaminant plumes are most likely to pass, in order to be effective. Small scale monitoring plans usually are site specific with a focused intent. To detect groundwater contamination from a large mine site, it is necessary to identify all potential sources and sinks. Sources would be the facilities on the mine site that could release contaminants. Sinks that could be damaged are downgradient wells, springs, or streams. Once identified, it is necessary to determine the potential flow path from the source to the sink. This requires an understanding of flow in the area, which requires a conceptual flow and transport model, prepared to a scale appropriate to the site. Regional models are insufficient.

Four steps emerge as being necessary for the establishment of an adequate monitoring plan.

1. Identify the groundwater dependent ecosystems and wells that should be protected. Determine what is necessary to protect them.
2. Develop a localized conceptual flow model (CFM) that describes the hydrologic system that supports each groundwater dependent ecosystem and water right. This would be

more detailed than a CFM used for a large region because broad-scale flows do not describe small features well. For example, some springs may be perched and therefore affect only by nearby local contaminations but larger sinks such as the Partridge and Embarrass Rivers could be supported by groundwater flow from much further away.

3. Implement the more refined CFM to estimate the detailed pathway between the potential sources and sinks. Because the sources could be a large area, such as the entire area beneath the Category 1 waste rock stockpile, the pathways could be defined as an envelope of paths. This may require numerical modeling or data collection to estimate the paths.
4. Determine the type and location of monitoring that would allow the prediction of changes. For water quality, this means determining the depths to screen the well. Understanding uncertainty should inform these decisions, with more monitoring required where pathways are difficult to estimate.

PolyMet's application does not describe how the location of monitor wells was determined. The introduction states the proposed monitoring strategy would be described (Vol. I, p. 30), but at no point in that volume, or other volumes, is a strategy actually described. Substantial changes to the flow paths caused by the project, such as mine dewatering at the mine site, must be considered. Where groundwater discharges to large sinks, such as the Partridge River, the pathway analysis must consider the depth of the flow path. In other words, how much groundwater discharging to the river comes from the bedrock, at what depth, and from which surficial aquifer? The travel time and attenuation properties could differ substantially among formations.

Detailed modeling of the mine site and the plant site presented in Appendix A show that contaminant plumes would miss much of the proposed monitoring. As noted, there was no CFM developed for the site. There was obviously no consideration given to dispersion of the contaminants or the advective path other than that the general direction was north or south. Contaminant plumes could easily pass between the point of compliance wells.

There are wells closely spaced around the tailings impoundment and the Category 1 stockpile designed to determine if the containment systems are leaking. They are close to the facilities and would provide a quick warning of a leak, but only if they lie on a pathway. The monitor wells or piezometers would only detect a leak directly upgradient, and any leaks from upstream would hit the well only if directly on the flow path. There would not be sufficient dispersion of most plumes to allow detection. Piezometers and monitoring wells may not be the best indicator monitoring available for sites near the containment walls.

PolyMet should develop a detailed conceptual model of flow and transport for all potential leaks from its proposed facilities. It must consider advective flow paths, reasonable dispersion that controls the shape of a plume, and travel times. It should ignore attenuation unless there is overwhelming evidence supporting it. PolyMet should use this model to locate its proposed monitoring wells, rather than relying on its relatively random placement that forms its application.

Mine Site

PolyMet's monitoring plan is also unlikely to detect contamination into ground and surface waters if and when leaks occur. PolyMet proposes 75 monitoring wells at the mine site (Vol. 1, p. 34), but that is insufficient. PolyMet's proposal includes monitoring to demonstrate compliance, indicator monitoring to allow for early detection of impacts, performance monitoring to examine the performance of engineering features, and background monitoring to track upgradient conditions (Vol. 1, p. 30-31). The proposal requires 15 compliance monitoring wells, with 9 existing in the surficial aquifer and 6 new wells proposed for bedrock (Vol. 1, p. 32). The proposal provides that there would be 28 indicator monitoring wells at the mine site, with 3 existing and 12 proposed in the surficial aquifer and 3 existing and 10 proposed in bedrock (Id.). There would be 32 performance monitoring wells with 1 existing and 6 new paired wells and 7 new paired piezometers along the Category 1 stockpile seepage containment system (Id.). PolyMet does not identify any background wells. Many surficial and bedrock wells are paired which should show connections between aquifers. As the modeling in Appendix A demonstrates, the proposed monitoring plans are insufficient because the wells are spaced too far apart to provide confidence that contaminant plumes would not pass through the monitoring well network (Appendix A, p. 9-24).

Compliance wells north of the Category 1 stockpile are spaced about one mile apart just north of the Category 1 stockpile. Compliance wells between the mine and the river southeast of the site are spaced by approximately 2/3 mile and are about 1/2 mile from the mine boundary and 1/4 mile from the river (Vol. 1, Large Fig. 6). Performance wells along the Category 1 stockpile seepage capture system would be spaced by around 1/3 mile, or 3 times as dense as the compliance wells. Because they are so close to the seepage containment system, they would likely detect contaminants only if the leak or bypass of the containment system is just upgradient of the well because dispersion would not be sufficient to reach the wells. The spacing could also allow contaminant plumes to pass through the perimeter monitoring well transect without being detected. Similar spacing issues apply for wells throughout the mine site, as demonstrated in Appendix A.

Volume II, section 3.1.2 describes the monitoring wells proposed to be installed at the site. PolyMet provides no information on why it chose the proposed locations. There is no conceptual flow and transport model that suggests those wells being on a pathway downgradient from a source. The proposed monitoring plan (Vol. II, § 3.2) does not include any monitoring wells beyond those currently installed; this may be seen by comparing Volume II Large Figure 3 (existing) with Large Figures 4, 5, and 6.

Surface water monitoring (Vol. II, § 3.1.1; Vol. I, § 3.3) is insufficient to demonstrate that the project is not contaminating surface waters. The mine site drains to the Partridge River and, although the PolyMet contends the mine site will have no surface water discharges, there are various potential groundwater pathways for contamination to reach surface water.

The headwaters of the Partridge River, including Yelp Creek, borders the north side of the mine site, especially the Category 1 stockpile, but there is no monitoring for about 2 ½ miles of river to station PM2/SW002 which is about ½ mile north of the site. Contaminants detected there could be from the Category 1 stockpile, the East Pit, Central Pit, or the Northshore Mine which is not part of this project. The next station PM3/SW003 is about 2 miles further downstream but near the east end of the Mine Site. Station PM4/SW004 is several miles further downstream and about 1 mile south of the mine site; station SW004a monitors the river a little further downstream below a tributary. Seepage from the Category 1 stockpile could reach Yelp Creek to the north and the Partridge River below SW004 to the south and from the Category 2/3 stockpile could reach the Partridge River near SW003 within 11 years (Myers 2014). The East Pit may prevent groundwater from flowing north, but runoff from the Category 4 stockpile, if not captured, could reach the river to the north through shallow groundwater and surface pathways. The groundwater section should also include an analysis of surface water discharge to show where the contaminants would discharge to surface waters.

Plant Site

There are 28 performance monitoring wells, or 14 pairs, to be used around the base of the tailings impoundment installed in the surficial aquifer. These wells are designed to show the effect of the cutoff trench capturing seepage. They will show a decrease in concentration due to seepage capture, but they will not show leaks with certainty because they are spaced too far apart.

Monitoring wells located midway between the impoundment and the river show contaminants reaching the wells, but do not begin responding for 20 or more years. This shows they would not be good indicators of a leak. Simulated plumes from leaks placed within the simulated tailings basin could miss the monitoring wells (Appendix A, p. 32-60). This is because the width of the plumes is less than the spacing of the monitoring well. The plume from the leaks barely approaches monitoring wells GW015 and GW109 (Appendix A, p. 54- 55). Proposed monitoring wells on the edge of area between the tailings and the Embarrass River are too far west and east to monitor most plumes emanating from either the entire tailings impoundment or from specific leaks within the impoundment. There should be more compliance wells along the center of the simulated plumes to increase the chances of detecting plumes, as shown in Appendix A (p. 32-60).

Dewatering (Sizing of the Wastewater Treatment Facility)

A final major issue with the mine site is that the size of the WWTS is inadequate for the volume of dewatering water in the system. Dewatering water is a primary source of water for production and the treatment facilities and pipeline must be able to accommodate the flow. Dewatering includes the pumpage of groundwater that seeped into the pits and runoff that has accumulated in the pits. Rainfall into the pit either runs off the pit walls to accumulate in the bottom of the pit or enters the formations surrounding the pit and flows through shallow groundwater or as interflow to the bottom of the pit. Precipitation within the pit does not recharge groundwater and therefore no longer supports the water table or maintains wetlands near the mine site.

Because PolyMet would treat the water, dewatering rates are very important to consider in the NPDES/SDS permit. The Water Management Plan (PolyMet 2017) describes PolyMet's predicted mine dewatering as follows. The East Pit would have the highest inflows due to it intersecting the Virginia Formation. PolyMet predicts the following: total inflow to the East Pit in year 1 would average 205 gpm and range as high as 252 gpm (the 90th percentile prediction using the GoldSim model), and during year 11 and 20 would average and range to 378 and 863 gpm and to 448 and 1096 gpm, respectively (PolyMet 2017, Table 2-2). Dewatering rates at the West and Central Pits would be lower because, according to PolyMet, the bedrock conductivity is much smaller. Regardless of PolyMet's expected bedrock conductivity, the dewatering inflow rates are highly uncertain. PolyMet's estimates are based on limited understanding of the hydrogeology of the bedrock at the site, especially the hydrologic properties of the bedrock which control the inflow rates to the pit.

In a study to design pit dewatering mitigation, Foth (2017) details many ways in which the dewatering estimates could be too low, including unplanned-for fractures.

Conductivity Assumptions

Myers (2014) predicted that overall dewatering rates would be significantly higher than PolyMet. Myers-estimated total dewatering is close to that of the FEIS model for the first few years but then exceeds the FEIS model by about 80% by year 12. After year 12, the Myers model predicts the total dewatering rates to remain high until about year 16, after which it begins a decrease. In contrast, the FEIS model predicts that dewatering rates would drop beginning in year 11. Figures 1 and 2 show predicted dewatering rates based on Myers (2014) modeling. Myers' (2014) dewatering rates are higher because much more groundwater needs to be dewatered in light of calibrated bedrock conductivity being higher than that used by PolyMet and the recharge rate is twice that used by PolyMet.

Dewatering rates could be several times higher (or lower) than predicted, especially during short-term periods, as a result of fractures draining into the pit or due to other sources.

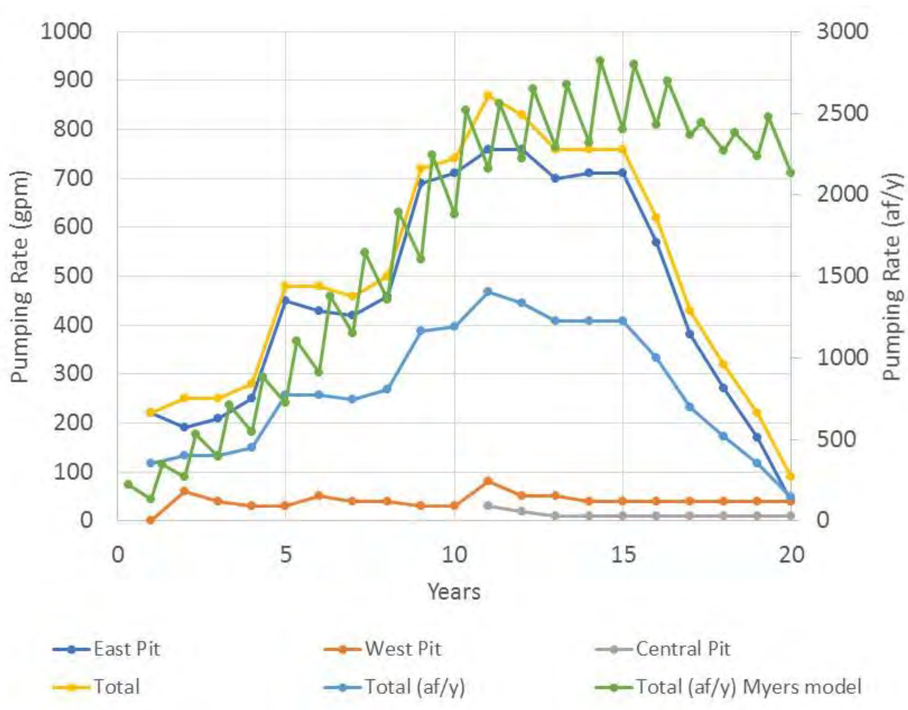


Figure 1: Groundwater dewatering rate by mine pit, based on FEIS Table 5.2.2-19 and Myers (2014).

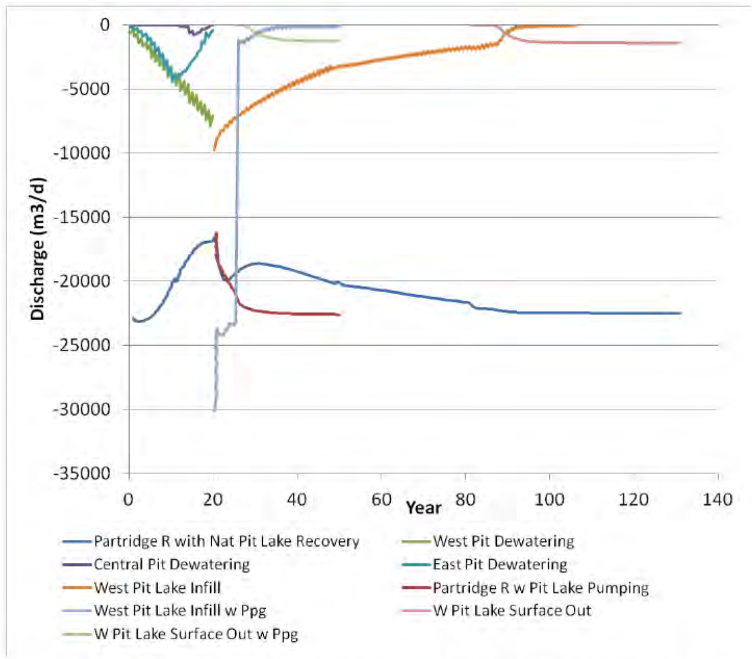


Figure 12: West Pit and Pit Lake Fluxes, Partridge River discharges for dewatering and pit backfill as described (Polymet 2013c) and natural pit lake inflow. The river flow is an average of the flow at the end of the recharge and no recharge periods.

*Figure 2: Snapshot of Figure 12 from Myers (2014) showing modeled fluxes through the simulation period. (Cubic meters per day * 0.18345 equals gpm)*

PolyMet would dewater the pits by pumping from sumps in the bottom of the pits (PolyMet 2017, p. 9). It would accommodate short-term flow exceedances by allowing water to pond in the bottom of the pit and temporarily not mining near the bottom until it can be pumped dry. The quality of the water ponded at the bottom of the pit would depend on the percentage of groundwater inflow that enters through various formations. PolyMet does not estimate the relative proportions of water entering through different layers or elevations in the pit, which could result in different water quality due to flow through different formations. PolyMet's treatment plans can accommodate short-term event-driven high flows by temporarily storing it (PolyMet 2017, p. 11), but not long-term changes. Rates that consistently exceed the forecasted rates could prove a problem for the treatment plans and cause PolyMet to change its dewatering plans. If significantly higher groundwater inflow rates manifest, PolyMet may need to install groundwater wells to capture the inflow before it reaches the pit. Groundwater wells could have the advantage of capturing water before it is contaminated by seepage through the pit walls.

Appendix A uses the updated Myers (2014) model to provide a more realistic estimate of the potential range of inflows to the pits (and to the mine site). Estimates would be based on realistic variability in transmissivity of flow to the pits (Appendix A, p. 24-29).

High Water Table

An additional source of water that PolyMet may need to manage is groundwater dewatered to lower the water table beneath the bottom of the sumps and ponds (PolyMet 2017, p. 18). PolyMet suggests several methods for lowering the water table to avoid pore pressures on the liner, but has not settled on a final design (Id.). There has not been sufficient groundwater analysis completed to know precisely the depth to groundwater near the ponds and sumps, so there has been no estimate of the additional required pumping, including flow rate and whether it would be seasonal or year-round.

The rate of dewatering to lower the water table beneath the stockpiles could vary seasonally, with substantial amounts of water needed to be dewatered during wet years. This water would be added to the inflow to the WWTS. If the rates are high enough, the design flow rate to the WWTS could be exceeded. PolyMet presented no analysis of the extra water; therefore, the permit should not be issued without additional analysis and assurance that extra flow would not exceed the WWTS capacity.

Plant Site NPDES/SDS Review

Like the mine site, there are also three problems concerning permitting the plant site. These are:

1. Groundwater and surface water degradation is highly likely because the assumption that containment system at the tailings impoundment will be 100% effective is improbable;
2. There is an underestimation of the amount of high concentration flow at the plant site; and
3. The project would likely violate the zero-discharge requirement in 40 C.F.R. § 440.104(b)(1).

This section, supported by the modeling in Appendix A, describes each of these inadequacies.

Plant Site/Tailings Basin Groundwater Protection

Like the mine site, it is also improbable that the plant site's containment system will be 100% effective. Groundwater downgradient from the tailings impoundment has been degraded by long-term seepage from the existing ferrous tailings. PolyMet indicates the state's policy is therefore one of "abating (existing) pollution" and "rehabilitating degraded waters" (Vol. V, p. 38). Groundwater downgradient has elevated concentrations of total dissolved solids, sulfate, chloride, fluoride, and molybdenum, among others (Id.), and manganese and aluminum at the tailings basin (Vol. V, p. 37). PolyMet suggests they will rehabilitate the groundwater by capturing the seepage beneath the tailings impoundment. Initially, their seepage capture system would replace existing pumpback systems that are capturing the existing seeps. PolyMet intends the system to capture most seepage from the existing tails and from the proposed future flotation tails to recycle for beneficiation use; this would intercept the contaminant source and allow the groundwater to remediate.

The FEIS presented results of a MODFLOW cross-sectional analysis of PolyMet's seepage containment system. Myers (2014, p. 38-41, appended in Appendix B) found the analysis was essentially hardwired to have a much higher efficiency than would be realistic, for the following reasons:

- A river boundary downgradient of the cutoff wall artificially keeps the water table at the ground surface which decreases the flow through the wall.
- The seepage inflow was assumed to be vertically and horizontally uniform which would maximize the amount captured by the drains.
- The vertical conductivity of the bedrock is unrealistically high which allows seepage to flow vertically upward more easily with the gradient toward the drain. This led to unrealistic modeled flow paths.
- The model did not consider the potential for the drain to clog.

Based on Myers (2014) PolyMet's seepage containment system at the tailings impoundment should not be assumed to be 100% effective.

Water Treatment Issues

PolyMet's NPDES/SDS application has also underestimated the amount of high concentration flow that would be delivered from the mine site. Two of the three pipelines delivering water from the mine site to the plant site for treatment would be a high concentration and low concentration line, with the former being drainage from the Category 2/3, Category 4, and ore surge pile (OSP) and the latter being from the Category 1 stockpile and other supposed low concentration sources. Mine dewatering water would report to the low concentration basin. However, once backfill of the East Pit begins, water pumped from that pit would have a high concentration, but the draft NPDES/SDS application fails to account for the change in concentration.[1] The NPDES/SDS application Volume I, Large Figure 4 shows that 820 gpm from the East Pit would report to the Low Concentration EQ Basin. However, the East Pit would be in the process of being backfilled with Category 4 waste; this water would be very high

[1] FEIS p. 3-64, 65 describes the plan for backfilling the East Pit after year 11.

concentration. The other two sources shown on the same figure total only 130 gpm, so adding the flow from the East Pit could substantially tax the ability of the high concentration treatment scheme, a chemical precipitation train (Vol. 1, p. 94). If it is added to the Low Concentration treatment scheme, a membrane separation technique (Id.), it could upset the process so that expected quality is much poorer.

Zero Discharge

Finally, the project would likely violate the "zero discharge" requirement. A "zero-discharge" requirement applies to the process facilities, including tailings impoundment. The zero-discharge standard is described as follows:

> 40 C.F.R. § 440.104(b)(1): Except as provided in paragraph (b) of this section, there shall be no discharge of process wastewater to navigable waters from mills that use the froth-flotation process alone, or in conjunction with other processes, for the beneficiation of copper, lead, zinc, gold, silver, or molybdenum ores or any combination of these ores. The Agency recognizes that the elimination of the discharge of pollutants to navigable waters may result in an increase in discharges of some pollutants to other media. The Agency has considered these impacts and has addressed them in the preamble published on December 3, 1982.

PolyMet argues that net precipitation from the tailings impoundment and water mixed from other sources may be discharged as part of the zero-discharge standard (Vol. III, p. 91). Other sources include mine drainage which will be treated at and pumped from the mine site. In Appendix D of Volume III, Barr presents an assessment of the legal requirements of "zero discharge," noting that no discharge is allowed from process facilities that use the froth-flotation method because recycling of the water is simple. The volume of net precipitation (precipitation – evaporation) on the tailings may be discharged. Mine drainage may also be discharged at the plant site, according to PolyMet, because it is part of a combined waste system with the net precipitation. Mine dewatering water could be considered mine drainage, so as not to be included in the zero-discharge requirement, because it would be pumped from a sump in the pits; it would be considered mine-impacted because it would have entered through and flowed along the mine pit walls according to PolyMet. The limits on discharge from the WWTS to surface water will include the amount of mine drainage coming from the mine site. Effectively, if the mine pumps new water for use in processing, discharge would be subject to the zero-discharge requirement because experience had shown the EPA that recycling could allow them to avoid discharge. Because the fresh process water is from mine dewatering, zero discharge does not apply. To the extent mine dewatering water substitutes for pumping new water, the zero-discharge requirement does not apply.

PolyMet would effectively meet the zero discharge by planning to collect and recycle all tailings water that seeps beneath the facility (Vol. III, § 5.2) even if the collected seepage would be treated and later discharged to surface streams. Seepage that escapes the tailings seepage collection system would violate the zero-discharge standard because it will not be a combined waste stream and will reach the Embarrass River or tributaries.

PolyMet will violate the zero-discharge standard in two ways.

- First, tailings seepage not captured by the collection system will violate the standard, regardless of the effect on groundwater quality. If PolyMet's assumption regarding seepage collection does not manifest, PolyMet will violate its permit.
- Second, mine dewatering water would violate the standard if dedicated dewatering wells become necessary. As discussed in the NPDES modeling section, there is a substantial chance that the dewatering requirements will exceed the predicted rates. If dewatering needs exceed the predicted rates, and PolyMet requires dedicated dewatering wells, PolyMet will violate the permit.

Conclusion

The NPDES/SDS permit for the PolyMet mine proposal should not be awarded because the application is based on overly optimistic design assumptions, modeling that does not consider flow path details near either the mine site or tailings impoundment, inaccurate analysis of pathways for contaminants to reach the rivers, and grossly insufficient proposed monitoring. The NPDES/SDS permit application for the PolyMet Project will not protect surface and groundwater in the area around the project for many reasons.

The nondegradation analysis assumes that the engineered seepage capture system, covers, and mine site will be 100% effective. The assumptions underlying the seepage capture system are questionable. Applying more realistic assumptions, there will definitely be leaks that would be very difficult to remediate, and result in groundwater and surface water contamination.

Dewatering rates will vary substantially and likely exceed the treatment facilities capacity to treat water. Increases in dewatering due to fracture flow will likely require dewatering techniques such as dedicated dewatering wells that will cause the mine to violate the zero-discharge standard.

Leaks emanating from different portions of the plant or mine site will follow different pathways to reach the rivers. Dewatering creates a groundwater divide under the mine site, creating pathways for contaminants to go both north and south, to the headwaters of or to downstream reaches of the Partridge River. Waste water seeping from both the tailings impoundment and waste sites on the Mine Site will reach surface water, as shown by transport analysis. Contaminant plumes released from both mine site and plant site sources will reach long stretches of surface water. This includes waste from the tailings impoundment reaching the Embarrass River and from mine site waste sources reaching the Partridge River both to the north and south.

The application fails to consider the high concentrations that will occur in the dewatering water from the East Pit, after it is backfilled with highly reactive waste. Also, the backfill would create a situation where pit water will flow into surrounding groundwater, at least temporarily, and contaminate it. Rapid fill of the West Pit will cause pit water to flow into surrounding groundwater, thereby degrading the groundwater. The application does not consider groundwater degradation due to groundwater flowing from either the West or East Pit into surrounding groundwater.

Surface water monitoring is grossly insufficient to determine the location of seepage that will eventually contaminate the river. Pathways from both sites show the need for substantially more surface water monitoring. Contaminants could reach the river along substantial reaches, and it is necessary to monitor at many locations to identify the source. Variable slopes in the cumulative load curve for the Embarrass River, both for with and without the cutoff wall, show areas of differing load reaching the river. This shows the need for at least four surface water monitoring points along the river, at about mile point 6, 8, 10, and 13.

Proposed groundwater monitoring is insufficient. Contaminant plumes would move between widely-spaced monitoring wells. This observation holds for monitoring between the mine site and Partridge River and between the tailings impoundment and the Embarrass River. Groundwater monitoring wells should be placed where contaminant plumes are most likely to pass. This requires an understanding of flow in the area, which requires a conceptual flow and transport model (CFTM), prepared a scale appropriate to the site. This would include identifying all potential sources and sinks, such as facilities on the mine site that could release contaminants. Sinks that could be damaged are downgradient wells, springs, or streams. Once identified, it is necessary to determine the potential flow path from the source to the sink.

For these reasons, the NPDES/SDS permit for the PolyMet Northmet mine proposal should not be awarded.

Appendix A: Numerical Modeling of Groundwater Pathways, Loads, and Monitoring

This appendix presents analysis completed with the Myers (2014) groundwater model, modified as described herein, for the mine site. Although the Myers (2014) model simulates the region, modifications for the mine site and plant site were made separately because they are separate source areas.

The objective for revised simulations for both areas is to consider flow paths from separate discrete sources rather than simply from seepage dispersed across the bottom of the facilities and to consider the adequacy of the groundwater monitoring. There are three goals to additional simulation of contaminants from the mine site, including seepage from the waste rock and OSP facilities and the backfilled and flooded pits.

- First, consider the time for contaminants to reach the river from the various sources.
- Second, consider whether the monitoring plan would detect contaminants moving offsite.
- Third, consider the sensitivity of parameters controlling the mine dewatering rates; mine dewatering water reports to the treatment facilities and significant changes due to a lack of understanding of the hydrogeology could require much larger dewatering facilities.

Proposed Mine Site Operations

This report used the description of the mine site operations as described in the FEIS, and verified the NPDES/SDS application used the same mine site operations. The Category 4 stockpile would produce seepage from years 1 to 11, after which the waste would be moved into the East Pit so that the Central Pit could be mined. Disposal of waste rock into the East Pit and subsequent flooding is simulated using injection wells for three years, with significantly decreasing concentration with time. The Category 1 stockpile would commence construction in the first year and be constructed by year 13, with reclamation commencing in year 14 and finishing in year 20 (FEIS, p. 3-65, 3-66). The facility would remain in perpetuity. There would be a groundwater containment system constructed around the facility to capture seepage.

The Category 2/3 stockpile would be constructed beginning in year 1 and continue until year 11. Category 2/3 stockpile would begin to be moved to a pit lake beginning at year 11, but the rock would not be fully moved until year 20 (FEIS, p. 3-44, 3-65). Some waste rock would remain in place until year 20, so the area would remain a contaminant source until the waste is fully removed and the area reclaimed. Leak modeling could conservatively assume the leak continues through year 20 or end at year 11, to simulate a range in times.

The OSP area would be used through the 20-year mine plan. Ore would be stacked as high as 40 feet to wait for transport to the process facilities. There would be a liner beneath the OSP. Constant addition of ore and removal of ore would cause significant wear to the liner, and leaks would be expected.

Waste Rock Stockpile Simulation

Mine development creates waste rock stockpiles and the OSP which have seepage rates and contaminant loads that differ from the natural recharge rates. Myers (2014) used four recharge zones, Zones 21-24, that were added to the model (Figure 3 and Table 1). Zone 21 is the permanent Category 1 stockpile. Zones 22 and 23 are the temporary Category 2/3 and Category 4 stockpiles, respectively. Zone 24 is the OSP.

PolyMet variously proposes to cover, line, provide underdrains, and construct seepage barriers for their waste rock facilities, as described above, so the modeling for pathways reflects those plans. For the Category 2/3 stockpile, the rock and overburden management plan (PolyMet 2012) suggests the seepage rate through the liner under the temporary stockpiles will be 0.6 and 0.16 gal/acre/day (1.84x 10^{-6} and 4.91x10^{-7} ft/d or 5.61 x 10^{-7} and 1.50 x 10^{-7} m/d) for the Category 2/3 and Category 4 stockpiles, respectively. These rates would apply from year 1 to year 11 after which the waste would be moved into the East Pit.

Infiltration to the Category 1 stockpile without a cover is 13.6 in/y and with the proposed cover is 0.14 in/y (0.000947 m/d and 9.74 x 10^{-6} m/d, respectively). The cover will be constructed starting in year 14. The Category 1 stockpile is proposed to have a groundwater containment and collection system that would allegedly capture 93-99% of the drainage over the life of the mine and closure (PolyMet 2013, 2012). Therefore, during the third mine period, simulation would have the seepage rate decrease from 0.0000947 m/d to 1/10 of that value in annual time steps.

Seepage concentrations from the stockpiles depends on oxidation based on the category as noted above. PolyMet (2013, Attach. H) shows concentration values for the sources that are mostly constant except for a few constituents with concentrations that drop off toward the end of a 200-year period. Concentration increases early due to oxidation occurring since the waste rock was emplaced. Concentrations in Figure 4 represent the median values from a series of tests and the peak is achieved at 20 years for Category 1 waste rock, 16 years for Category 2/3 waste rock, and 11 years for Category 4 waste rock. The concentration becomes steady for the

Category 1 waste rock after closure. Seepage rates for the OSP equal those of the Category 2/3 stockpile. The sulfate concentration increases to 8 million ug/l by year 11, after which it decreases to 6 million ug/l at year 18 and zero at year 20 (Figure 4).

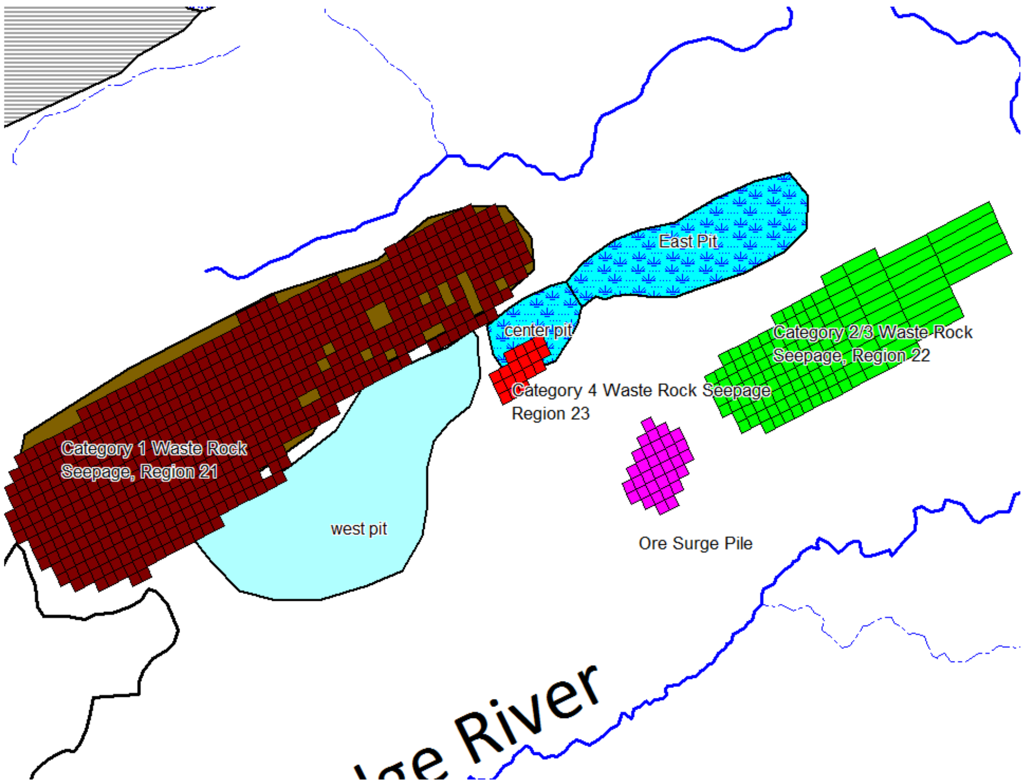


Figure 3: Waste rock seepage areas, near the mine site. See Table 3 and the text for a description of the seepage, rates, and concentrations.

Table 1: Recharge rates for the transient production model. See Figure 3 and Table 3 in Myers (2014), p. 3-12, for the location of the recharge areas.

Recharge zone	Rate (m/d)	Source	Years
1	0.000946*	Embarrass River watershed	All
5		West pit lake rain on surface	After 20
6	0.001144	Tailings seepage	All
10	0.000239*	Partridge River watershed, organic soils	All
11	0.000687*	Partridge River watershed	All
12	0.000449*	Lower Partridge River watershed	All
21	0.000947, 9.74×10^{-6}	Category 1 stockpile	All
22	5.61×10^{-5}, 5.61×10^{-7}	Category 2/3 stockpile	1-11
23	1.49×10^{-5}, 1.497×10^{-7}	Category 4 stockpile	1-11
24	5.61×10^{-7}	Ore surge pile	All
	* - seasonal. All recharge during four-month period.		

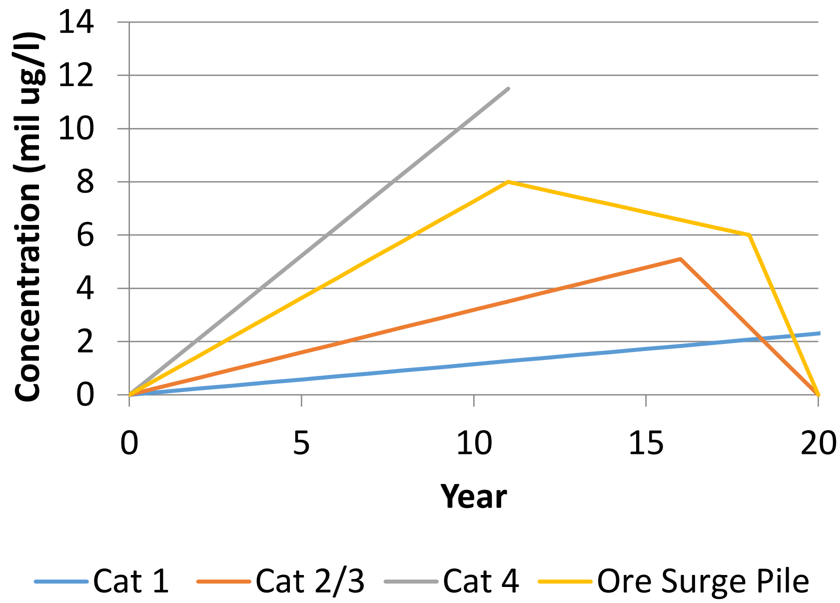


Figure 4: Simulated SO4 concentration for seepage from the various waste rock stockpiles and the OSP (PolyMet 2013). Concentration for Category 1 waste equals 2.6 mil ug/l in perpetuity.

After mining the East Pit ceases in year 11, it is backfilled with waste rock from the Category 2/3 and Category 4 waste rock stockpiles. The moist rock will have undergone oxidation while on the stockpile and while in the pit until the groundwater level covers the rock and reduces oxidation. The transport model used (Myers 2014) MT3DMS does not model oxidation or the development of these products, so a load was specified as input to the model to represent the backfill. Dewatering has continued through year 11, so SO4 loading due to pit backfill occurs from year 12 through year 20 according to the mass indicated by PolyMet (2013, Figure 6-39). These loads exceed the load for the pit walls by three orders of magnitude, therefore pit walls as a source were ignored. This model simulates loading to the East Pit as 100 m^3/d well injection spread over three injection wells into layer 3 with concentration varying as described here - for years 12 through 20, the injected SO4 concentration equals 88, 30, 5.5, 0, 16, 22, 22, 22, and 11 mil ug/l, respectively. The injection rate was low, compared to other flux values, to not upset the water balance.

Model Improvements

The numerical model, originally developed and presented in Myers (2014), has been improved in two ways. First, the updated model improved the discretization near the mine site and plant site by halving the size of the model cells over a significant area. This resulted in four cells where the original model had one cell (Figures 5 and 6 for the mine site and Figures 7 and 8 for the plant site). The second improvement was that layer 2 was split into two layers of equal thickness. Originally, layer 2 was an upper bedrock layer, where conductivity values are closer to those of the surficial aquifer. In the updated model, layers 2 and 3 have the same conductivity, and other parameters, so layers 2 and 3 are the same as layer 2 in the original model. These changes improve the water balance and contaminant transport computation. Steady state calibration statistics changed only slightly, so I performed no additional calibration (Table 2).

Table 2: Model calibration statistics for the original model (Myers 2014), the original model with just model cell discretization, and the updated model including five layers.

		Mine site		Tailings
	original	4 layers	5 layers	5layers
Residual mean	0.19	0.01	0.42	0.61
Residual std dev	2.45	2.71	2.74	2.46
Abs Res Mean	2.01	2.19	2.26	2.04
Res Sum Squares	374	455	477	399
RMS error	2.46	2.71	2.77	2.54
Min Res	-5.04	-6.27	-5.33	-4.32
Max Res	5.16	7.26	7.26	7.26
Range	53.97	53.97	53.97	53.97
Scaled Res Std Dev	0.045	0.05	0.051	0.046
Scaled Abs mean	0.037	0.041	0.042	0.038
Scaled RMS	0.046	0.05	0.051	0.047

The changes were made within the GWVistas graphical unit interface (GUI) framework, which automatically adjusts the conductance for boundaries such as DRAINs. Resulting boundary cells have the conductance as determined by GWVistas, so the overall boundaries are the same as Myers (2014) even if the features are two or more cells in width (Figure 6).

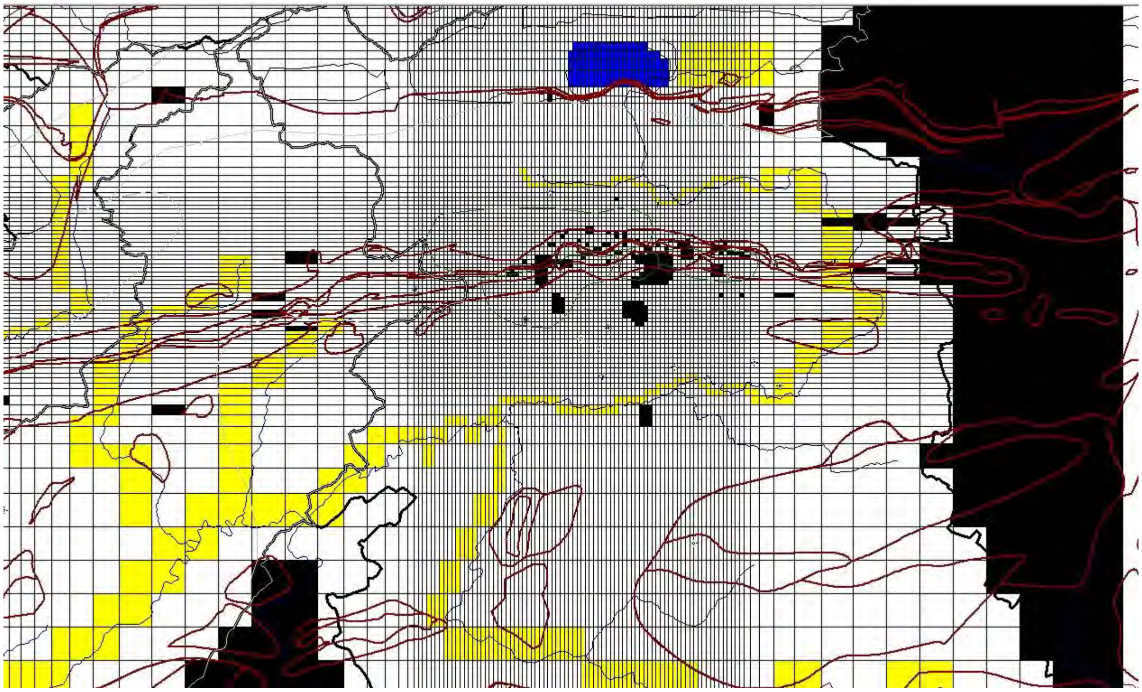


Figure 5: Grid of mine site portion of the original model (Myers 2014). 125 rows and 154 columns. Taken from the steady state model files.

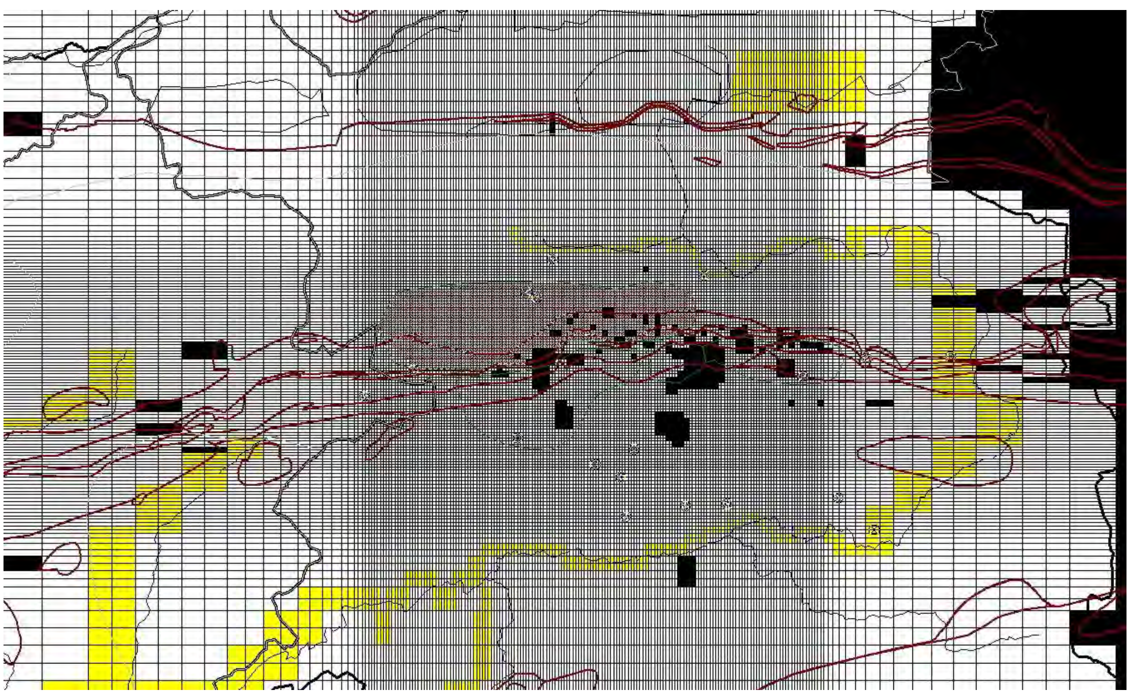


Figure 6: Revised grid for the mine site portion of the model, showing increased detail around the mine site. 192 rows and 250 columns. Taken from the transient model, first period.

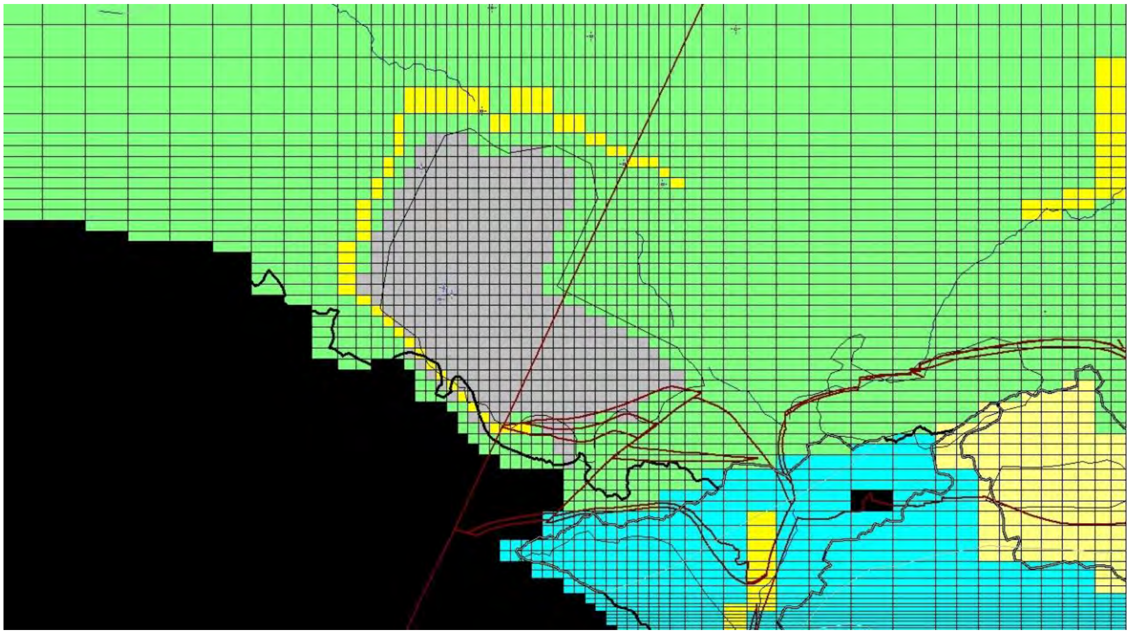


Figure 7: Grid of plant site portion of the original model (Myers 2014). 125 rows and 154 columns. Taken from the steady state model files. Grey is recharge for the tails and yellow is DRAIN simulating seep around tails.

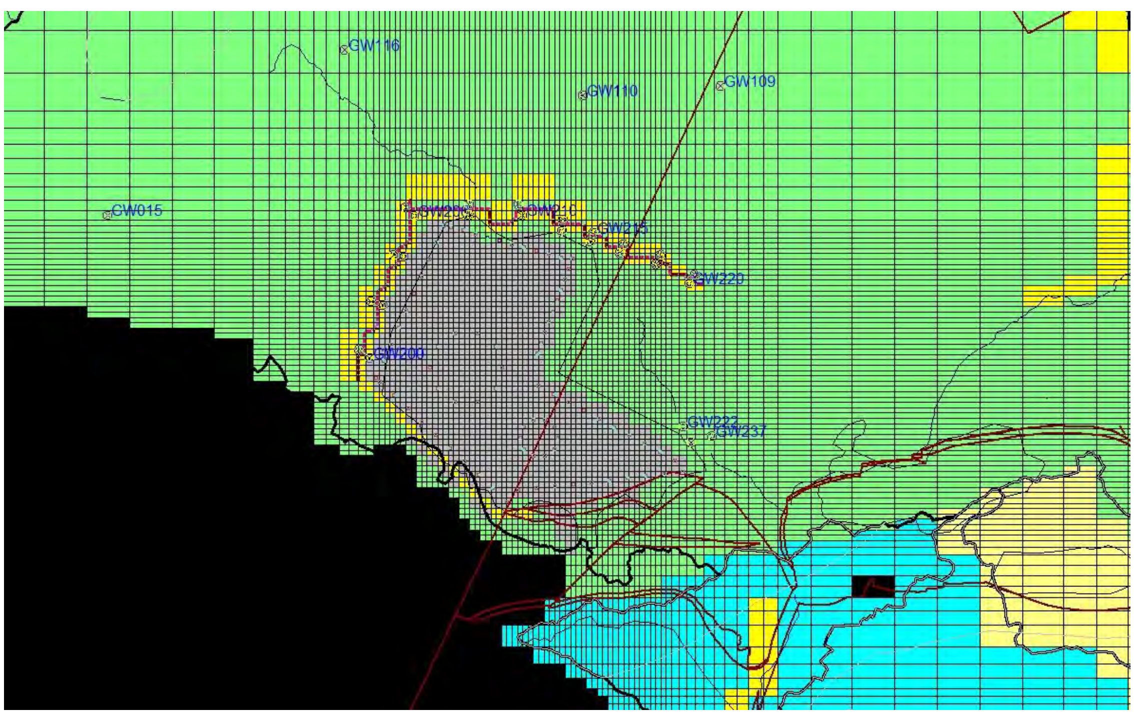


Figure 8: Revised grid for the mine site portion of the model, showing increased detail around the mine site. 163 rows and 192 columns. Taken from the transient model, first period. Grey is recharge for the tails and yellow is DRAIN simulating seep around tails.

Results of Simulation

As with the FEIS model, groundwater flow and contaminant transport simulations for the three mining periods: years 1 to 11, years 12 to 14, and years 15 to 20 (Myers 2014). These simulations are specifically for seepage distributed evenly around the base of the sources.

Groundwater flow paths control contaminant advection on the site, with dispersivity controlling the lateral and vertical spread of the contaminant plumes. After 11 years, the groundwater levels show that the flow direction is generally toward the West Pit and East Pit (Figure 9) because the facilities are being dewatered, which creates a drawdown toward the pits (Figure 10). Exceptions include the east half of the Category 2/3 stockpile which lies over a groundwater divide so that some water will flow south. The OSP also lies near the divide and some groundwater would flow south. Finally, contours west of the West Pit and south of the Category 1 stockpile are complicated and indicate the flow could occur south of the West Pit.

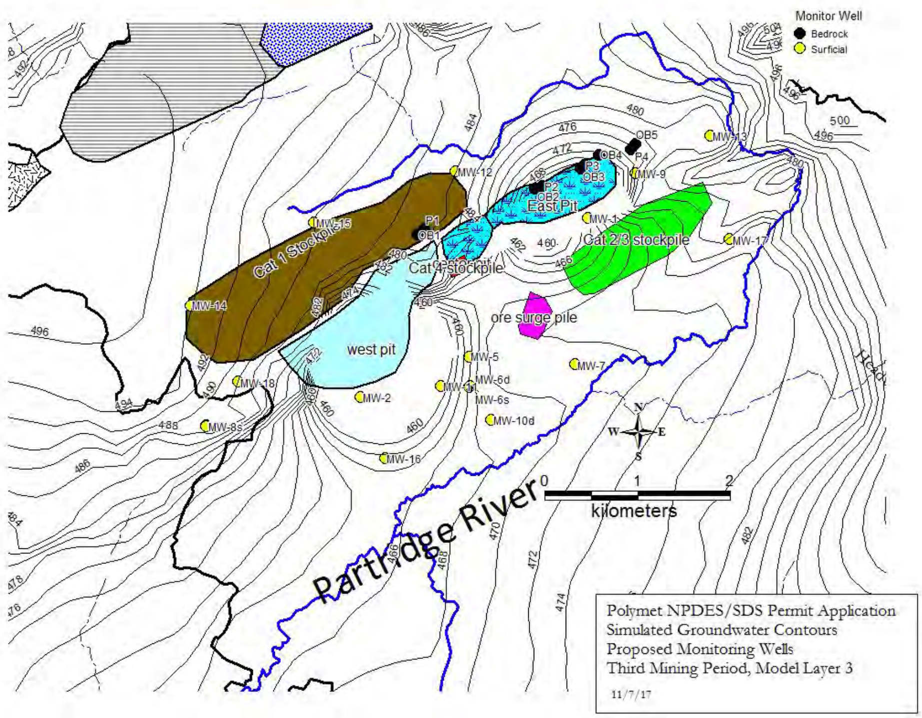


Figure 9: Groundwater contours (meters above mean sea level), mine site, year 11, layer 3.

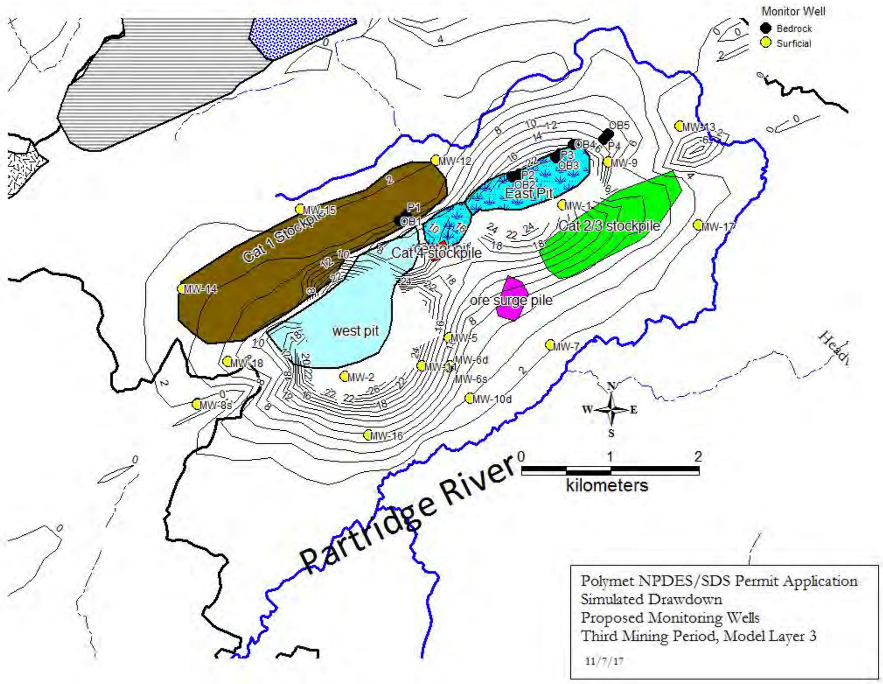


Figure 10: Drawdown contours (meters), PolyMet mine site, year 11, layer 3.

Figures 11 through 13 show the SO4 concentration contours for years 11, 14, and 20, and the proposed monitoring network for layer 3, the upper portion of the bedrock aquifer. Layer 1, the surficial aquifer, and layer 2, the highest part of the bedrock, have substantial dry areas that make the contours more difficult to interpret. However, they generally parallel the contours in layer 3. Figure 14 shows that the contours in layer 4 generally parallel those in layer 3.

The plumes reach a maximum extent in year 14 for three reasons. The recharge rate in the Category 1 stockpile begins reducing in year 14. Second, the Category 4 stockpile is removed after year 11 so the source is gone. Third, the drawdown caused by dewatering the three pits draws groundwater (and contaminants) toward the pit lakes.

Contours shown on the figures away from the facilities peak at between 1000 and 10,000 ug/l. These predictions are based on PolyMet-estimated rates and concentration. If leaks occur in addition to the predicted rate or the overall seepage rates exceed the assumed rates, the concentrations will be much higher. The plumes demonstrate the overall pathway contaminants would follow through the aquifer.

Simulated plumes down to 1 ug/l would mostly miss the proposed monitoring wells south of the mine site (Figures 11-14). The plumes miss monitoring wells MW-5, MW-6s and d, MW-10s and d, and MW-11. At 14 years, the shape of the plume in layer 4 (Figure 14), deeper bedrock, paralleled that in layer 3 (Figure 12). Simulated seepage from these facilities was distributed across the facilities, so the plume footprint should be representative of the extent of the footprint even for a more substantial leak.

Contaminant plumes emanating from various facilities reach the Partridge River within 11 years (Figure 11). This occurs because the OSP and Category 2/3 stockpile are wholly or partly south of the groundwater divide and because seepage from the Category 1 stockpile flows west of the drawdown caused by the West Pit, as noted above (Figure 9).

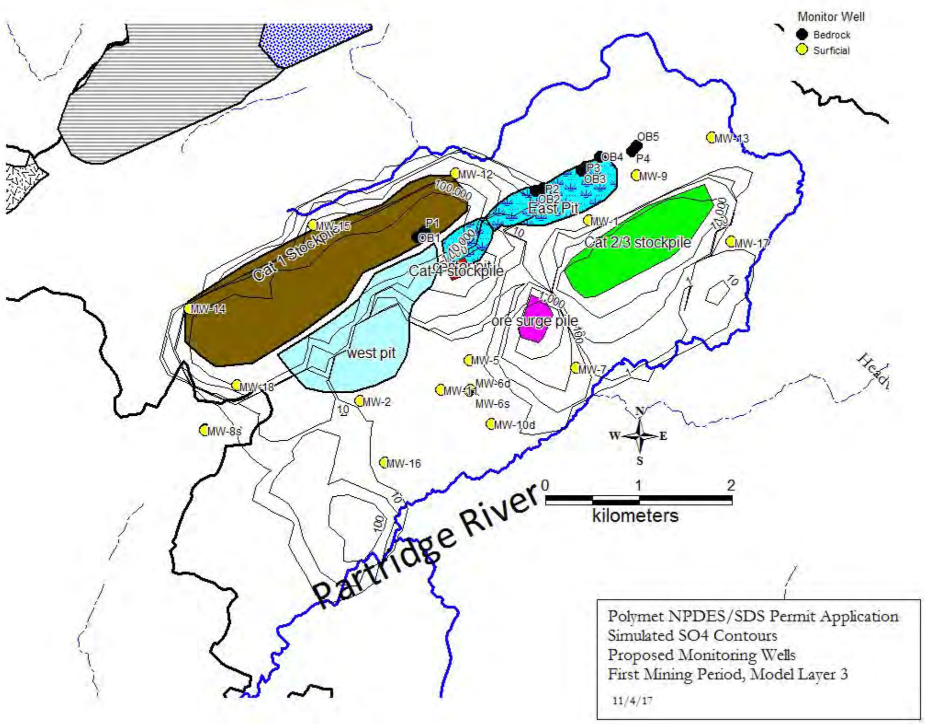


Figure 11: Sulfate concentration at PolyMet mine site, year 11 after start of mining, layer 3.

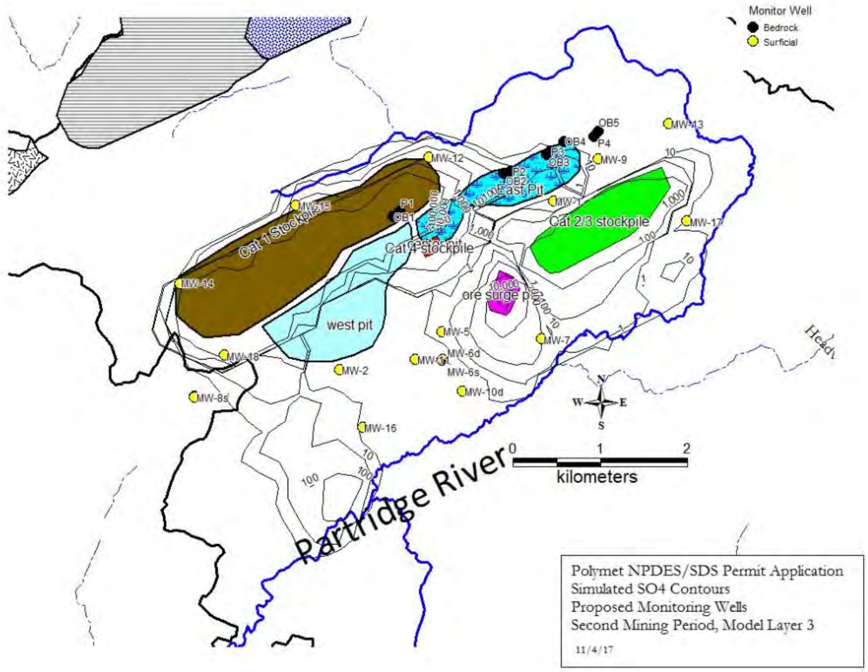


Figure 12: Sulfate concentration at PolyMet mine site, year 14 after start of mining, layer 3.

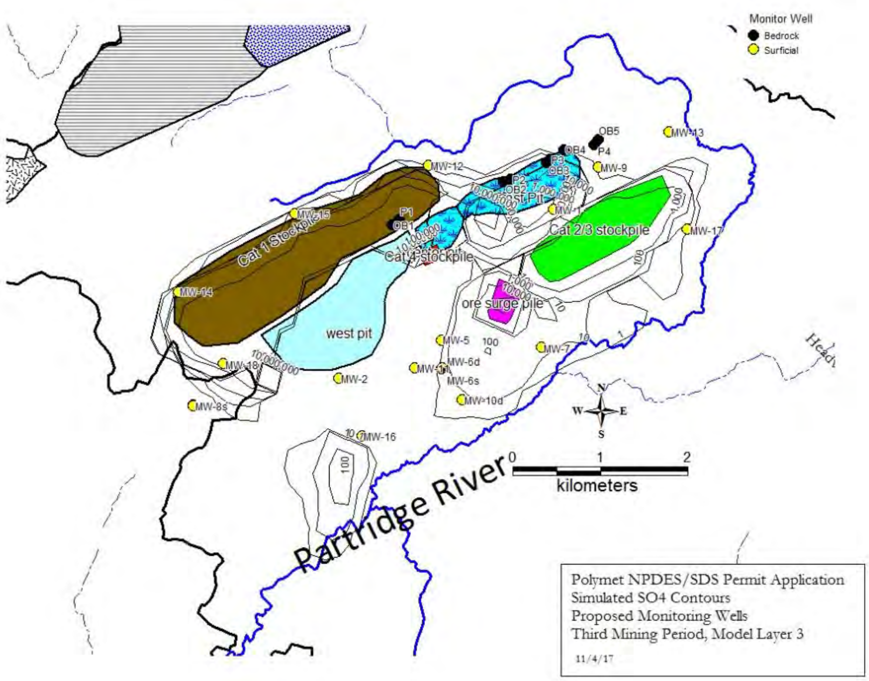


Figure 13: Sulfate concentration at PolyMet mine site, year 20 after start of mining, layer 3.

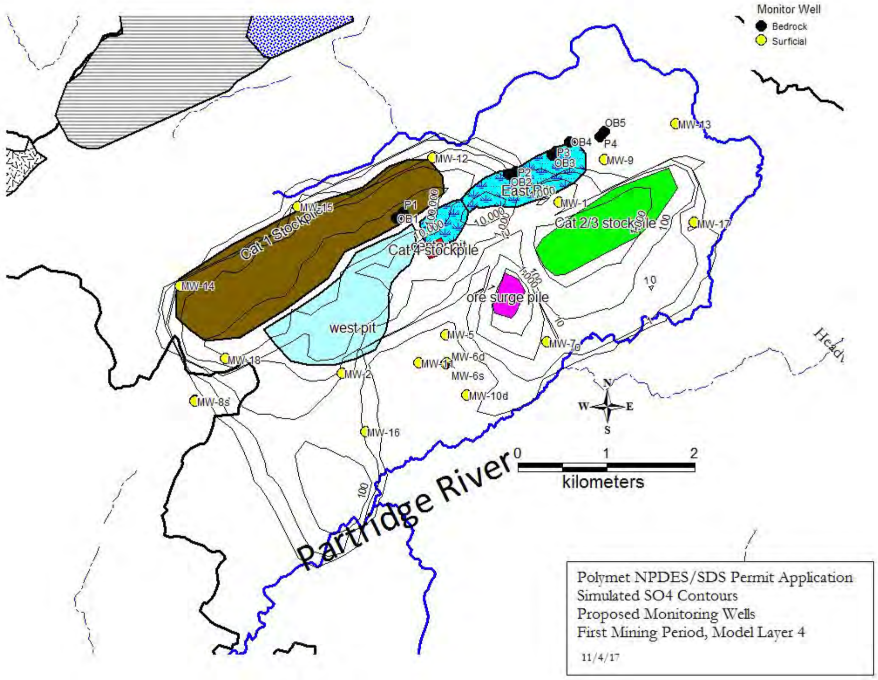


Figure 14: Sulfate concentration at PolyMet mine site, year 14 after start of mining, layer 4.

Simulated sulfate concentrations at various monitor wells peak within the first 20 years, with some peaking within the first 11 years (Figures 15 through 20, the contour plot maps, Figures 9 through 14, show the location of the monitor wells). Monitor well MW-14 demonstrates how the general groundwater flow direction prevents significant transport north of the Category 1 stockpile. MW-14 lies in the middle of the closely-spaced contours. Concentration peaks at 1000 ug/l (Figure 15), but if the well was a couple hundred meters closer to the stockpile, it would have been much higher. Well MW-05-09 is also on the north edge of the Category 1 stockpile and concentration peaks more than 400 times higher than at MW-14 (Figure 16). Monitor well MW-12 (Figure 17), on the northeast corner of the Category 1 stockpile, peaks at levels in between those of MW-14 and MW-05-09. It also peaks at about 8 years, presumably reflecting the influence of dewatering drawing groundwater back toward the West Pit. Deeper well OB-1 peaked later than the other wells and maintained a high concentration for a longer period (Figure 18). This reflects the longer transport time to reach the deep aquifer level. It also indicates that contaminants reaching the deeper layer could provide a contaminant source to downgradient sinks after the shallower wells have shown that contamination has begun to dissipate.

Monitor well MW-7 lies just east of the Category 2/3 stockpile (Figure 9). If transport went southeast from that stockpile, the monitoring well would detect it, but instead it peaks at or near 200 ug/l (Figure 19). The plume lies southwest of this monitor well. Monitor well MW-05-

02 lies toward the south portion of the site, and its concentration peaks at about 15 years (Figure 20),but varies by layer.

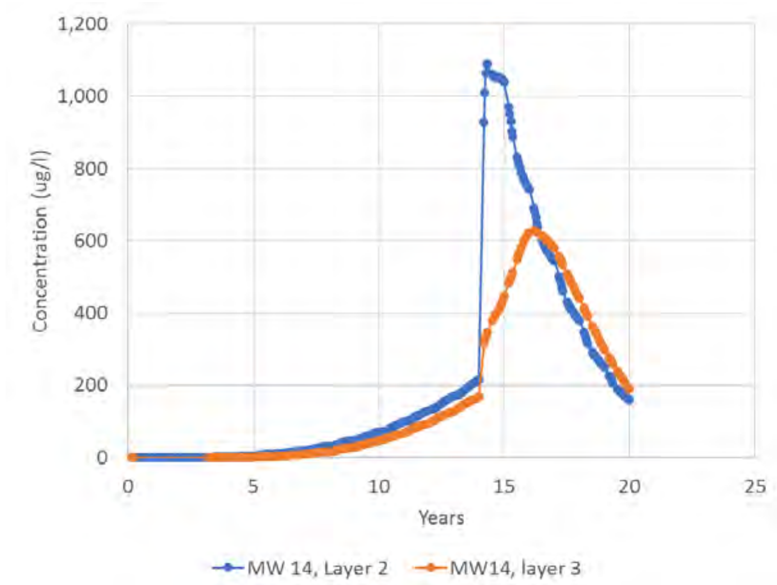


Figure 15: Sulfate concentration graph at well MW-14.

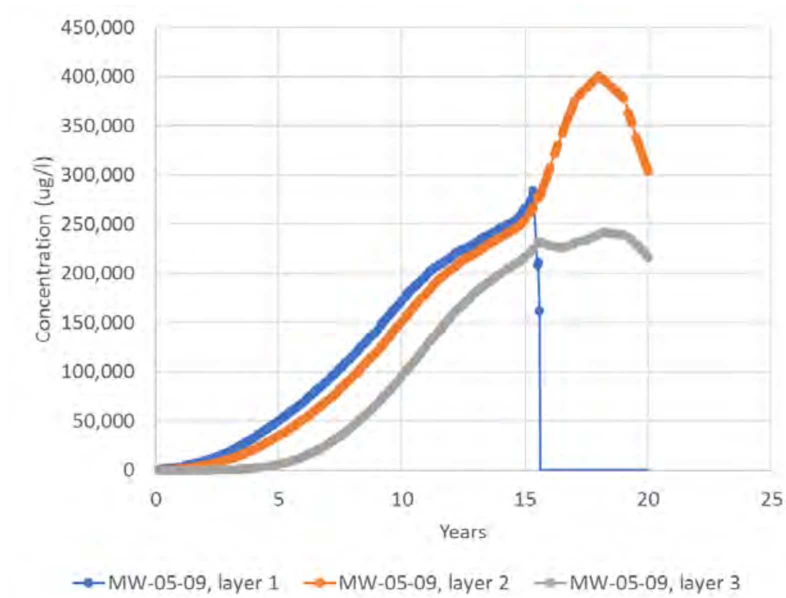


Figure 16: Sulfate concentration graph at well MW-05-09.

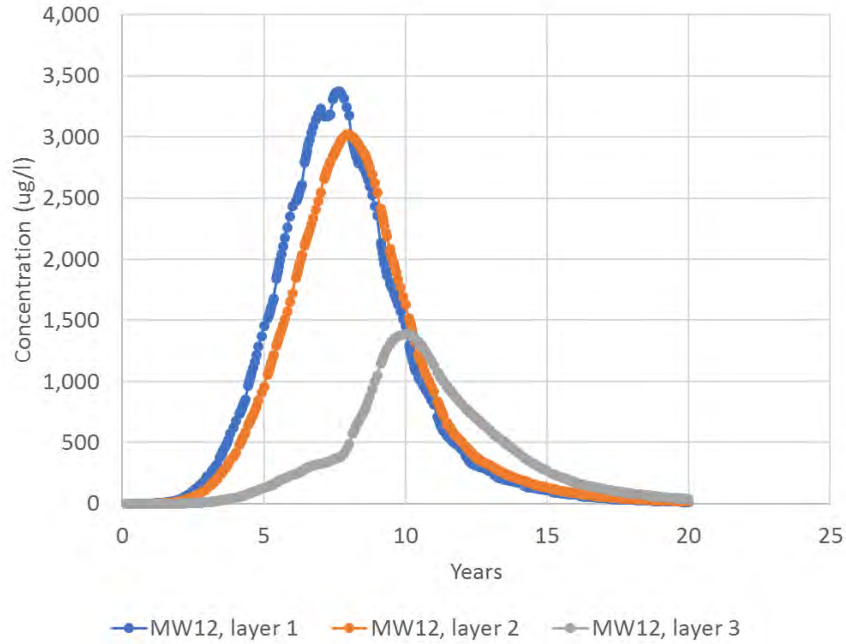


Figure 17: Sulfate concentration graph at well MW-12.

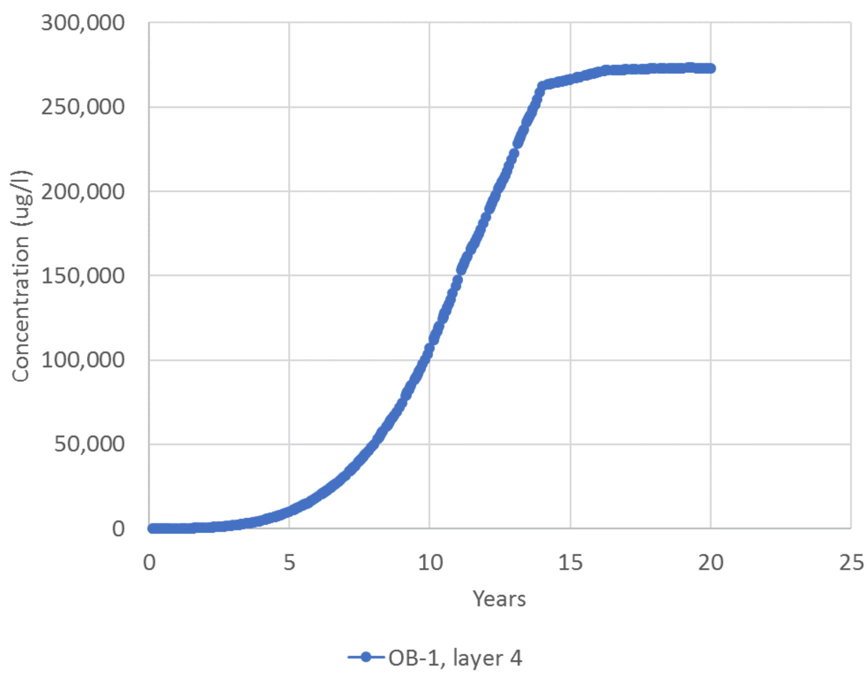


Figure 18: Sulfate concentration graph at well OB-1.

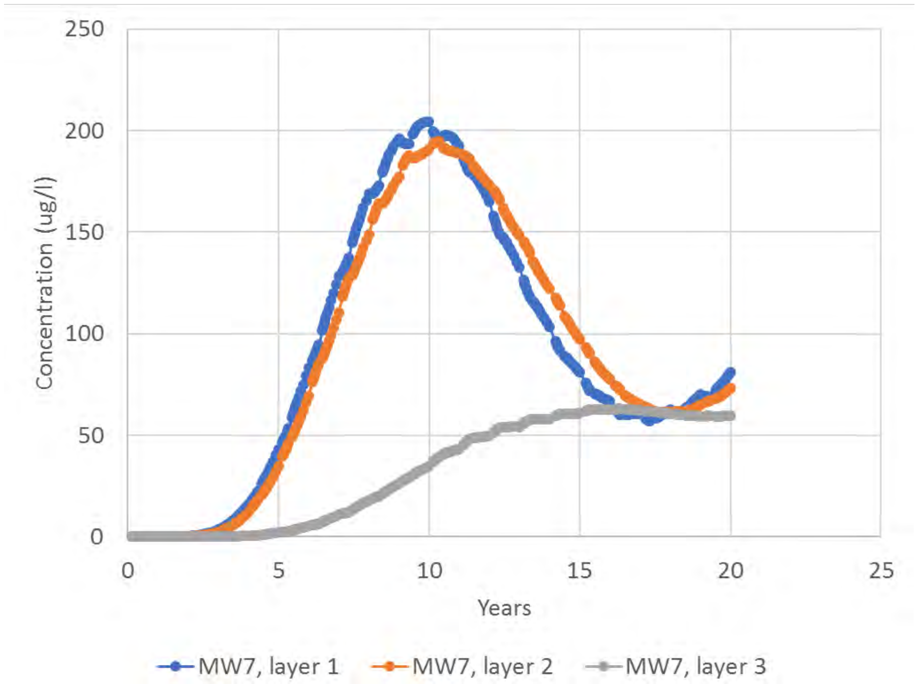


Figure 19: Sulfate concentration graph at well MW-7.

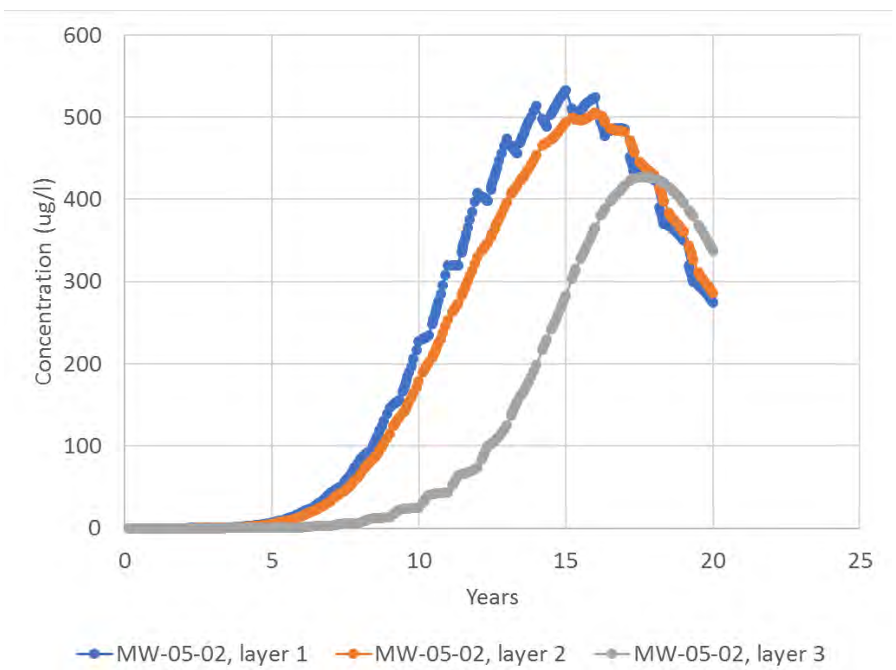


Figure 20: Sulfate concentration graph at well MW-05-02.

Individual Mine Features

The effect of each mine site feature, the three waste rock stockpiles and the OSP, were considered separately by simulating each feature individually for the first mine development period (year 1 to year 11). This scenario was completed by setting concentration for the three not being simulated equal to zero and allowing seepage rates through each facility as simulated for the whole mine site analysis. The assumption is that each feature would be in place and the purpose of the analysis was to determine the individual contribution to the contaminant plume that had been estimated in Figure 11. These scenarios provide a test of the proposed monitoring network, by testing whether contamination released from a specific facility would be detected. The magnitude of the contours is not important because the simulations here do not consider the background concentration, with initial conditions simulated as being zero, and because these simulations assume seepage distributed evenly beneath the facility, not as a large leak at an individual location.

Releases from the Category 1 stockpile transport less than a 1/4 mile to the north because that is effectively upgradient into groundwater flow toward the West Pit (Figure 21). Releases from the west end of the West Pit flows toward the Partridge River south of the mine site (Figure 21). The transport passes west of the groundwater divide that occurs in the groundwater table due to dewatering the West Pit (Figure 21); dewatering the West Pit does not capture the seepage from the Category 1 stockpile. Monitor well MW-18 would detect the concentration increases near the Category 1 stockpile, but there are no wells south of the stockpile that would detect concentration increases before they reach the Partridge River (Figure 21).

Releases from the Category 2/3 stockpile flow south toward the Partridge River, which is a primary discharge point for contaminants from that stockpile (Figure 22). A groundwater divide directly beneath the Category 2/3 stockpile (Figure 9) allows transport to the south. The plume flows undetected between the proposed monitor wells, MW-7 and MW-17. The SO4 graph for MW-7 (Figure 19) showed a modest increase, but that could be linked to the Category 4 stockpile and the OSP.

Seepage from the Category 4 stockpile, which has the highest concentrations (Table 1), is drawn to the dewatered pits until year 11 when it would be backfilled into the East Pit. The plume extends about a mile south of the Category 4 stockpile, but is obviously drawn toward the West Pit (Figure 23). Residual SO4 would draw to the pit, although some would flow toward the Partridge River.

The OSP lies south of the groundwater divide, so the plume extends south to a discharge point at the Partridge River (Figure 24). The edge of the plume intersects well MW-7, but the midline of the plume lies between that well and a line of monitoring wells to the west that are outside of the plume area.

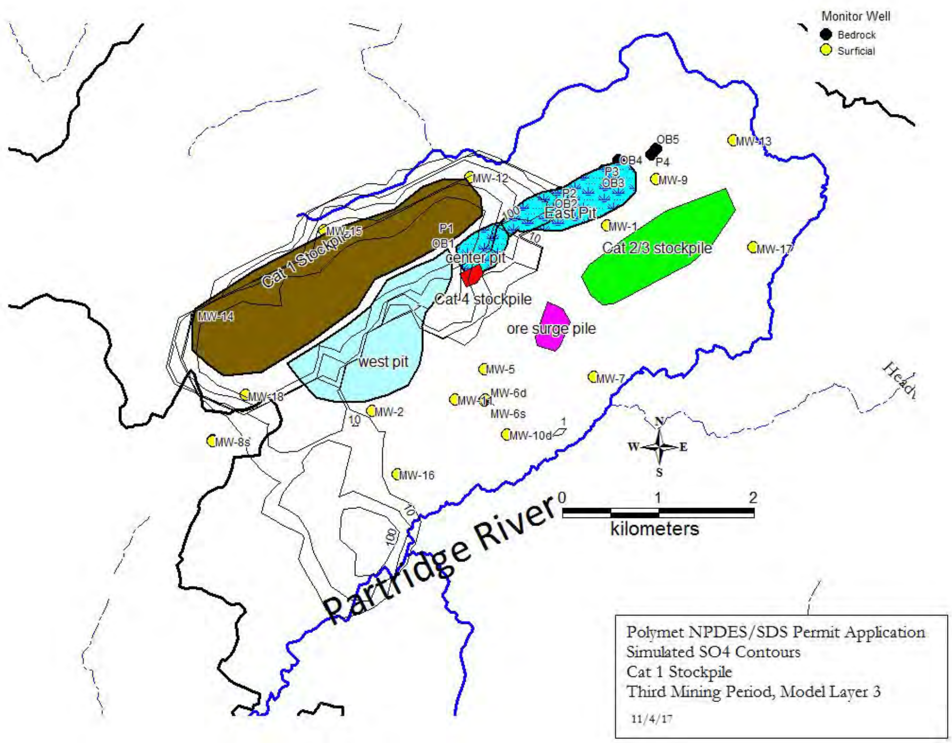


Figure 21: Sulfate contours, Category 1 stockpile only, year 11, layer 3.

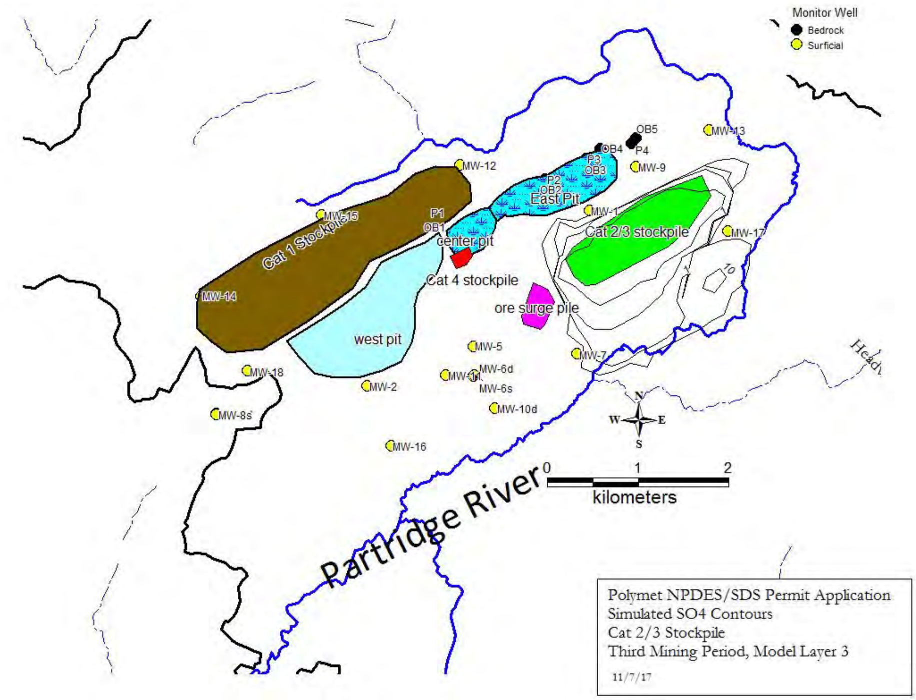


Figure 22: Sulfate contours, Category 2/3 stockpile only, year 11, layer 3.

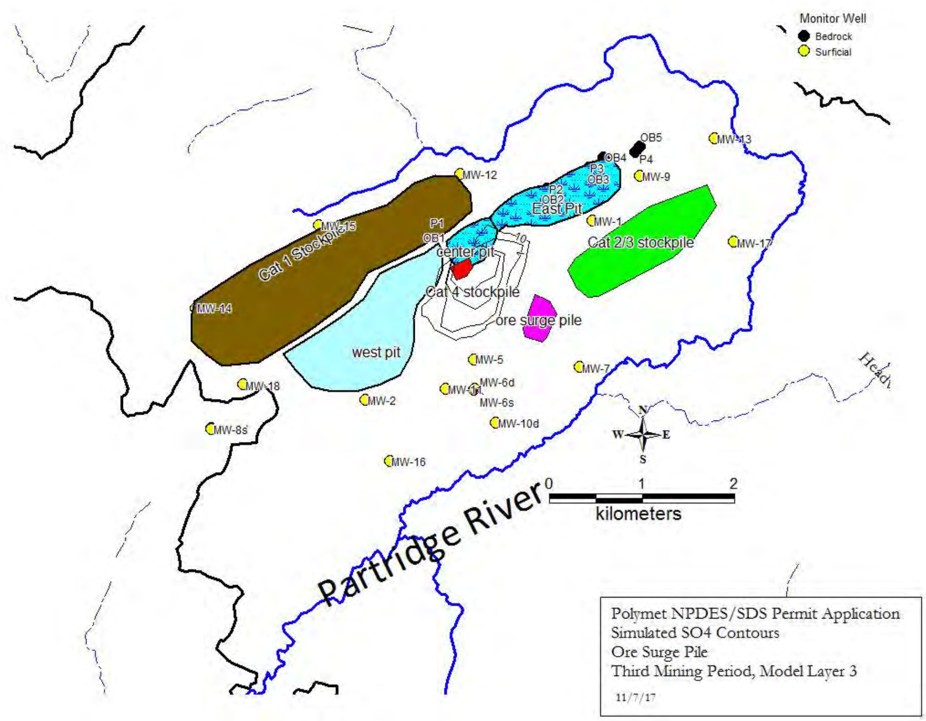


Figure 23: Sulfate contours, Category 4 stockpile only, year 11, layer 3.

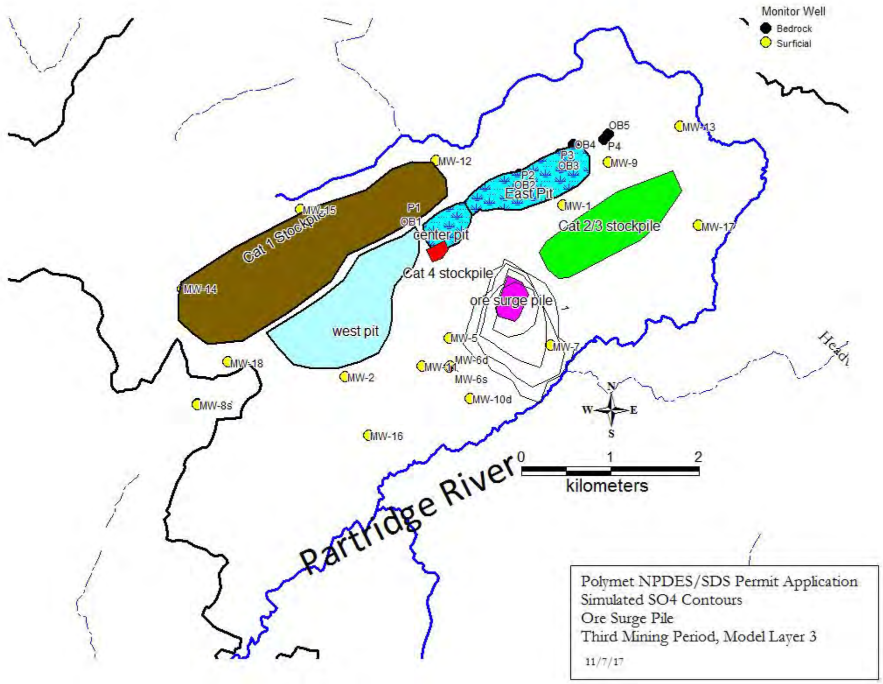


Figure 24: Sulfate contours, OSP, year 11, layer 3.

The following simulations consider the facilities separately, with the addition of a substantial leak to the seepage, except for the Category 4 stockpile. Two potential leaks in the Category 1 stockpile, one in the far west and one in the far east portion, and leaks in the center of the OSP and Category 2/3 stockpile were considered separately. Each leak was at the concentration as simulated for the entire facility, but with a rate equal to the rate of the entire facility. The simulation for seepage from an entire facility and from a specific leak was that each facility leaked at twice the predicted rate with half of the seepage discharging through one model cell.

Adding a leak to the west end of the Category 1 stockpile essentially added sulfate load to the seepage on the west end of the stockpile that transports around the west end of the West Pit. Although the plume shape did not expand substantially, the concentration increased from 100 to 10,000 ug/l (Figures 21 and 25). Concentrations at monitor well MW-16 may have increased slightly, but it lies far outside the centroid of the plume and would not provide an indication of the true magnitude of the contamination emanating from the west end of the Category 1 stockpile.

Adding a leak to the east end of the Category 1 stockpile does not expand the plume substantially but increases by an order of magnitude the concentration contours (Figure 26). There is little change in the west from the scenario without a leak. There is little overlap between the plumes emanating from the leaks. A leak on the east end of the Category 1 stockpile would increase the load reaching the far upstream end of the Partridge River, or Yelp Creek, because the transport from the east of the Category 1 stockpile is north and east. Some would be captured by dewatering the East Pit. Monitoring well MW-12 should detect the increased concentration, but monitor wells P2 and OB2 are too far south and close to the East Pit to provide any information about the plume moving northeast. There is no monitoring that would detect the movement of contaminants northeast from the Category 1 stockpile toward the Partridge River.

The plume from the Category 2/3 stockpile with a leak near its centroid expanded about half a kilometer further south of the river than did the plume for the Category 2/3 stockpile without a leak (Figure 27). The magnitude increased about ten times, with a closed contour representing a peak in the middle of the plume (Figure 27). As for the plume without a leak (Figure 20), the monitor wells would not detect these changes.

Adding a leak to the OSP caused little change in the plume extent (Figure 28 and 21), but the magnitude increased about ten times. Monitor well MW-7 would detect an increase, but the threshold for detection would have to be low. MW-5 might detect a slight increase because of a small expansion to the southwest, but likely not raise an alarm. The monitor well layout is far from the center of the plume.

Summarizing, leaks that occur under the mine site facilities have little effect on the size of contaminant plumes emanating from the facilities because dispersivity coefficients control the spread of the plume. The plumes simulated for PolyMet predicted seepage rates would fit between the monitor wells in some areas, and essentially discharge to downgradient sinks undetected, or with minor increases at some wells. The exception would be monitor wells that lie within the footprint of the facilities which would record high concentrations if the predicted seepage manifests. The leaks as simulated would increase the load by up to 200 times, considering concentration increases of 100 times and a doubling of the seepage rate. Most of the plumes miss the monitor well layout. The monitoring well network should be established based on an accurate conceptual flow model for the transport from the specific facilities (see the section in the primary text).

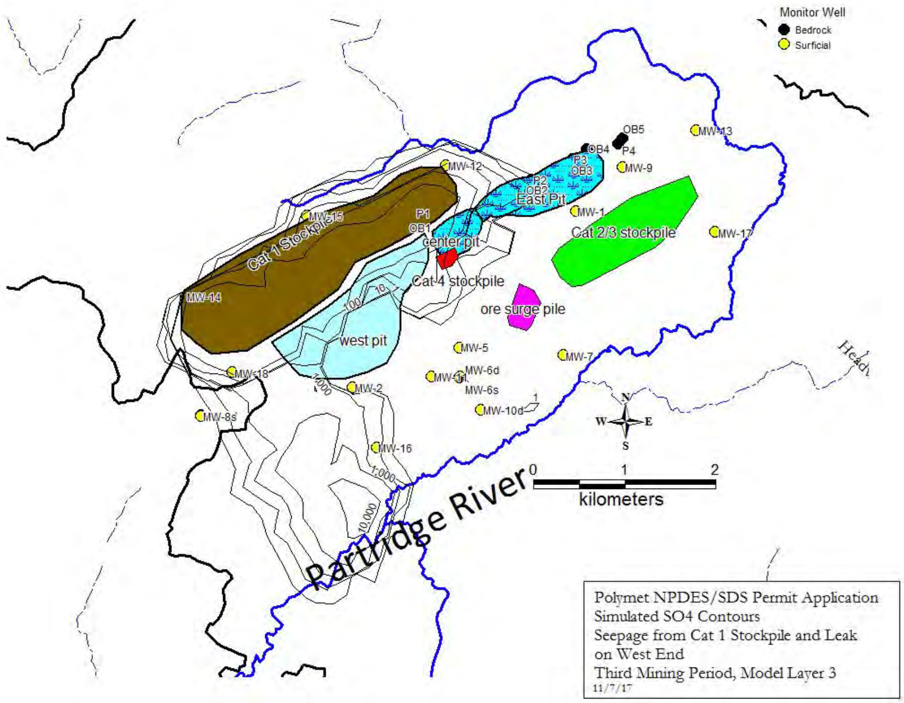


Figure 25: Sulfate contours, Category 1 stockpile with leak on the west side of the pile, 11 years, layer 3.

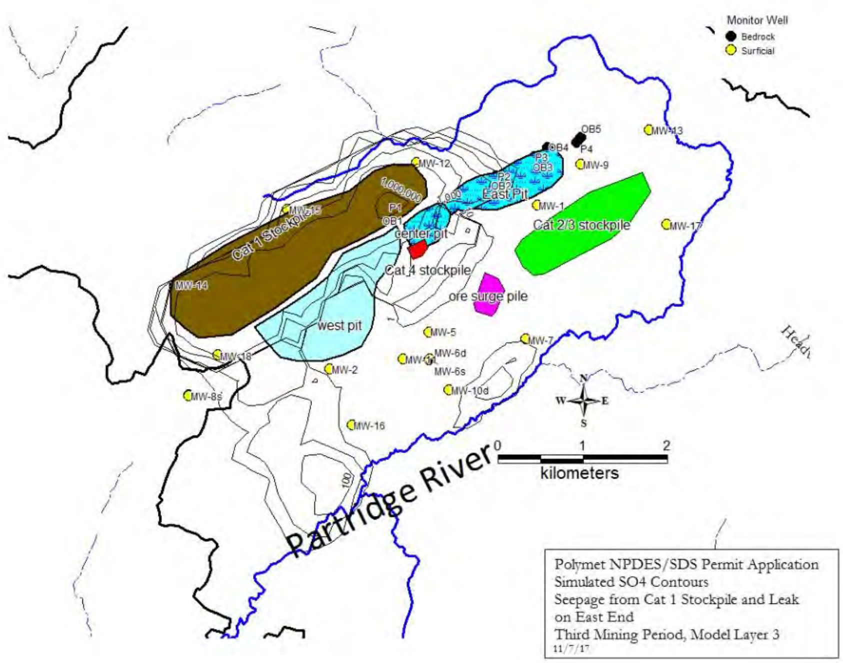


Figure 26: Sulfate contours, Category 1 stockpile with leak on the east side of the pile, 11 years, layer 3.

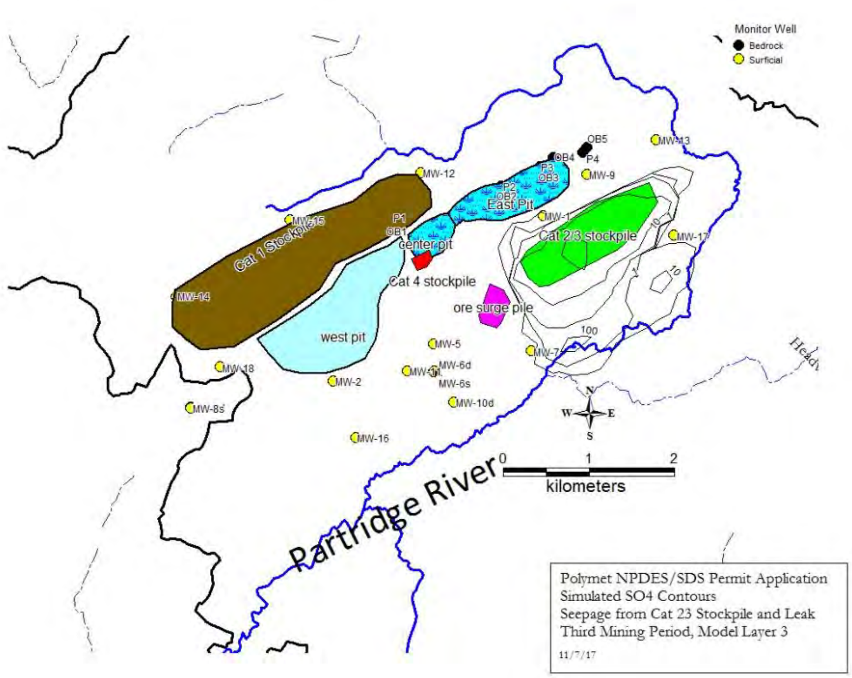


Figure 27: Sulfate contours, Category 2/3 stockpile with leak in the middle, 11 years, layer 3.

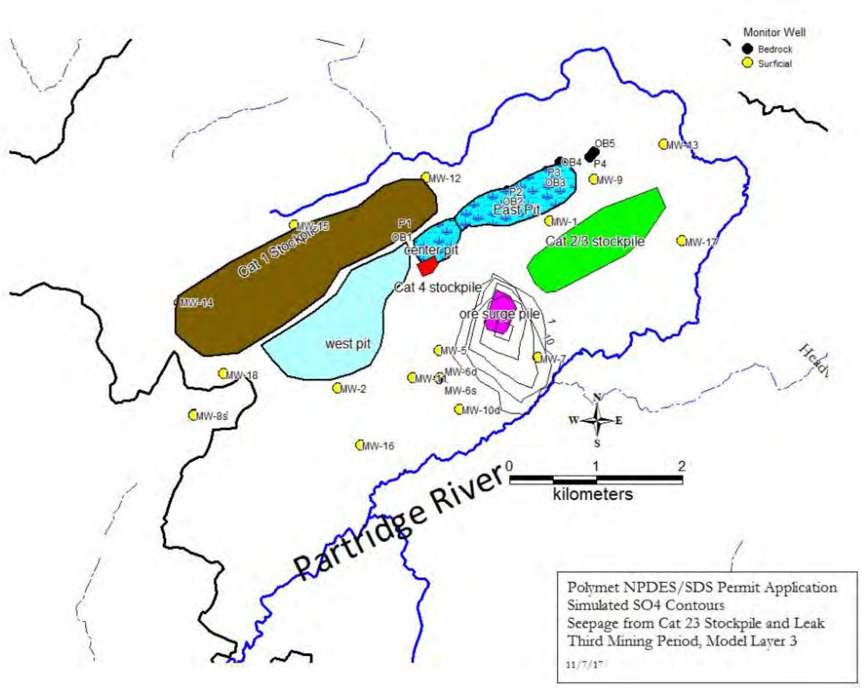


Figure 28: Sulfate contours, OSP with leak in the middle, 11 years, layer 3.

Sensitivity Analysis of Dewatering Discharge

The discharge permit, and the entire mine plan, depends on treating mine water prior to reuse or discharge. Dewatering water would be mine water that requires treatment because it would be pumped from sumps in the bottom of the pit. The treatment plans have used rates that were determined in PolyMet (2015), as described in the primary text of this report. If the actual rates differ or vary substantially, the ability to treat the water may be compromised. If the aquifer parameters differ from calibrated values, the amount of dewatering could differ substantially from the predicted rates. This section evaluates how dewatering rates could vary with variable parameters and how seasonal variation in recharge affects the dewatering rates.

I used the Myers (2014) model modified as described above to assess the sensitivity of dewatering rates to increased hydraulic conductivity (K). I increased the horizontal and vertical K for each parameter zone intersecting the pits by two times and ten times, separately for each zone. By doing it separately, the effect of variation in just one zone is being considered rather than a more cumulative consideration of changing all zones. I determined the mass balance for the section of the model including each pit to determine flux to the DRAIN cells used for dewatering using the mass balance feature in GWVistas. To complete this analysis, I digitized an area around the pits and GWVistas summed the water balance for all model layers so that the DRAIN flux equaled total dewatering. I completed the water balance for each of the 22 stress periods used to simulate the 11 years of mining. Recharge occurred for 122 days and no recharge occurred for 243 days. Comparison of hydrographs of predicted dewatering for the first 11 years of mining shows the effect of differing K values. Additionally, I plotted drawdown after 11 years for each K value. The Central Pit requires no dewatering during the first 11 years of mining, so, the analyses were for the West and East Pit.

The parameter zones that intersect the West and East Pit are Zones 19 through 23. As described in Myers (2014, Table 1, p. 1-6), Zones 20 through 23 are the Partridge formation and Zone 19 is Pokegama Quartzite. Also considered here is Zone 24 just north of the East Pit, which is the higher conductivity to the Virginia formation.

Table 3 compares the dewatering rates after 11 years for the original model runs (using calibrated parameters as used for mine site transport simulations above) and sensitivity model runs during which six different parameters zones were increased by ten times. Increasing this parameter, Zone 20 had the largest effect by far on dewatering rates, which reflects the Zone 20 intersecting the south half of the West and East Pit. Increasing parameter Zone 23 had the second largest effect, almost exclusively due to its large effect on dewatering the East Pit. Zone 23 underlies and intersects a larger portion of the East Pit, which may be why dewatering the East Pit was not sensitive to changing most zones (other than Zones 19 and 23). Parameter

Zone 19 had the third largest effect, reflecting that its east-west trend intersects the middle of the pits. However, its effect is smaller because Zone 19 represents a much smaller section of the aquifer and affects flow over a much smaller area. The increase due to changing other parameters zones was less than 10%.

Dewatering the West Pit increased most for increasing K for parameter Zone 20, while for the East Pit there was almost no change (Figure 29). Increasing parameter Zone 19 increased dewatering rates for each pit by almost equal amounts (Figure 30), which reflects that the pits excavated into and essentially split the Zone 19 formation. Because the conductivity values differ by direction (Table 3), dewatering would have increased drawdown along the formation substantially and drawn groundwater into either East or West Pit as it was being dewatered dewatered.

The hydrographs (Figures 28 and 30) show seasonal changes in dewatering rates that indicate seasonally changing recharge rates cause substantial seasonal variation around an average. Dewatering rates would also increase substantially during a wet year. In fact, wet years would likely have a threshold effect, meaning that the increase in recharge beyond the average rate would occur because precipitation increments above average are likely to exceed the average evapotranspiration and soil water holding capacity so that more will seep past the soil layer. Wet years would lead to substantial increases in dewatering and, therefore, treatment rates.

Changing K values affect drawdown less than dewatering rates. After 11 years, drawdown spread slightly further for increasing K19 than drawdown for the calibrated model (Figure 31). Increases in the extent of drawdown reflect the lower gradient needed with higher conductivity controlling the flow rates. Increasing K24 had little effect on drawdown contours (Figure 32) because dewatering increased only slightly (Table 3), except that the 5-m contour spread far to the west from the pit through that parameter zone. Changing K caused the model to draw groundwater from different formations even if the overall rate does not change substantially. Spreading drawdown further from the mine site could increase the drawdown effects on wetlands further from the mine than expected.

In summary, if the actual conductivity exceeds that used to estimate dewatering rates, dewatering will be much higher than predicted, and drawdown would expand further into nearby wetland areas. If conductivity is underestimated by an order of magnitude for just one formation intersecting the pits, the dewatering rate could be almost doubled. Seasonal changes during average recharge years indicate that wet years that could increase recharge substantially, without regard to the accuracy of K values, and could also cause much higher dewatering rates. If either factor manifests, the rate of water requiring treatment would be much higher than predicted for the draft NPDES/SDS permit.

Table 3: Dewatering rates (gallons per minute) for the West Pit, East Pit, and Total, after 11 years of mining, for the calibrated model and for six conductivity parameter zones with K (meters/day) increased by ten times, as shown in the table.

	West Pit	East Pit	Total	Kx	Ky	Kv
Original	637.1	615.7	1252.8			
K19	756.0	846.8	1602.8	0.05	0.002	0.05
K20	1768.8	613.6	2382.5	0.36	0.36	0.0774
K21	643.9	684.1	1328.0	0.0265	0.0265	0.318
K22	640.6	671.1	1311.7	0.0043	0.0043	0.043
K23	654.5	1019.6	1674.2	0.08	0.0043	0.128
K24	639.5	705.0	1344.5	1	1	1

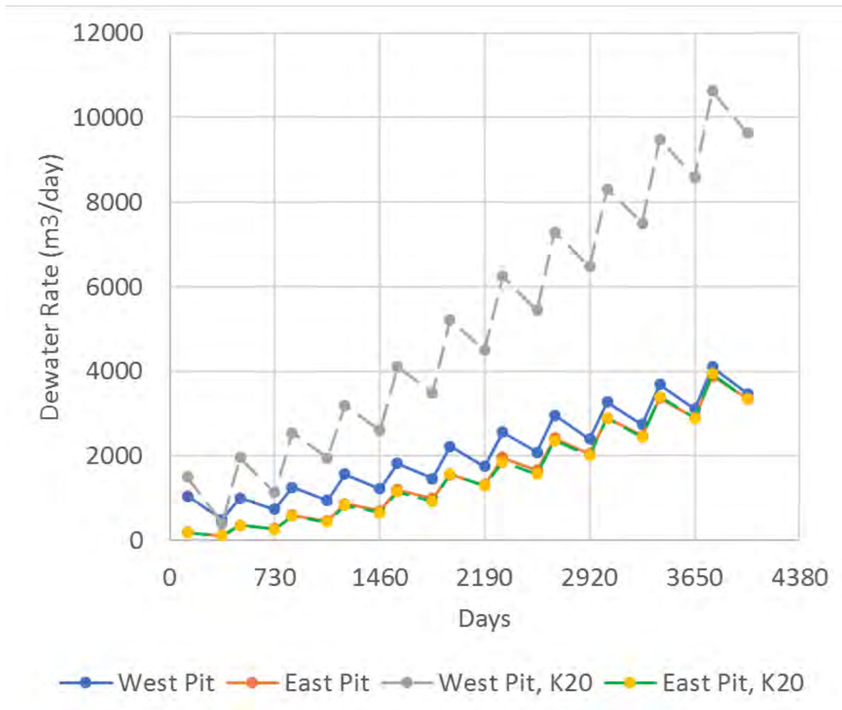


Figure 29: Hydrograph of dewatering rates for the West and East Pit as calibrated and with hydraulic conductivity values for parameter Zone 20 increased by 10 times.

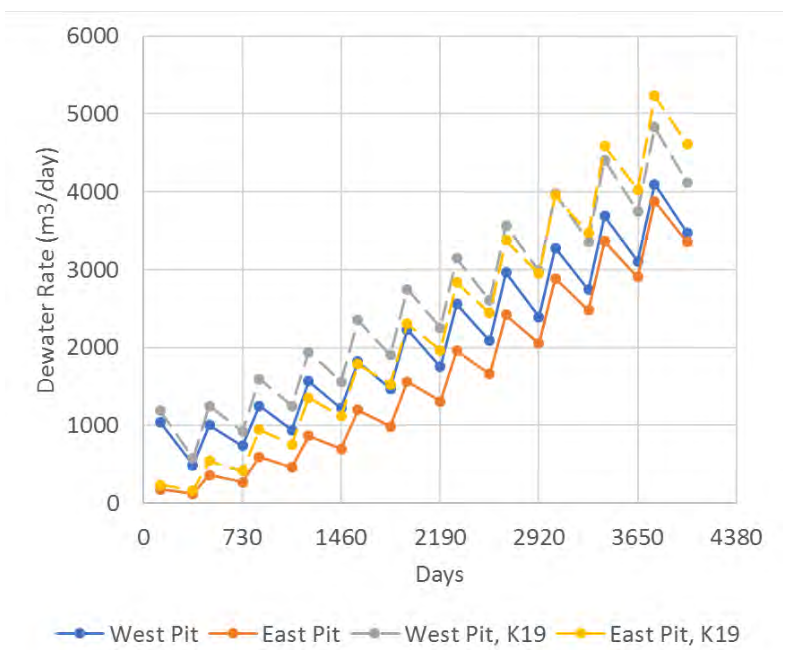


Figure 30: Hydrograph of dewatering rates for the West and East Pit as calibrated and with hydraulic conductivity values for parameter Zone 19 increased by 10 times.

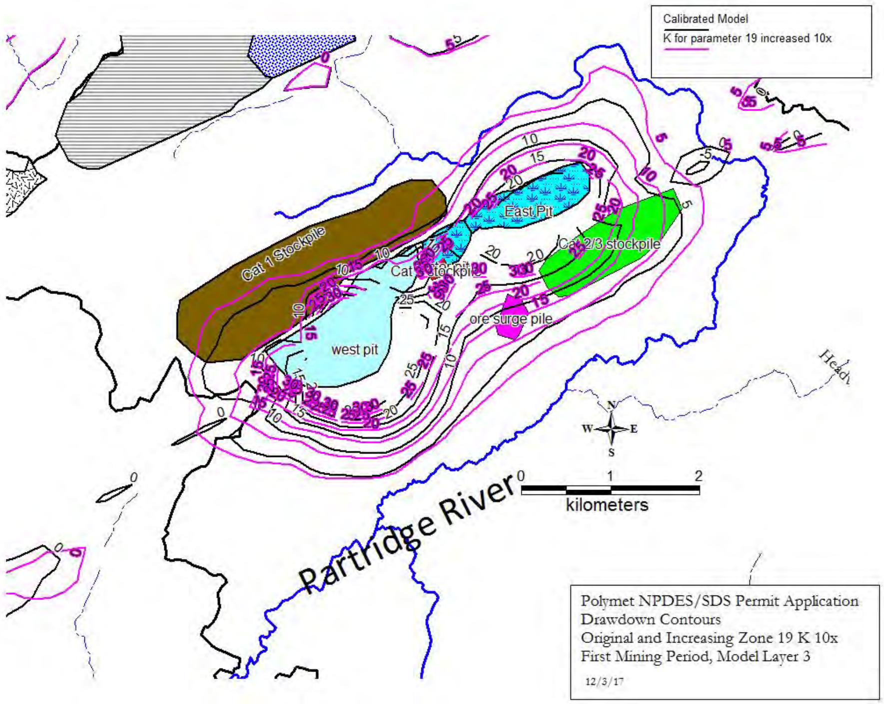


Figure 31: Drawdown contours for the calibrated model and for increasing K for Zone 19 by 10 times.

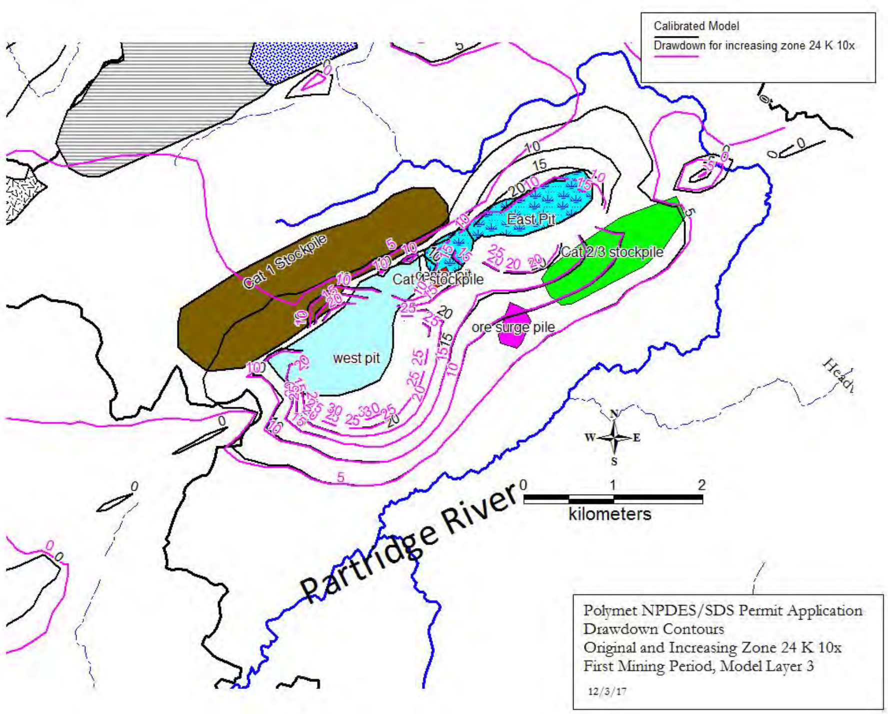


Figure 32: Drawdown contours for the calibrated model and for increasing K for Zone 24 by 10 times.

Load and Discharge to the Partridge River

Groundwater seepage in the Mine Site area discharges to the Partridge River, simulated as DRAIN reach 15 through its upstream reach near the mine site. Reach 15 extends from the headwaters to the confluence with the South Partridge River, or about 9.96 miles. The confluence is near surface water management station SW004a (Figure 33). Both simulated groundwater discharge and load rates are highly variable along the reach (Figure 34).

Almost half of the simulated load, seepage from the Category 1 stockpile, reached the river at the upstream end (Figure 34). For about three miles, no groundwater discharges to river (the horizontal flow reach in Figure 34). Groundwater discharge occurs from upstream of mile 4 to about mile 6.5, but the load curve remains flat indicating groundwater flow with no contaminant, as would be expected east of the mine site. The discharge increases substantially after mile 6 through about mile 10, a reach through which the load also doubles, but from the load that entered at the very upstream end (Figure 34).

Groundwater concentration reaching the river can be estimated by dividing the load reaching a reach by the flow rate reaching a reach, as shown in Figure 34. Up to mile 0.77, the load entering the river at the upstream end would have a concentration of about 60 mg/l. Failure to capture seepage discharging from the west part of the Category 1 stockpile during mine operations could have a substantial deleterious effect on the Partridge River. The concentration reaching the reach between mile 6.5 and 0.96 is about 8 mg/l. The river reaches flowing from east to southwest of the mine site receive contaminated groundwater along the entire reach. Because of the short horizontal section between about mile 8.2 and 9.6, the actual concentration is higher in the other portions of the reach. Thus, there is significant variability in the groundwater fluxes and loads reaching the river, probably based on the contaminant source (the mine feature with seepage into groundwater) and the actual pathways.

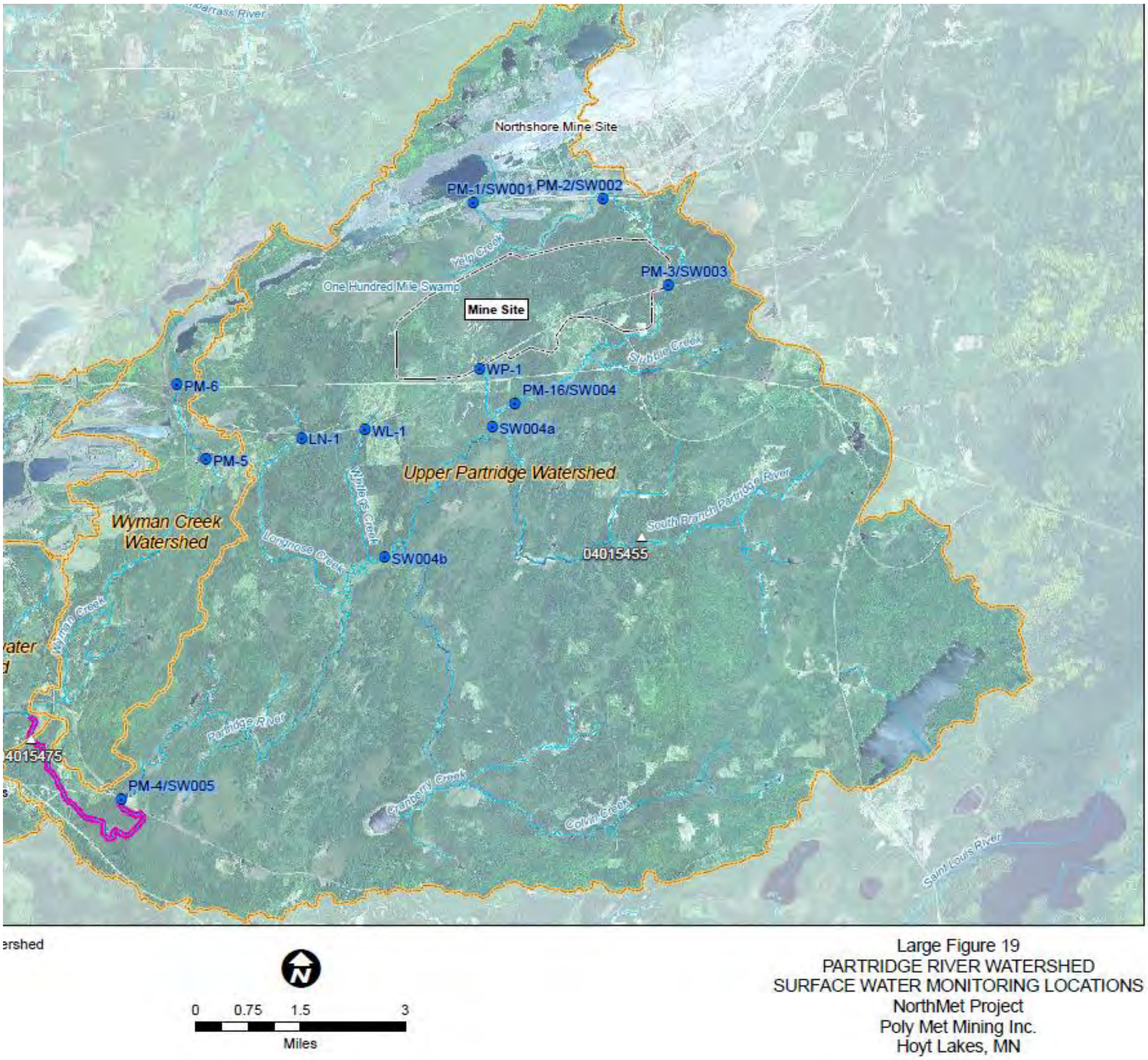


Figure 33: Snapshot of a portion of Large Figure 19, PolyMet (2015), showing the rivers near the Mine Site.

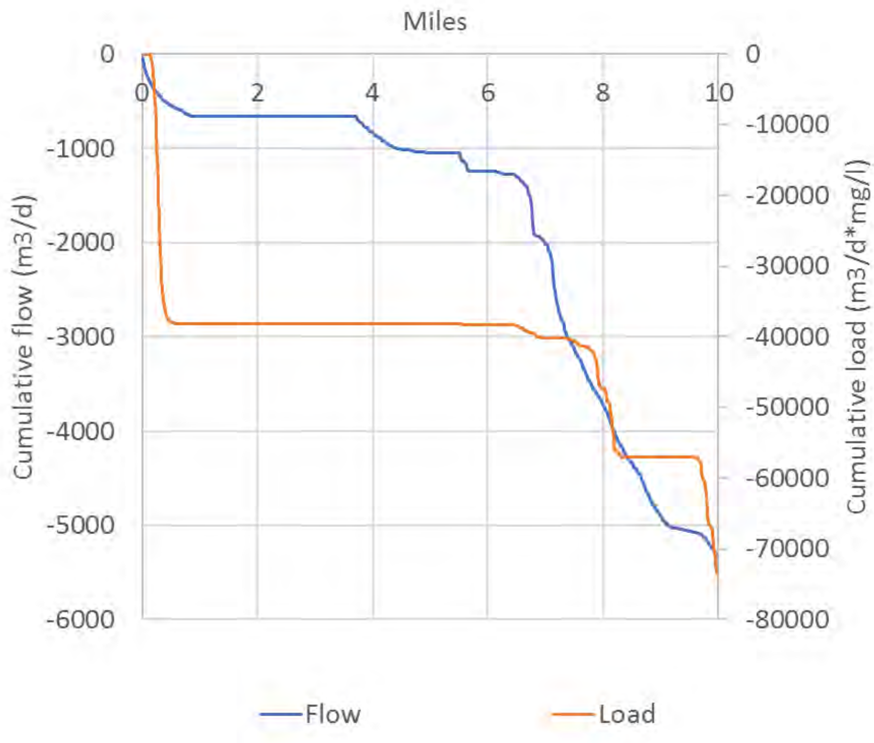


Figure 34: Cumulative flow and load on reach 15, the Upper Partridge, by mile from up- to downstream.

Plant Site Operations

This section considers the NPDES/SDS application for discharges from the plant site. The NPDES application (Volume V) references Northmet Project Water Management Plan – v6, dated 2017, but the MPCA reference for it is version 5, dated 2016 (https://www.pca.state.mn.us/sites/default/files/wq-wwprm1-50a_0.pdf, accessed 12/19/17).

Discharges from the Plant Site reach surface water through groundwater pathways. The PolyMet tailings impoundment would be constructed on top of an existing tailings impoundment, with the plan including the addition of bentonite to the ponds on top of the impoundment to reduce the seepage and the addition of a cutoff wall around much of the tailings impoundment to capture the continuing seepage. This section reports on modeling of seepage from the tailings impoundment to assess pathways and monitoring well plans.

Three scenarios are considered. First is a baseline with seepage distributed through the impoundment without a cutoff wall. The second scenario included a cutoff wall and DRAIN boundary to simulate the PolyMet proposed wall. The simulation, as described below, does not capture 100% of the seepage as estimated by PolyMet. See the detailed review of the cutoff wall in Appendix B. The assumption holds only if the surface of the bedrock is impervious so that no seepage can enter it and flow beneath the cutoff walls. The modeling used herein and described below captures much of the seepage but realistically simulates some going beneath the cutoff wall and continuing downstream. The goal is to consider how that seepage develops downgradient, when the cutoff wall does not perform as modeled by PolyMet.

Third, with the impoundment seeping at its average rate, specific leaks were added to four locations in the impoundment, with the leak equaling ten percent of the total rate. The intent is to estimate how fast a plume would develop and whether the monitoring as designed would show it.

There are 28 performance monitoring wells to be used around the base of the tailings impoundment (Figure 35). They are paired wells, with both installed in the surficial aquifer, installed up- and down-gradient of the new cutoff wall.

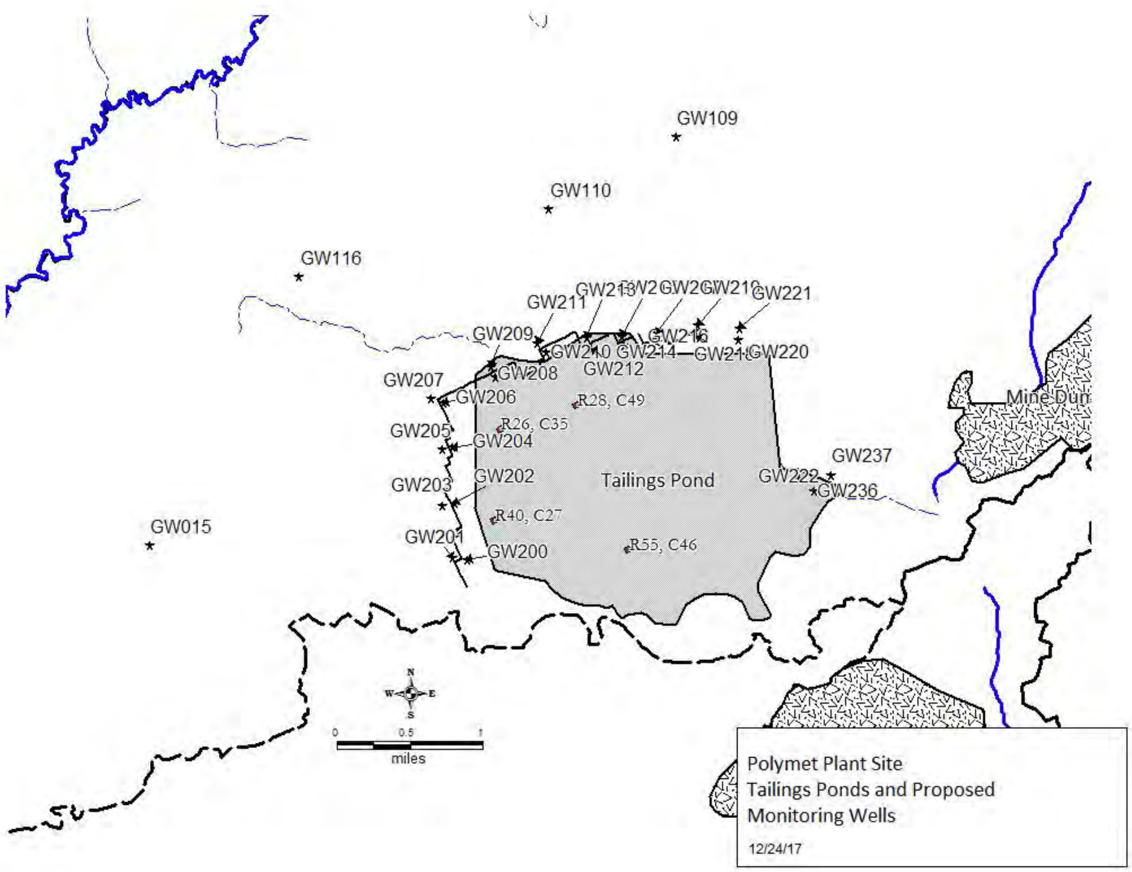


Figure 35: Existing PolyMet plant site, showing tailings pond and waste rock dumps, and proposed monitoring wells and cutoff wall/drain as simulated in the groundwater model. The

*map also shows the location of four simulated leaks, labeled as R**, C**, where R** and C** are row and column numbers.*

Groundwater Modeling of the Plant Site

Discretization of the model around the impoundment was improved, as described above (Figures 7 and 8), to improve the water balance and transport calculations near the impoundment. The top of layer 1 is the top of the existing tailings impoundment. The cutoff wall was simulated using the horizontal flow barrier (HFB) package to prevent horizontal flow and a DRAIN boundary to remove captured seepage (Figure 8). The seepage DRAIN simulated in Myers (2014) is seepage around the base of the current tailings impoundment, and changes in flux from this boundary would demonstrate changes due to the new cutoff DRAIN. The newly established cutoff drain elevation is 8 m below the bottom of layer 1 in both layer 1 and 2. The DRAIN used an effective K of 10 m/d and the HFB used an effective horizontal K of 10^{-4} m/d. Sensitivity analyses of these boundaries showed that decreasing K for the HFB made the drain more effective at increasing the capture of seepage. Increasing K in the DRAIN to 100 m/d increased captured flux by just a few percent, but decreasing K in the HFB from 10^{-3} to 10^{-4} m/d increased seepage capture by 30%. This demonstrates the importance of a tight cutoff wall as part of the seepage capture system. If K varies substantially, these calculations demonstrate that the drain will not successfully capture all of the water.

Transient simulation of the mining and reclamation periods was completed in eight steps. The first was a 20-year period simulating the mining period. It was 7300 days using 40 time steps and a time step multiplier of 1.05. The following six periods were 5 years, or 1830 days, with 20 times steps and a time step multiplier of 1.20. The eighth period was 200 years, or 70,000 days, with 200 time steps and a time step multiplier of 1.05. The simulation did not account for seasonal variation in seepage rate because there was little difference in the results, unlike at the mine site.

Tailings seepage reductions lowered the groundwater level sufficiently that, even without the simulated cutoff wall and drain, DRAIN reach 2 representing the seeps at the base of the impoundment reduces to zero. The DRAIN flux rate at the end of mining was 3260 m^3/d for simple distributed tails seepage, and reflects the drawdown caused by reducing seepage through the tailings impoundment.

For modeling, each of the pairs is simulated as up- and down-gradient of the simulated wall, with each well close to the middle of each cell. Digitization was based on locations shown in Volume I, Large Figure 7. The simulated wells will be completed in layers 1 through 3, meaning they will monitor upper two layers of the bedrock in addition to the surficial layer.

Mass Balance for the Tailings Impoundment

Changes in groundwater flow from the tailings impoundment area with and without the cutoff wall was estimated for the area near the tails (Figure 36), and computed using the mass balance feature in GWVistas. Slight variations in some fluxes which should be the same occurred because the polygon was digitized separately into each model file. Tables 4 and 5 present fluxes for the polygon in layers 1, 2, and 3 and for the total model thickness. The Xmin, Xmax, Ymin, and Ymax fluxes are fluxes through the left, right, lower, and upper directions of the polygon (Figure 36). Bottom and top are fluxes through the bottom or top of the polygon by layer, with inflow being into the layer meaning downward through the top or upward through the bottom. Storage inflow is water leaving storage and entering the model and storage outflow is water that is stored.

Flux through the top of the polygon is decreased to about half by adding a cutoff wall, although the reported flux is for all five model layers (Figures 37 and 38). This reflects the cutoff wall deflecting flow mostly into the drain. Flux to the natural seeps that surround the tailings impoundment decreased by more than two-thirds initially. By the end of the simulation, flux to the seeps decreased to zero for both scenarios due to the decreased seepage rates. Both reductions are due primarily to discharge to the cutoff wall DRAIN (Figure 38).

There is a substantial flux both up and down through the bottom of layers 1 and 2 (Tables 4 and 5). However, the next flux outward through the bottom of layer 2 is greatest with the cutoff wall (Figures 37 and 38), although there are substantial fluxes in each direction (Tables 4 and 5). The increased downward flow is due to the cutoff wall causing a higher groundwater level within layer 2. The gradient for flow through the cutoff wall increases, so there is more downward gradient to force flow deeper. This would primarily occur in the center of the tailings impoundment. A paradoxical effect of the cutoff wall is to increase flow deeper into the bedrock.

Much more recharge occurs in layer 2 within for the with cutoff wall scenario because the DRAIN in layer 2 (the cutoff) lowers the water table causing parts of layer 1 to be unsaturated. Dry cells are inactive. Because recharge is added to the highest active layer, it occurs in layer 2, and some in layer 3.

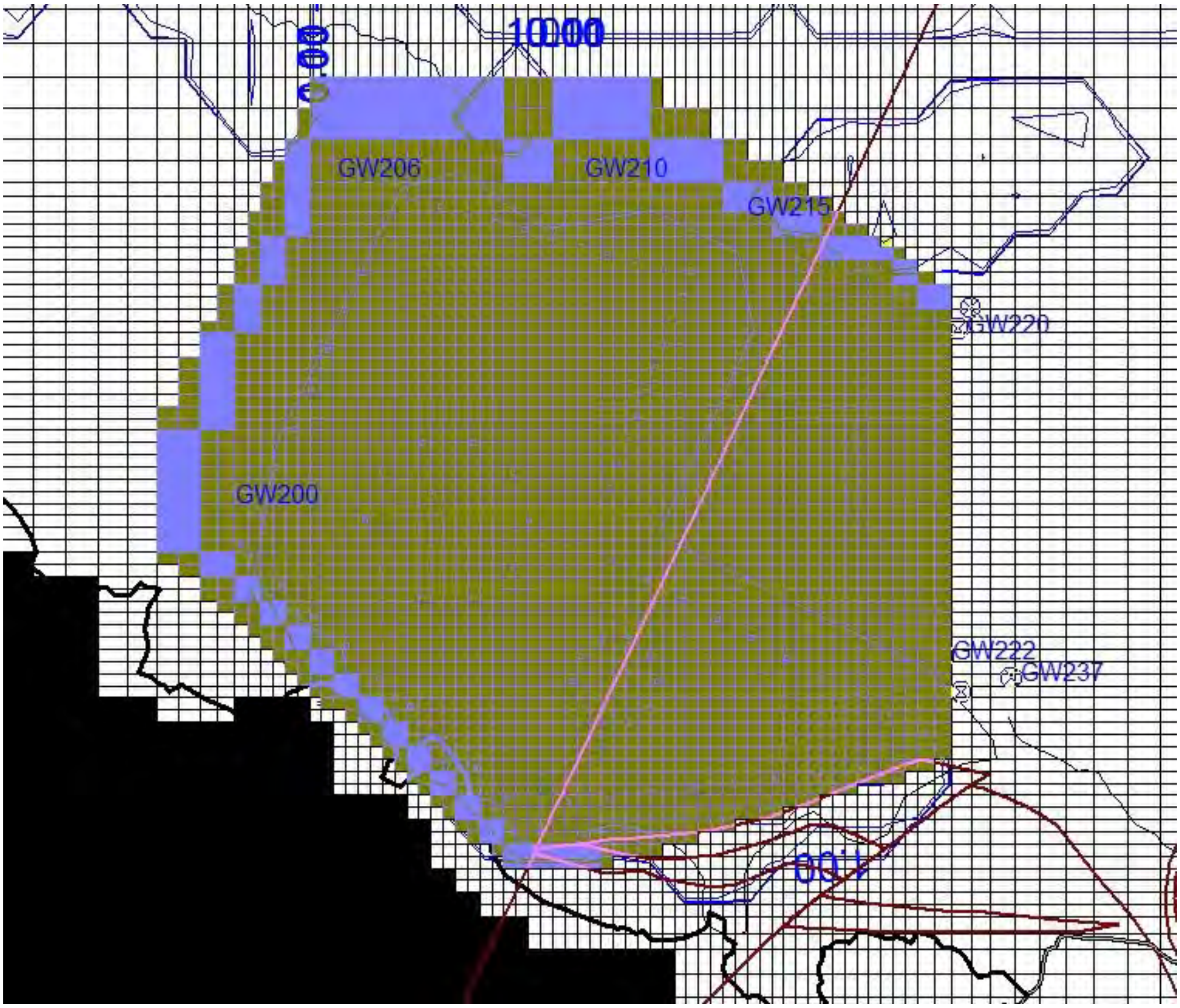


Figure 36: Polygon used for mass balance calculations at the tailings impoundment. The area includes the existing seep. The cutoff wall and drain are inside of this polygon. The polygon connects the outer edge of the DRAIN for the existing seep, and the corner in the east, bottom right, is at Row 65, column 78.

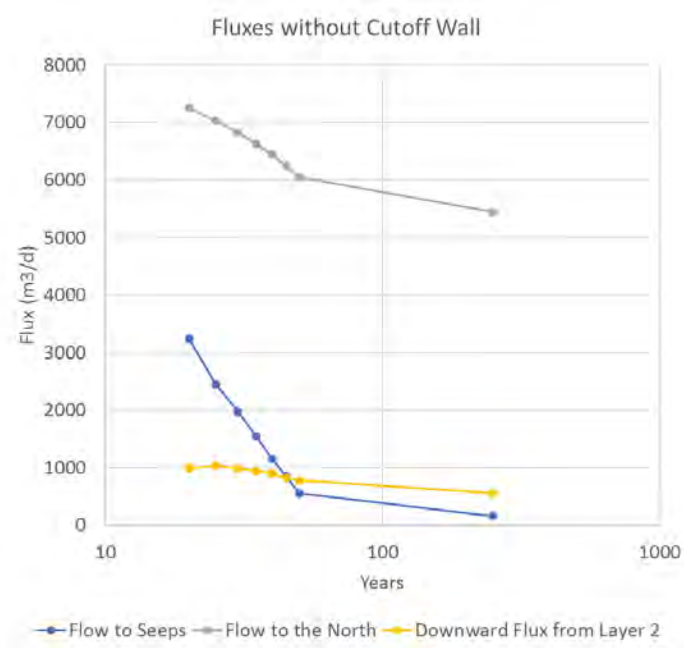


Figure 37: Representative fluxes for mass balance for area in Figure 36, without the simulated cutoff wall. Flow to north is vertical upward on Figure 36. Downward flux is the net, outflow – inflow, for the bottom of layer 2.

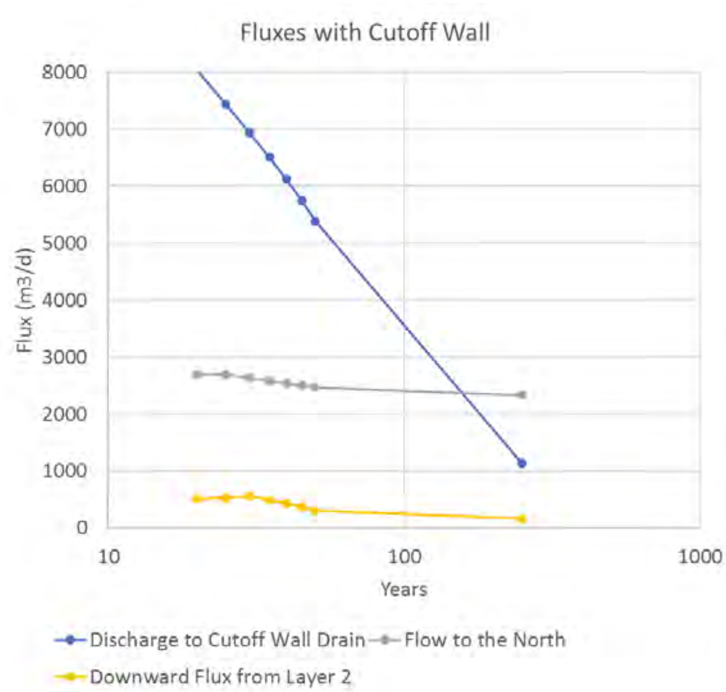


Figure 38: Representative fluxes for mass balance for area in Figure 36, with the simulated cutoff wall. Flow to north is vertical upward on Figure 36. Downward flux is the net, outflow – inflow, for the bottom of layer 2.

Table 4: Water balance fluxes for layer 1, 2, and 3, and the total thickness for the polygon shown in Figure 36, without the cutoff wall.

		Layer 1	8	Layer 2		Layer 3		Total	
Cum Time		Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
20	Bottom	7606	10555	1520	2503	617	1120		
25	Bottom	6732	9739	1367	2403	572	1069		
30	Bottom	6087	8970	1283	2269	542	1010		
35	Bottom	5523	8287	1216	2159	522	958		
40	Bottom	5088	10589	1178	2078	508	918		
45	Bottom	4623	8046	1144	1966	497	874		
50	Bottom	4286	6591	1121	1899	491	832		
250	Bottom	3346	5076	999	1552	449	686		
Period	Drain		3240						3240
2	Drain		2451						2451
3	Drain		1973						1973
4	Drain		1543						1543
5	Drain		1148						1148
6	Drain		848						848
7	Drain		549						549
8	Drain		157						157
1	Recharge	9562		646		21		10230	
2	Recharge	8952		686		22		9661	
3	Recharge	8340		725		28		9092	
4	Recharge	7719		784		27		8531	
5	Recharge	7110		821		31		7963	
6	Recharge	6486		871		37		7394	

7	Recharge	5874		911		41		6826	
8	Recharge	5005		1194		58		6257	
1	Storage	1018	3	180		191		1408	3
2	Storage	764	8	125		129		1031	8
3	Storage	652	7	102		103	0	868	7
4	Storage	572	6	81	0	81	0	742	6
5	Storage	525	2	73	0	69	0	674	2
6	Storage	540	1	70	0	69		686	1
7	Storage	561		69	0	64		700	1
8	Storage	0	1	0	0	0	0	0	1
1	Top			10555	7606	2502	1520		
2	Top			9739	6732	2403	1367		
3	Top			8971	6087	2269	1283		
4	Top			8286	5526	2159	1216		
5	Top			10589	5087	2078	1178		
6	Top			8046	4623	1967	1144		
7	Top			6591	4287	1899	1121		
8	Top			5075	3346	1552	999		
1	Xmax	199	184	37	421	24	229	270	1008
2	Xmax	147	159	28	421	16	224	197	975
3	Xmax	120	166	24	398	12	213	160	941
4	Xmax	108	166	22	383	9	201	142	904
5	Xmax	97	165	21	364	6	189	126	862
6	Xmax	88	157	19	345	5	176	115	811
7	Xmax	83	145	20	329	4	163	108	760

8	Xmax	56	108	24	269	3	103	85	555
1	Xmin	129	409	23	571		362	152	1665
2	Xmin	130	410	13	551		351	143	1622
3	Xmin	116	386	11	535	0	339	127	1556
4	Xmin	114	384	6	522		328	121	1520
5	Xmin	107	370	5	512		320	112	1481
6	Xmin	108	364	2	519		312	110	1465
7	Xmin	102	341	2	505		304	104	1415
8	Xmin	84	284	1	484	0	269	85	1271
1	Ymax		4387		2085		465		7260
2	Ymax		4217		2050		455		7036
3	Ymax		4057		2015		446		6824
4	Ymax		3905		1983		437		6625
5	Ymax		3763		1957		430		6444
6	Ymax		3595		1934		422		6240
7	Ymax		3451		1897		414		6044
8	Ymax		2987		1799		390		5441
1	Ymin	294	3	206	10	343	2	1130	15
2	Ymin	282	6	191	7	328	4	1079	17
3	Ymin	256	4	185	4	336		1063	8
4	Ymin	255	2	177	3	342		1067	5
5	Ymin	248	1	173	4	345		1066	5
6	Ymin	240	1	162	1	352		1061	2
7	Ymin	171		166		374		1032	
8	Ymin	126	0	153	0	384	30	1000	0

Table 5: Water balance fluxes for layer 1, 2, and 3, and the total thickness for the polygon shown in Figure 36, without the cutoff wall.

		Layer 1	8	Layer 2		Layer 3		Total	
Period		Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
1	Bottom	1074	9071	2050	2557	827	1144		
2	Bottom	1092	7821	1950	2478	795	1109		
3	Bottom	939	8416	1851	2404	765	1056		
4	Bottom	817	6630	1787	2272	743	1015		
5	Bottom	717	6795	1734	2165	726	973		
6	Bottom	674	5633	1688	2056	711	930		
7	Bottom	609	5569	1647	1945	697	887		
8	Bottom	475	3747	1432	1595	612	712		
1	Drain		973		8026				8999
2	Drain		773		7433				8206
3	Drain		575		6940				7514
4	Drain		389		6513				6902
5	Drain		293		6119				6411
6	Drain		120		5746				5866
7	Drain		50		5382				5432
8	Drain				4511				4511
1	Recharge	7930		2230		22		10181	

2	Recharge	7397		2259		27		9682	
3	Recharge	6819		2257		38		9114	
4	Recharge	6275		2232		46		8553	
5	Recharge	5703		2234		48		7984	
6	Recharge	5179		2183		55		7416	
7	Recharge	4649		2134		64		6848	
8	Recharge	3788		2416		76		6279	
1	Storage	827	39	148	5	159		1149	44
2	Storage	682		116		120		930	0
3	Storage	559		86		86		739	1
4	Storage	469	2	69		68		612	2
5	Storage	473	1	65		66		610	2
6	Storage	465	1	58		58		586	1
7	Storage	505		59	1	60		630	1
8	Storage	0	0.6	0		0		0	1
1	Top			9071	1075	2557	2050		
2	Top			7822	1092	2478	1950		
3	Top			8416	939	2404	1851		
4	Top			6630	817	2272	1787		
5	Top			6795	717	2165	1734		
6	Top			5633	674	2057	1688		

7	Top			5569	609	1945	1647		
8	Top			3748	475	1595	1432		
1	Xmax	367	76	152	266	25	165	555	635
2	Xmax	371	81	107	236	17	165	503	609
3	Xmax	334	75	107	224	13	146	459	561
4	Xmax	309	69	100	199	10	136	422	513
5	Xmax	293	62	97	187	8	126	401	474
6	Xmax	280	55	96	178	6	115	385	438
7	Xmax	273	48	97	171	6	105	377	405
8	Xmax	239	21	89	131	6	52	339	243
1	Xmin	18	155	62	144		303	80	907
2	Xmin	3	134	65	141		287	68	852
3	Xmin	3	128	54	136		281	57	825
4	Xmin	2	122	55	126		275	57	796
5	Xmin	2	116	54	125		266	57	771
6	Xmin		114	55	123		261	55	757
7	Xmin		108	55	126		256	55	741
8	Xmin		78	56	113	0	215	57	622
1	Ymax		799		1264		349		2683
2	Ymax		997		1121		323		2690
3	Ymax		945		1121		321		2633

4	Ymax		906		1115		317		2579
5	Ymax		878		1107		313		2538
6	Ymax		857		1100		309		2501
7	Ymax		838		1091		305		2466
8	Ymax		760		1065		293		2336
1	Ymin	309	1	221	6	425	3	1315	11
2	Ymin	273	6	186	6	396	1	1190	13
3	Ymin	264	8	182	3	396	1	1179	11
4	Ymin	252	6	172	2	393		1159	8
5	Ymin	245	6	165	2	399		1155	8
6	Ymin	182		168		417		1125	
7	Ymin	175		169		428		1138	
8	Ymin	112	8	144	3	414	25	1038	80

Comparison of Concentration Changes through the Cutoff Wall

The NPDES/SDS permit application (Vol. I and V) prescribes paired performance monitoring wells up- and down-gradient of the tailings impoundment. These were simulated within the model to compare the effect of the cutoff wall. Figure 35 shows these wells and Figure 36 shows some of these wells on a model figure of the tailings impoundment.

The concentration decreased substantially as it passed through the cutoff wall. This would be due to a much-decreased load mixing with the background groundwater downgradient from the cutoff wall. From GW202 to GW203, concentration decreased by half prior to 50 years (Figures 39 and 40). After 50 years, concentration increased more steeply but the decrease remained almost half for another 25 years. In the long-term, the downgradient concentration at GW203 remained less than the upgradient concentration up to about 150 years, after which the cutoff loses its effectiveness.

Between upgradient GW208 and downgradient GW209, the reduction was almost two-thirds (Figures 41 and 42). After about 200 years, however, the downgradient concentration increased to equal the upgradient concentration. Between GW216 and GW217, the concentration also decreased by more than half, although the upgradient concentration was much lower initially (Figures 43 and 44). The walls effectiveness was gone by about 100 years.

For all performance monitoring wells, the concentration was higher in layer 2 than in layer 3 up to more than 100 years, after which the concentration values converged. This was due to dispersion into layer 3 lagging. Layer 1 was dry except for initially at GW217 (Figure 44). While layer 1 is saturated under most of the tailings impoundment, it is not near the edge. More of it is unsaturated with the cutoff because the DRAIN in layer 2 lowers the water table to capture flow.

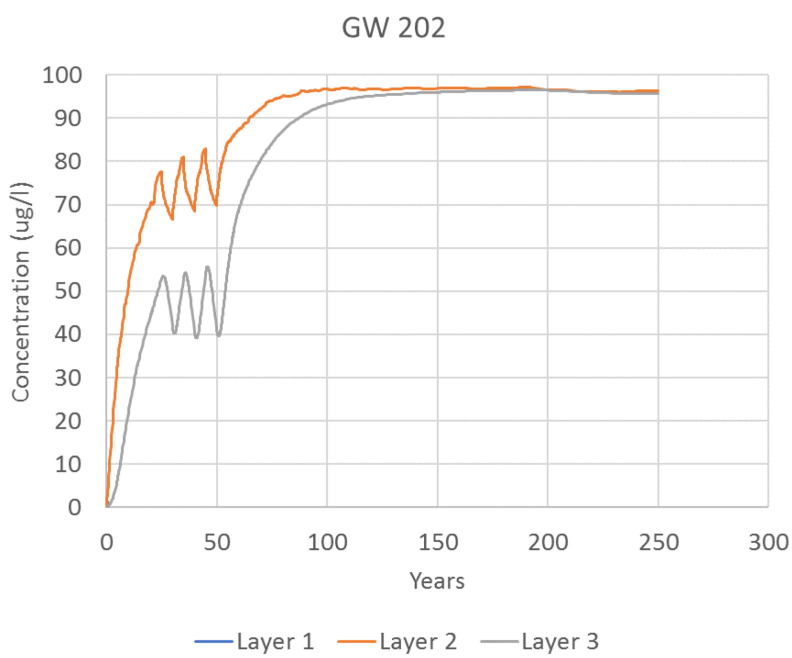


Figure 39: Graph of concentration for monitoring well GW 202, layers 1, 2 and 3.

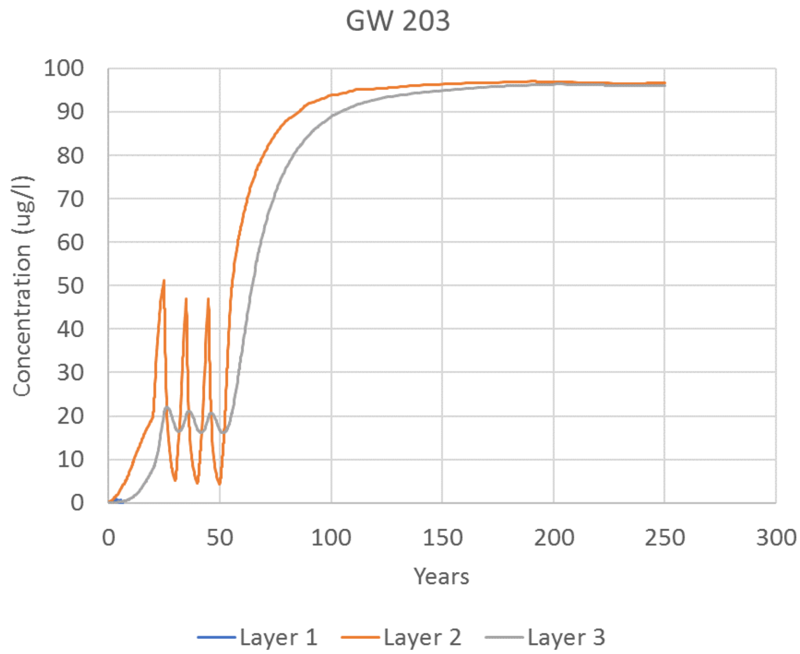


Figure 40: Graph of concentration for monitoring well GW 203, layers 1, 2 and 3.

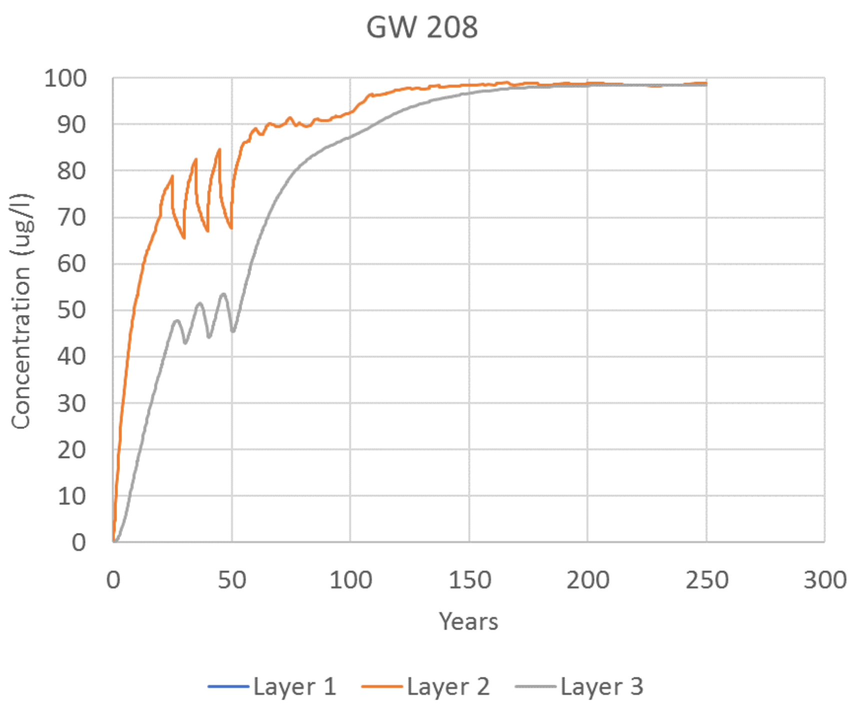


Figure 41: Graph of concentration for monitoring well GW 208, layers 1, 2 and 3.

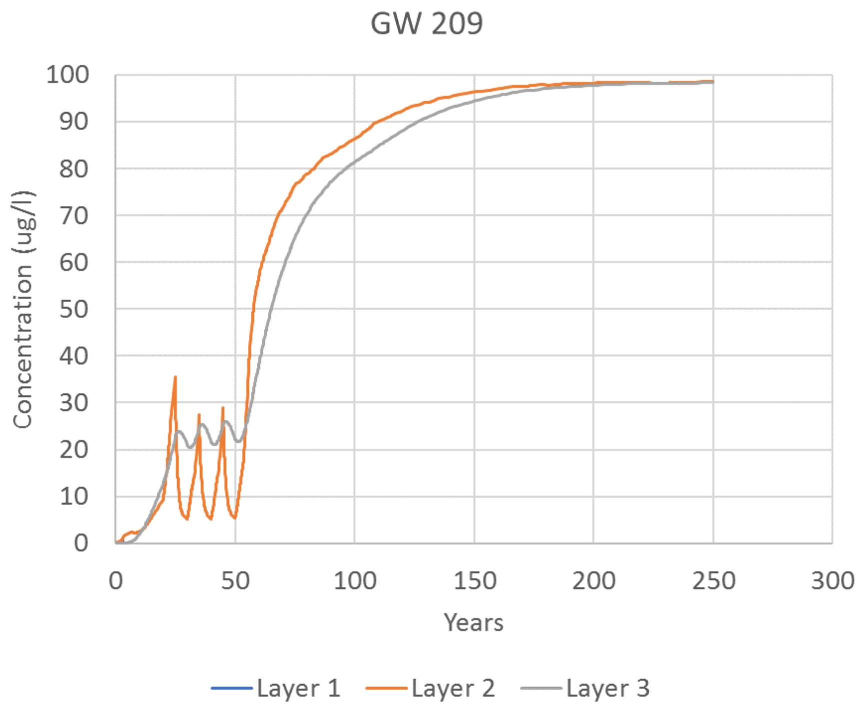


Figure 42: Graph of concentration for monitoring well GW 209, layers 1, 2 and 3.

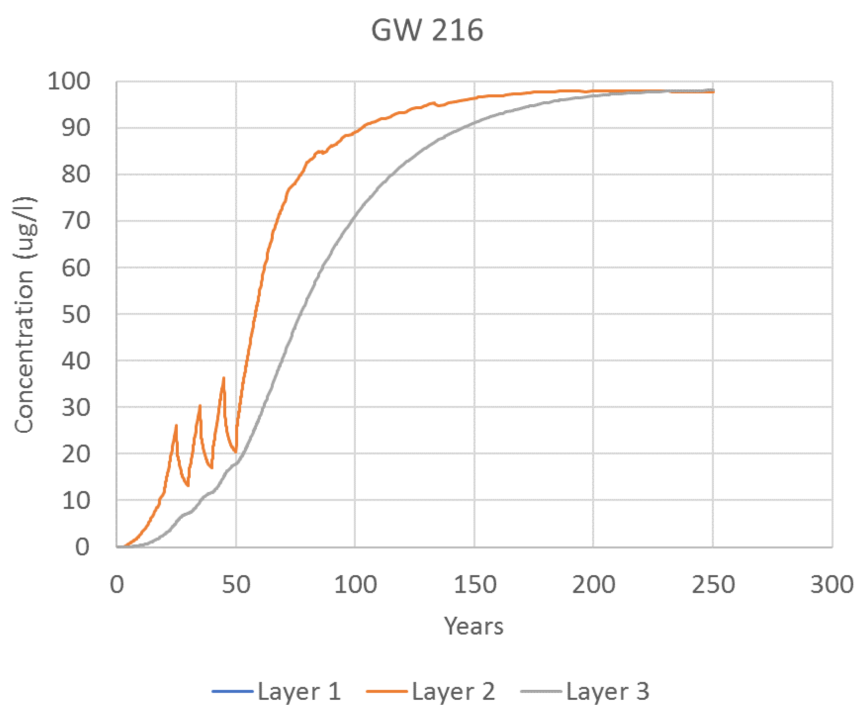


Figure 43: Graph of concentration for monitoring well GW 216, layers 1, 2 and 3.

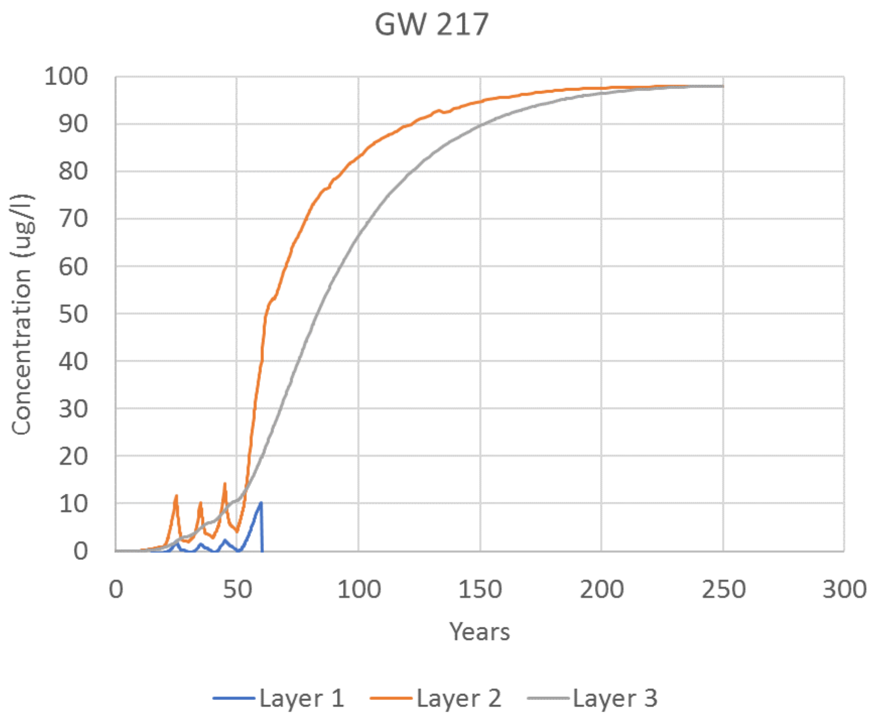


Figure 44: Graph of concentration for monitoring well GW 217, layers 1, 2 and 3.

Growth of Plume with and without Cutoff Wall

The cutoff wall has a significant effect on the expansion of a contaminant plume away from the tailings impoundment. Without the wall, after 20 years, the 10 mg/l contours have spread to the Embarrass River, but only to the edge of the impoundment for the scenario with the cutoff wall (Figures 45 and 46). After 250 years, with no cutoff wall, the 10 mg/l contour has completely opened and the 50 mg/l contour extends about halfway to the river (Figure 47). Groundwater reaching the Embarrass River over a long stretch has a concentration between 10 and 50 mg/l (Figure 48). With the wall, the 10 mg/l contour remains closed about two-thirds the distance to the Embarrass River, and the 50 mg/l contour remains near the impoundment cutoff wall (Figure 48). The horizontal extent of smaller contours is much less with the wall. The simulated cutoff wall has decreased the groundwater flux, thereby capturing contaminants, which delays the spread of and lower concentration of the contaminants. However, the simulation shows that contaminants will seep into weathered bedrock and move away from the mine site, contrary to claims by PolyMet (*see* Vol. V).

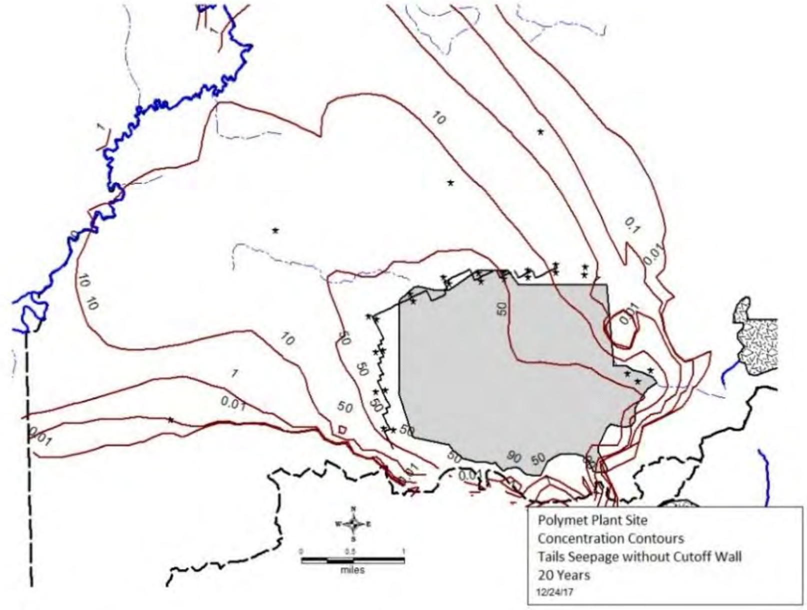


Figure 45: Concentration contours at the Plant Site, 20 years after start of mining, no cutoff wall. Layer 2.

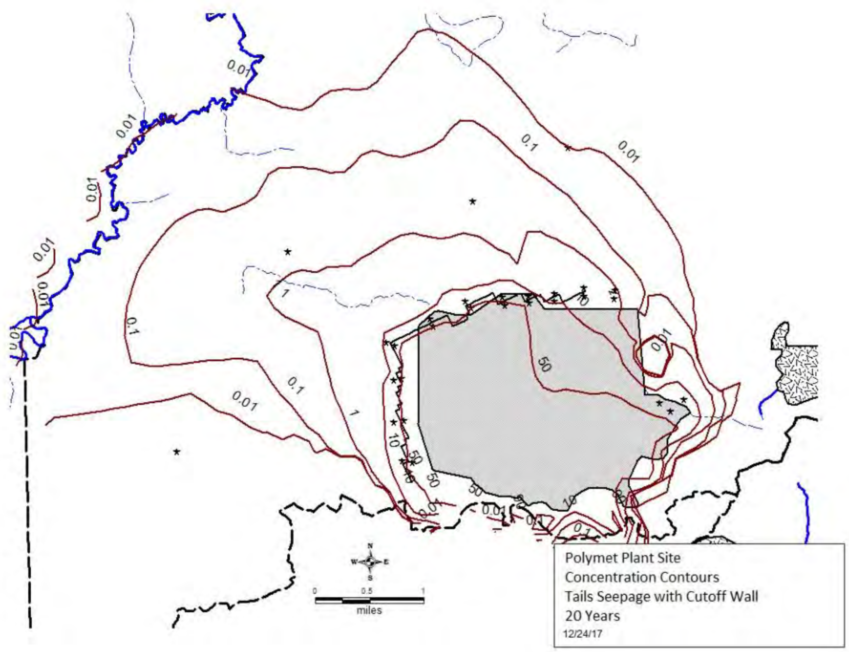


Figure 46: Concentration contours at the Plant Site, 20 years after start of mining, with cutoff wall and drain. Layer 2.

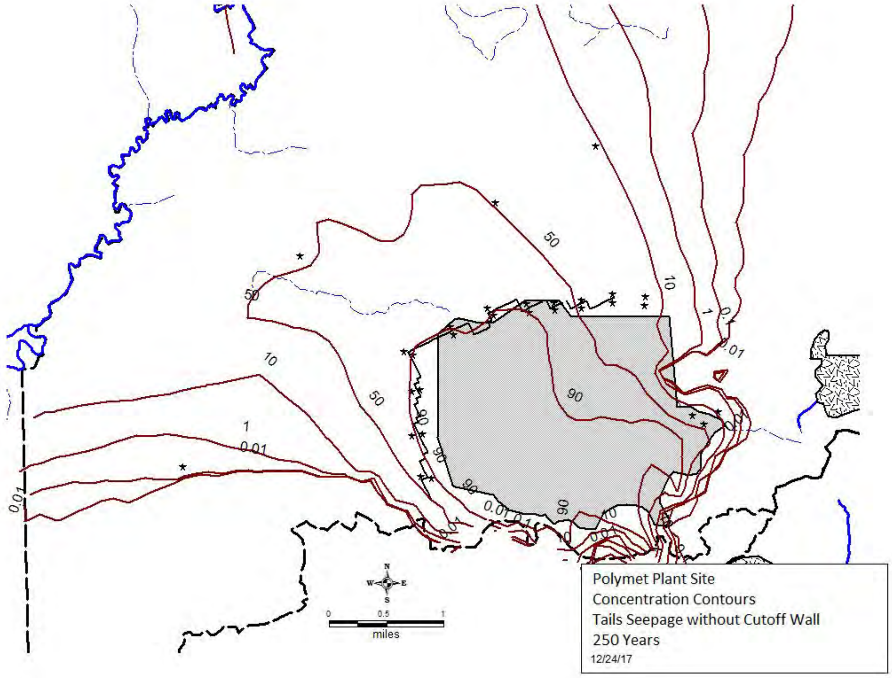


Figure 47: Concentration contours at the Plant Site, 250 years after start of mining, no cutoff wall. Layer 2.

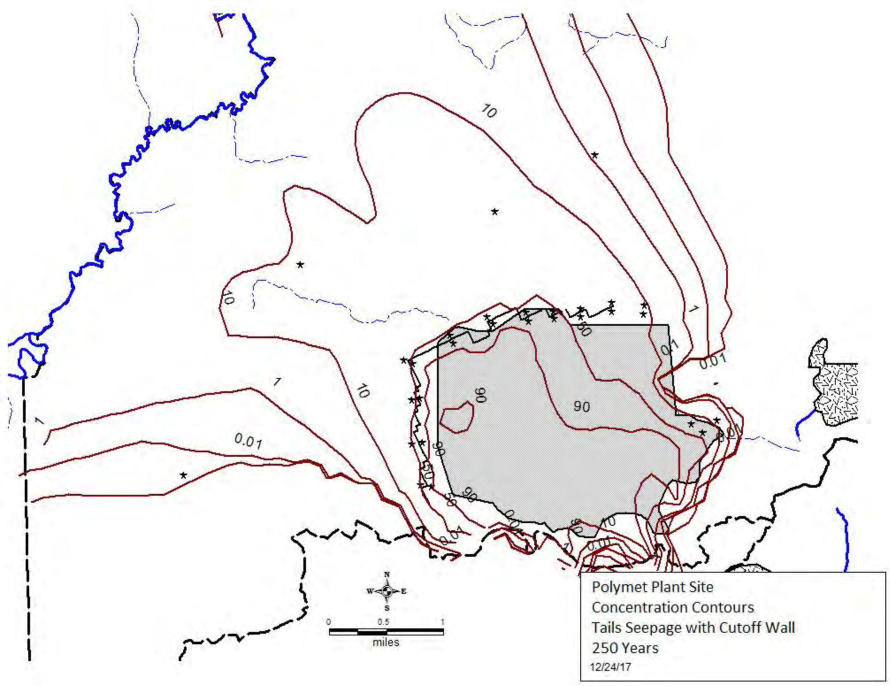


Figure 48: Concentration contours at the Plant Site, 250 years after start of mining, with cutoff wall and drain. Layer 2.

Monitoring wells midway between the impoundment and the river show a delay in contaminants reaching the wells (Figures 49 through 51). The monitoring wells do not begin responding for 20 or more years, and at least two of them began to decrease before reaching 250 years. This would be due to the lower seepage rate causing a smaller load that becomes diluted by fresh recharge. Monitoring wells, for the without cutoff wall scenario, show that concentration begins to increase within a few years (well concentration graphs not shown), so that the wells show significant concentrations years before contamination reaches the wells with the cutoff wall. Discharge to the Embarrass River (DRAIN reach 10) also reflects the differences in flow. The with-wall scenario decreases baseflow discharge by about 10%; initially the load is almost zero, but the load without a wall increases quickly. In the long-term, there is more groundwater flow and lower loads reaching the river because there is more water for dilution and the lower load concentration tailings seepage is also reaching the river.

In summary, the cutoff wall as simulated captures substantial load and slows the passage of contaminants. The response at the monitoring wells with the wall lags several decades behind the response without a wall. For some wells, the peak has not been reached after 250 years. This demonstrates that monitoring must continue for hundreds of years after closure, even if the wells show little contamination at closure.

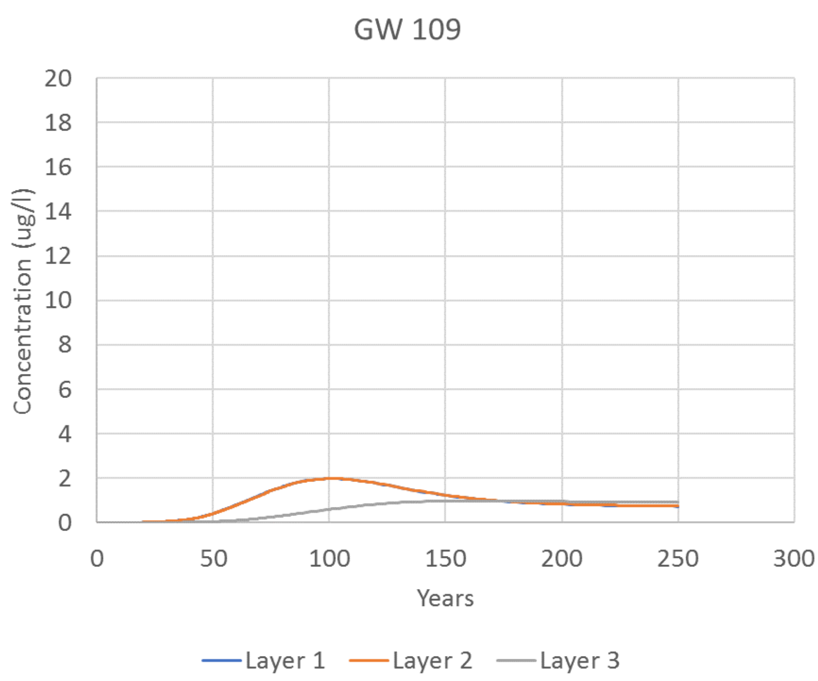


Figure 49: Graph of concentration for monitoring well GW 109, layers 1, 2 and 3, with cutoff wall.

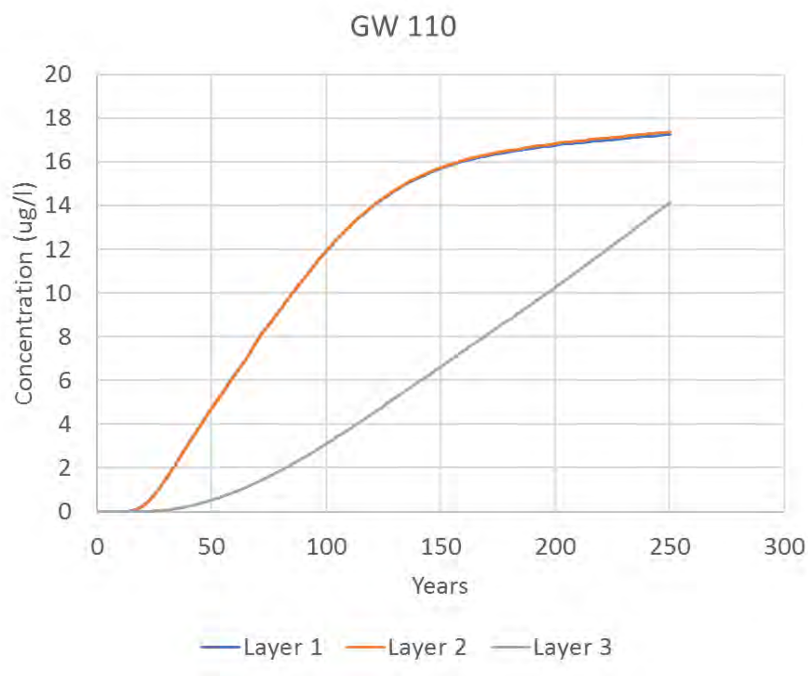


Figure 50: Graph of concentration for monitoring well GW 110, layers 1, 2 and 3, with cutoff wall.

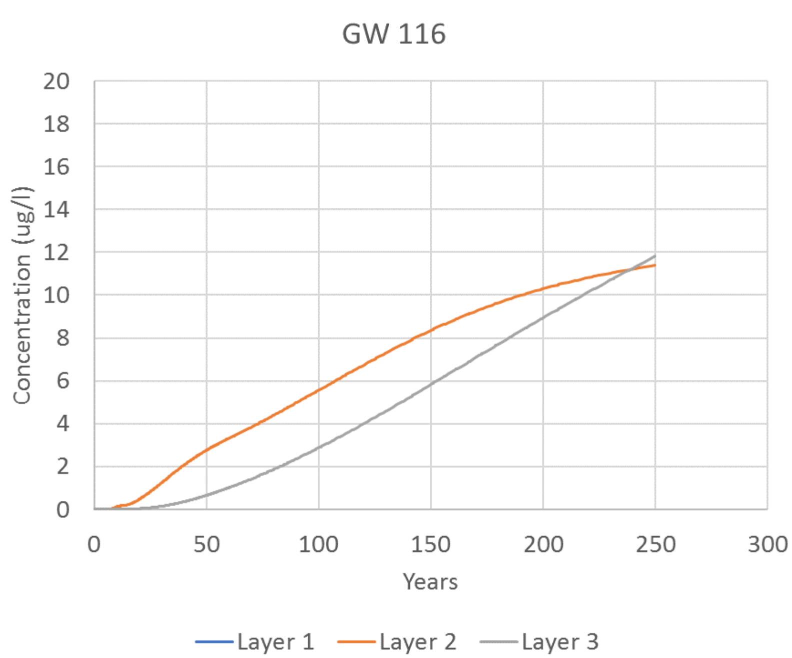


Figure 51: Graph of concentration for monitoring well GW 116, layers 1, 2 and 3, with cutoff wall.

Growth of Plume with Leaks

The with-wall scenario was also considered with four leaks occurring at different locations in the tailings impoundment. They were considered to leak at 10% of the rate for the entire impoundment while the entire impoundment continued to leak with concentration equal to zero. All contaminants in the simulation would be the result of the leak, and therefore the contours show the growth of a plume simply from one location. The magnitude of the contours is important only from a relative perspective and should be considered with respect to a contaminant reaching a given point, such as a monitoring well or the river.

Leaks at row 28, column 49, cause a plume to elongate in a northwesterly direction (Figure 52 and 51). Comparison with the plumes generated for the entire area (Figure 46) shows a direction generally more north for the leak than for the overall impoundment. Similar observations apply to leaks at row 26, column 35 (Figures 54 and 55). The plume at row 40, column 27, initially grows mostly northward, to a point near the northwest corner of the impoundment where it turns northwest (Figures 56 and 57). The leak at row 55, column 46, is closer to the middle of the impoundment, and the plume from it grows wider and resembles the plume emanating from the distributed seepage (Figures 58 and 59).

The performance monitoring wells around the perimeter of the tailings impoundment would detect the individual leaks. Because the plumes expand past the perimeter much sooner than 20 years, these wells could be sufficient monitoring for leaks. Based on the expansion of the plume, the initial detection would occur early and concentrations would increase several orders of magnitude over the simulation period. If the threshold is low enough, the performance monitoring wells could detect the leaks.

It is a different situation for the compliance wells between the impoundment and the Embarrass River. Although the plume for the leak at row 28, column 49, encompasses two monitoring wells, the center of the plume would have concentrations almost two orders of magnitude higher than at the wells after 250 years (Figure 52). At 20 years, the change at any compliance well is more than four orders of magnitude less than near the impoundment. This is due to the slow expansion of the plume, but is also due to the middle of the plume being far from the monitoring well.

The center of the plume emanating from the leak discharging from row 26, column 35, goes over a monitoring well. The plume from the leak at row 40, column 27, also goes directly over a monitoring well, but due to its northward followed by northwestward growth, compliance well GW116 would eventually detect the plume but only with a long lag time from the mining period. Two monitoring wells, would detect the plume from the leak at row 55, column 46. None of the plumes approach well GW015.

All leaks follow a general northwest pathway toward the Embarrass River. The pathway is especially obvious for the leak at row 26, column 35 (Figure 53). The plume from the leaks barely approaches monitoring wells GW015 and GW109. These monitoring wells are on the edge even of the plumes emanating from the entire tailings impoundment. The plume shapes indicate there is strong advection pulling contaminants from the impoundment in a northwesterly direction. There should be more compliance wells along the center of the plumes to increase the chances of detecting plumes.

The simulations herein are based on the standard simplifications of the hydrogeology into heterogeneous, anisotropic cells. These cells do not replicate flow through significant fracture preferential flow zones. The results herein do not obviate the concern over potential pathways not simulated herein (or by PolyMet). PolyMet should use geophysical methods to identify pathways that should be monitored.

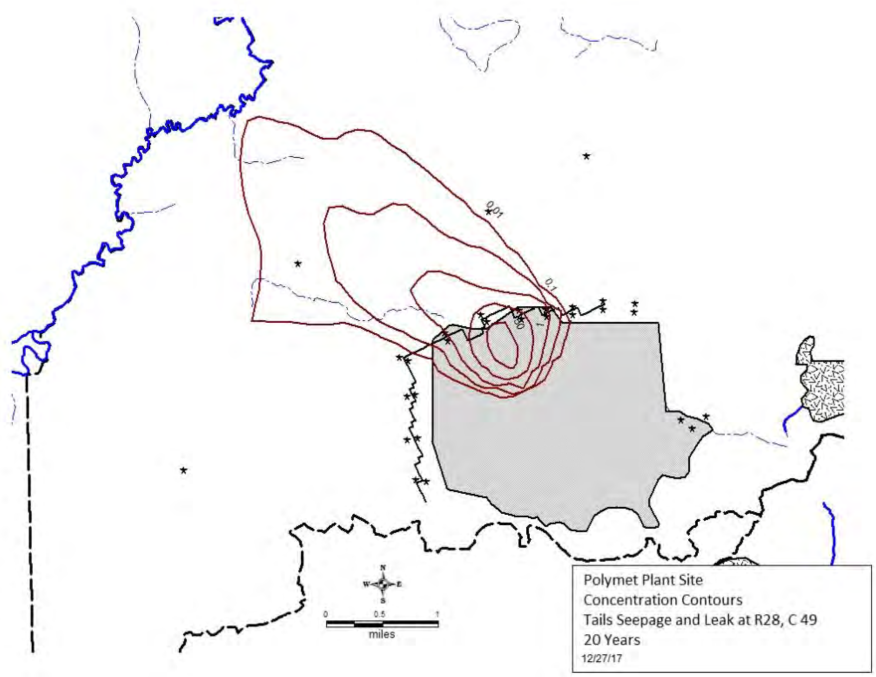


Figure 52: Concentration contours at the Plant Site, 20 years after start of mining, with cutoff wall and drain, and with leak at Row 28, Column 49. Layer 2.

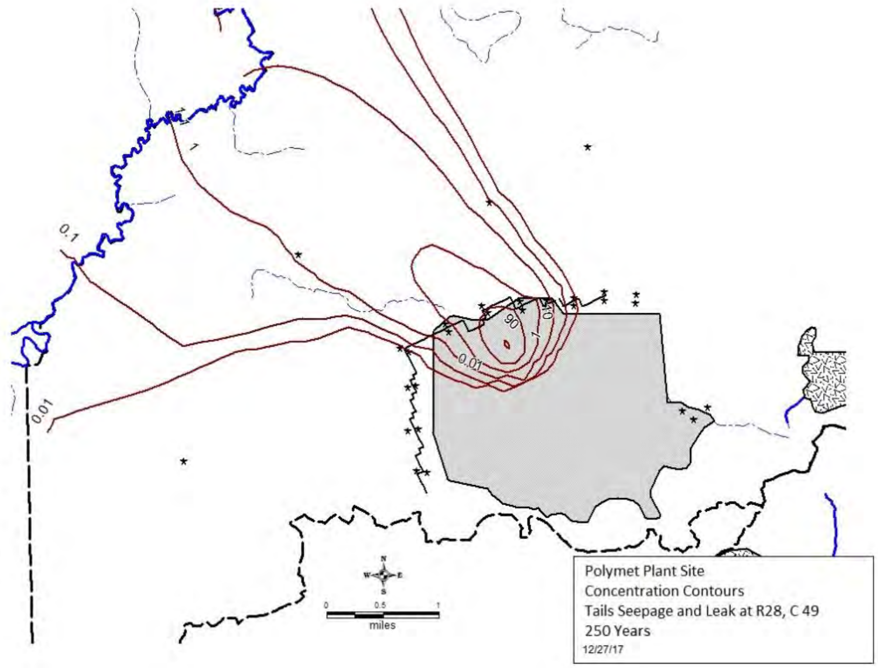


Figure 53: Concentration contours at the Plant Site, 250 years after start of mining, with cutoff wall and drain, and with leak at Row 28, Column 49. Layer 2.

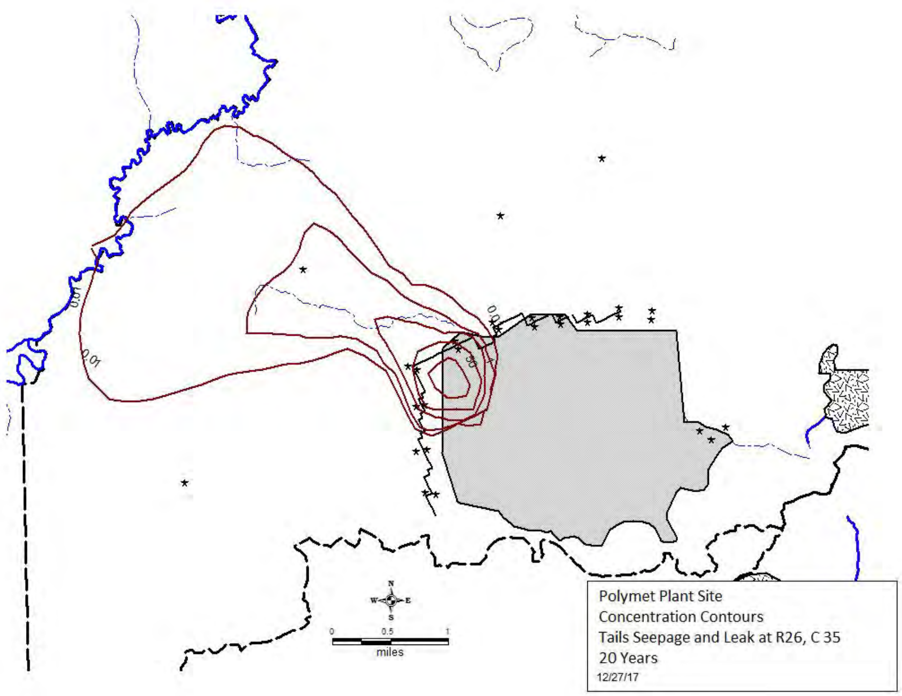


Figure 54: Concentration contours at the Plant Site, 20 years after start of mining, with cutoff wall and drain, and with leak at Row 26, Column 35. Layer 2.

Figure 55: Concentration contours at the Plant Site, 250 years after start of mining, with cutoff wall and drain, and with leak at Row 26, Column 35. Layer 2.

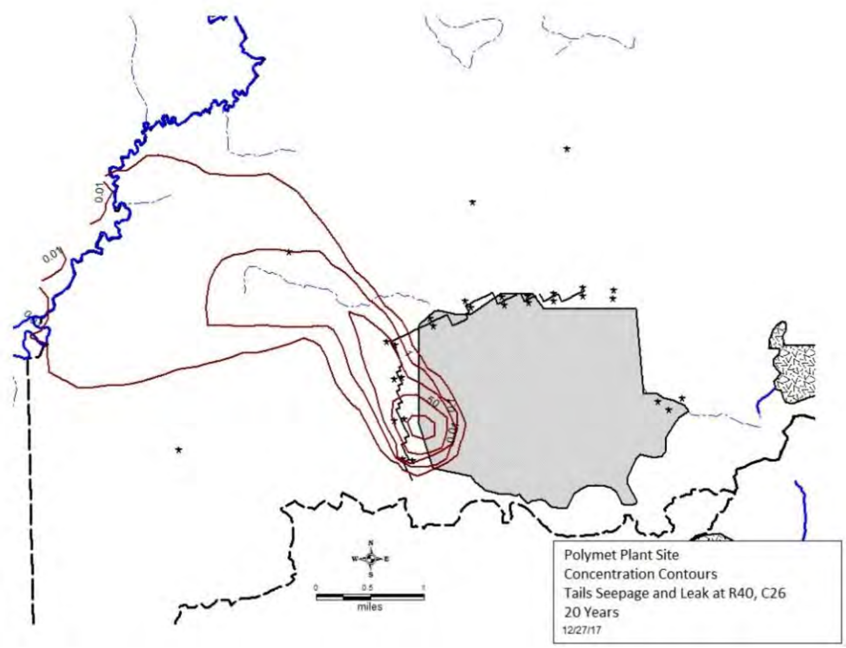


Figure 56: Concentration contours at the Plant Site, 20 years after start of mining, with cutoff wall and drain, and with leak at Row 40, Column 27. Layer 2.

Figure 57: Concentration contours at the Plant Site, 250 years after start of mining, with cutoff wall and drain, and with leak at Row 40, Column 26. Layer 2.

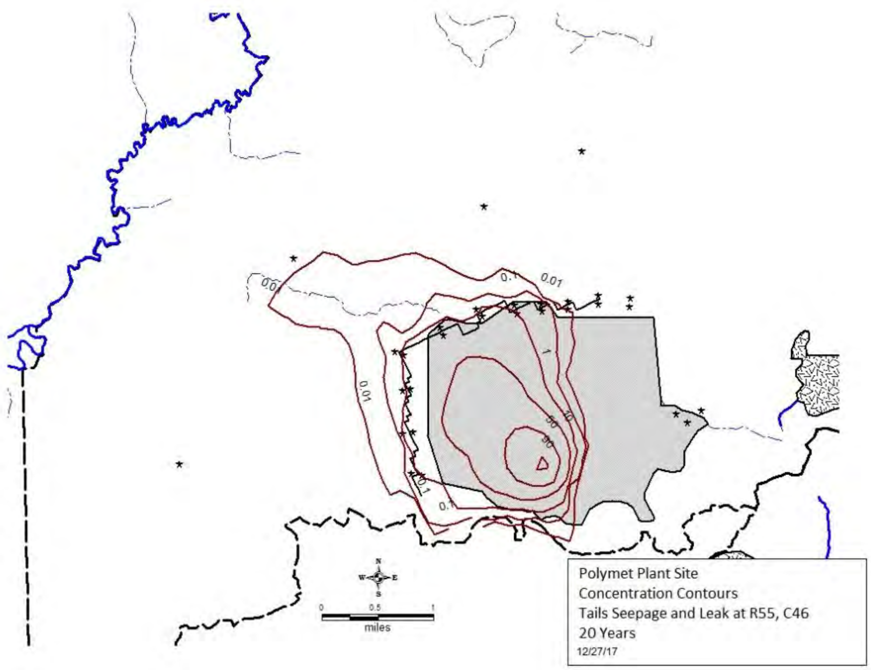


Figure 58: Concentration contours at the Plant Site, 20 years after start of mining, with cutoff wall and drain, and with leak at Row 55, Column 46. Layer 2.

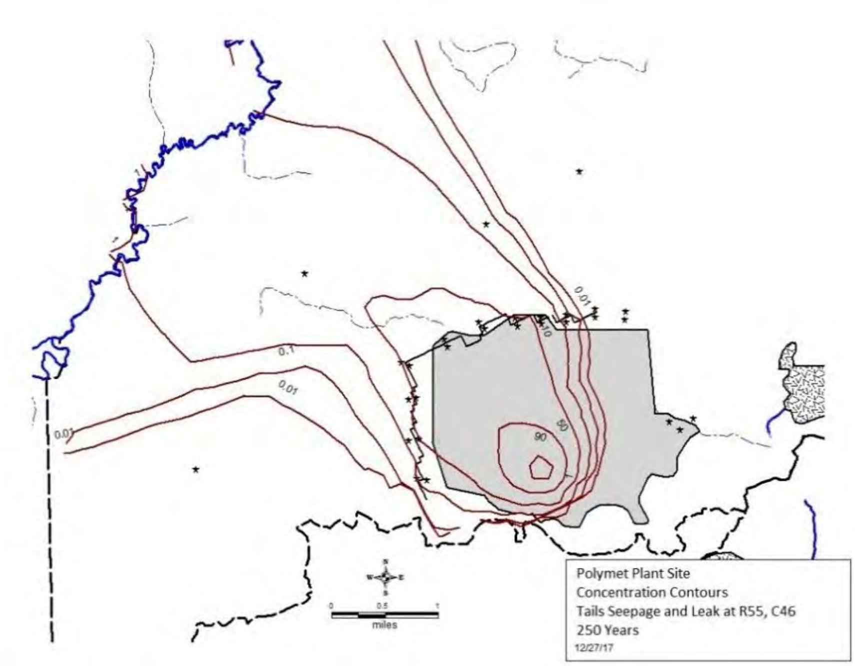


Figure 59: Concentration contours at the Plant Site, 250 years after start of mining, with cutoff wall and drain, and with leak at Row 55, Column 46. Layer 2.

Load and Discharge to the Embarrass River

Groundwater seepage in the Plant Site area discharges to the Embarrass River, simulated as DRAIN reach 10. Reach 10 extends from the headwaters to the confluence with Bear Creek, or about 13.7 miles. There are no mainstream monitoring sites for several miles upstream from this confluence. Both simulated groundwater discharge and load rates are highly variable along the reach (Figure 60), with a substantial difference between the with and without cutoff wall scenarios.

The cutoff wall made a significant difference in the load being delivered to the river, reducing from about 370,000 m^3/d*mg/l to 60,000 m^3/d*mg/l (Figure 60). About 8% of the reduction was due to a decrease in flow, which primarily is the flow captured by the cutoff wall. Because that flow contained a high concentration of contaminant, the remaining groundwater reaching the river had a low concentration.

Based on the load and flow rate reaching the river after about mile 6 where the inflow was affected by plant site load, the average concentrations with and without the cutoff wall was about 5 and 29 mg/l. The variable slopes in the cumulative load curve, both for with and without the cutoff wall, shows the need for at least four surface water monitoring points along the river, at around mile point 6, 8, 10, and 13.

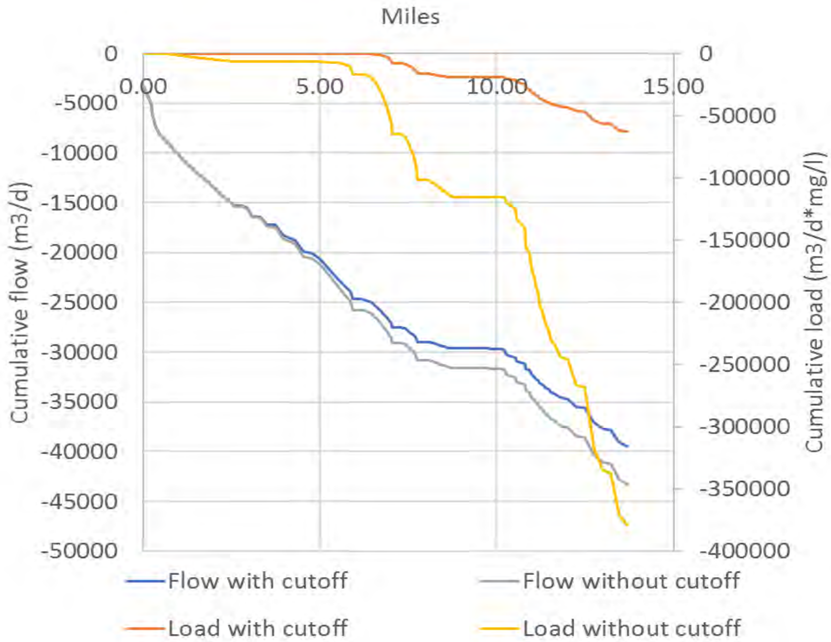


Figure 60: Cumulative flow and load on reach 10, the Embarrass River, by mile from up to downstream

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Appendix B Review of Tailings Seepage Collection System, excerpted from Myers (2015)

Tailings Seepage Containment System: The FEIS presents a new report, Barr (2015b), to justify the estimate of seepage capture, or "to support the simplifying assumption that 90% of groundwater will be captured" (Barr 2015b, p 2). That is an interesting purpose for a study – to justify a previous assumption. Barr (2015b) describes a cross-sectional model that simulates the capture by the trench and cutoff walls, completed with MODFLOW. The next paragraphs summarize several errors with the modeling that suggest that the model results are not reliable or accurate.

The model is a cross-section, one foot wide, from near the edge of the tailings impoundment to the Embarrass River. The size of the model cells near the edge of the tailings impoundment is two feet. The model cell size expands systematically to 150 feet in the rows between the cutoff wall and the river. Vertical layers are also 2 feet thick. Figure 5 shows part of one of the cross-sections showing the area downgradient from the tails near the cutoff branch. The surficial aquifer (upper layer in green) is 10 model layers, or 20-feet, thick. Three scenarios were used to simulate bedrock, with fractured bedrock either 25, 50, or 100 feet thick. The bottom is a no flow boundary so that no flow leaves the bottom of the model. The discretization and model layer thicknesses are reasonable and should provide an accurate computation of the flow paths through the cross section.

Boundaries are a specified flux on the upgradient end at the edge of the tailings. The model uses a well boundary to inject seepage uniformly into each model layer. The rate for each cross-section is determined as total seepage from the tailings spread uniformly along the perimeter of the impoundment. The top of the model has average steady recharge as a specified flux recharge boundary. The top of the model also simulates a wetland, using a DRAIN boundary upgradient of the cutoff wall (to the left of the cutoff wall in Figure 5) or as a river boundary downgradient of the cutoff wall. A drain boundary is a head-dependent flux boundary that only allows water to leave the model domain and a river boundary is the same type except that water also enter the model domain if the head in the model falls below the head specified in the boundary. Only discharge from the model into the upper boundary on the surface upgradient of the cutoff wall can occur but flow can enter or leave the domain downgradient of the wall. A river boundary downgradient of the wall is not appropriate for this model because the river boundary will allow water to discharge into the model and artificially maintain the model head at a higher level. This will effectively be a hydraulic barrier preventing flow from continuing from above to downgradient of the containment wall. The report does not specify actual flux from this boundary (or to the Embarrass River), so it is difficult to be certain of its effect. This would depend on the relative difference between boundary conductance and the K in the surficial aquifer because it is possible for the head to fall below the river boundary such that the river would provide flux to the model based on a unit gradient. These boundaries may impose inaccurate controls on the flow through the section.

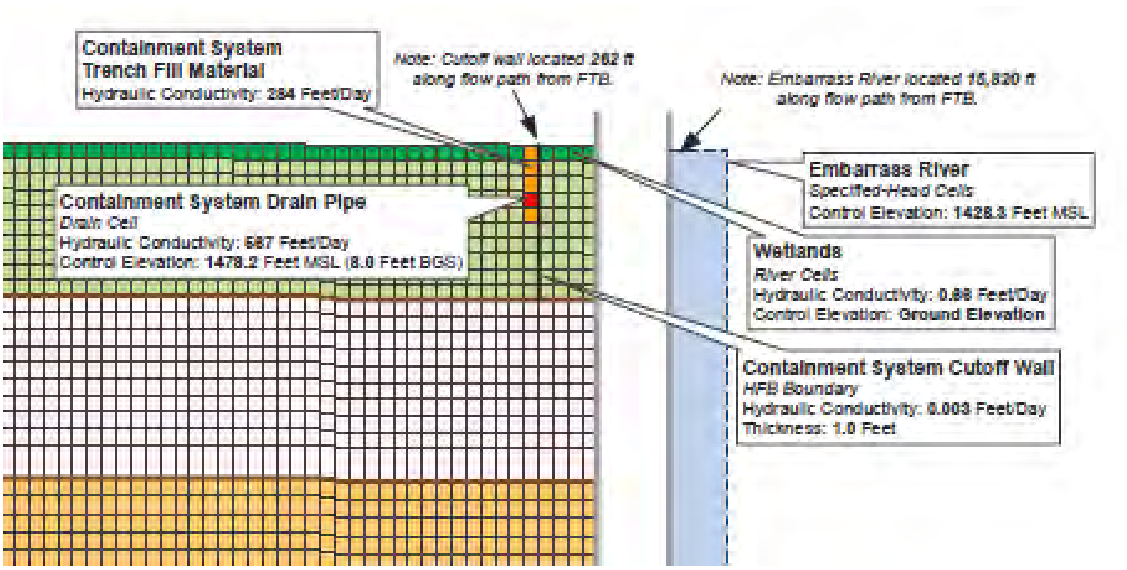

*Figure **5**: Snapshot of small portion of Large Figure 1 in Barr (2015b) showing the MODFLOW cross-section for the North Flow Path from the Plant Site.*

At the upgradient end of the cross section (at the edge of the tailings basin on the left of the section shown in Figure 5), specified seepage depends on the modeled seepage from the tailings impoundment as described above. This conceptualization forces the estimated seepage to reach the base of the tailings impoundment uniformly through a vertical section, weighted based on the relative K values. The same flow enters every possible one-foot thick cross-section spread uniformly along the vertical section. Thus, the discharge to a cross-section assumes the same amount of seepage occurs under every foot of the perimeter of the tails and that the vertical distribution of flow depends on the transmissivity of each layer.

The problem with this specified flow is that actual flux from the bottom of the tailings impoundment into the ground is not uniformly spread but rather would have substantial preferential flow pathways due to variable K in the surficial aquifer. Data presented for the plant site MODFLOW model (Barr 2015b) reviewed above shows a large horizontal variation in conductivity. The high K zones would have preferential flow, possibly many times higher than simulated here due to the large order of magnitude difference in K.

Stratification in the surficial aquifer leading to lower vertical K would cause the flow to be distributed nonuniformly vertically along the section. Seepage from the tails would flow vertically downward into the surficial aquifer where it would divert laterally and flow with the general gradient in the surficial aquifer. It would contact the underlying bedrock over all of its footprint and some would flow into the bedrock through which it would also flow downgradient to the edge of the tails. The plant site model did not even simulate bedrock, rather treating it as a no flow boundary. Because of the layering in both the surficial and bedrock aquifer, the horizontal flow would not be distributed uniformly along the vertical section. The large variability in bedrock K, from near zero to more than 3 ft/d, discussed above would lead to significant seepage in some bedrock sections and none in others.

Thus, the specified flux boundary with constant flow for each layer of the surficial and bedrock aquifer is not realistic. Because some 1-foot wide cross sections would have much more flow and it would not be uniformly distributed vertically through either bedrock or unconsolidated deposits, the model overestimates the efficiency of the drain and likely underestimates the amount of flow under the cutoff wall.

Modeled horizontal K equaled 13 ft/d with a vertical anisotropy of just 2.5 in the surficial aquifer. The bedrock layer, representing the fracture zone, had horizontal K equal to 0.14 ft/d and conditions were assumed isotropic (Barr 2015b), which means there would be no more resistance to vertical flow than to horizontal flow. Compared to the PolyMet plant site MODFLOW model which assumed bedrock beneath the unconsolidated deposits to be a no flow boundary, this is a very high vertical K. The report does not justify assuming the fractures are as extensive in the vertical as in the horizontal direction, which is necessary for horizontal K to equal vertical K. Fracturing due to weathering would have occurred along the bedding plane, which in these formations is closer to horizontal, thus horizontal K should be ten or one hundred times the vertical K.

Specified horizontal K values for both surficial and bedrock aquifers are reasonable but the vertical K is not. In this cross-section model, the low vertical anisotropy very much allows vertical flow, through both aquifer layers. The model parameters for bedrock provide almost no resistance to vertical flow which allows the seepage entering the bedrock portion of the section to flow vertically into the upper part of the surficial aquifer.

The conceptualization of the containment system is reasonable, with a horizontal flow barrier and high K cells representing a DRAIN and then a drain cell at the bottom of the drain on the upgradient side of the HFB (Figure 6). Barr (2015b) should provide references for K values in the drain because they are much higher than the surrounding formation. The design is similar to a French drain with gravel and cobbles in the trench adjacent to the wall. The bottom would have perforated irrigation pipe which Barr modeled as a DRAIN in the bottom cell. Barr set the conductance extremely high. This DRAIN would effectively control the head in the entire cross section because of the high conductance and the fact that the DRAIN elevation would be half the surficial aquifer thickness below the ground surface. The model does not consider varying conductance to reflect changes that could occur if the drain becomes clogged.

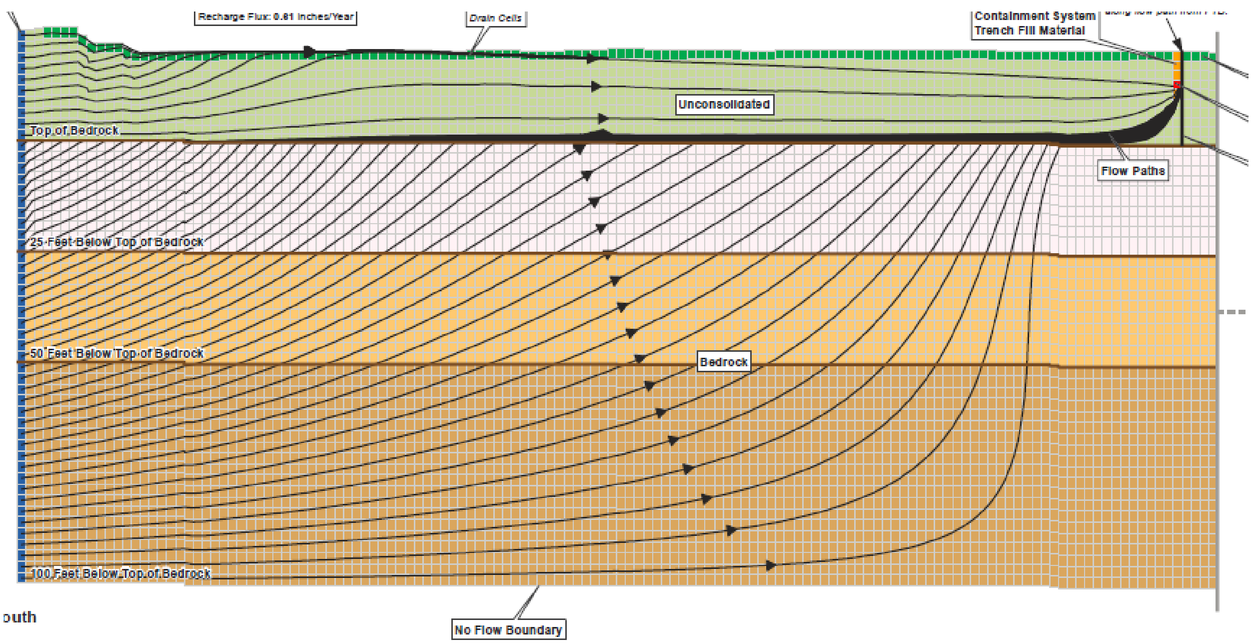

Figure 661: Snapshot of part of Large Figure 4 in Barr (2015b) showing flow paths for the cross section simulation for the North Flow Path.

Thus, at the upstream edge of the section, the well injection establishes an even flux profile in the two aquifer formations and it could be assumed the head distribution is hydrostatic. The report does not show the head at the upstream end of the section, so this is an assumption. In reality, the seepage emerging from under the tails would likely be close to hydrostatic. The DRAIN would be a local low head sink for flow. Depending on the K of the formations, the DRAIN could effectively draw most of the flow otherwise passing the wall through the section profile to the DRAIN. The high simulated vertical conductivity eases the flow to the drain. Barr should also consider a sensitivity analysis which assesses what would occur if the DRAIN conductance became significantly less; this would be a test of potential clogging of the drain.

The method of simulating flow in steady state with particle tracking was acceptable for this purpose. Essentially, the method shows the ultimate sink for flow discharging into each model layer at the edge of the tailings impoundment. However, they should also introduce particles into the river boundary below the cutoff trench.

For all but one of the simulations, none of the particle paths continued past the DRAIN, as shown in Figure 6 for the North Flow Path simulating the flux during operations. A few paths discharge into the DRAIN representing the wetlands but most discharge into the DRAIN. These results are highly unrealistic. Flow paths curve upward from 100 feet below the surficial aquifer in just a few hundred horizontal feet only because of the high relative vertical K as discussed previously. Additionally, the RIVER boundary downstream of the wall may also create a hydraulic barrier which helps divert the flux from upstream into the DRAIN; it could do this just as downstream injection wells may act as a flow barrier[2]. These factors lead to a much higher capture efficiency than is realistic.

Additionally, spreading recharge uniformly through the year, as occurs with a steady state model, would artificially increase the efficiency. Considering that factors affecting flow near the cutoff trench occurs on a much shorter time frame, recharge should be considered with more temporal variability. Seepage from the tails may not vary due to precipitation events, but recharge near the cutoff may dilute it or add to the flow rate. The flows could vary so that the capture efficiency is more variable than specified in the FEIS and at times the load passing the cutoff wall could be much higher than disclosed.

The FEIS's statement that "[m]odel results indicate that all seepage from the Tailings Basin would be captured along the north and northwest flowpaths under all assumptions of the bedrock fracture zone thickness" is true only because the model was set up in a highly biased fashion. The model was set up to confirm: "These results indicate that the Plan site Goldsim model assumption (that groundwater seepage equal to 10 percent of the aquifer's transmissive capacity bypasses the Tailings Basin containment system) is conservative" (Id.). The model was hardwired to show what the modelers were told by PolyMet to make it show. The evidence for this is that the model parameters do not resemble the parameters used for other modeling and the boundaries were set to create hydraulic barriers and sinks that will not be present in the field.

Recommendation: The cross section model is biased toward a high estimate of capture efficiency of seepage from the tails. The model should be reconceptualized with realistic vertical K in the formations and seepage from the tails that accounts for heterogeneity. The wetlands downstream from the wall should be simulated with a DRAIN boundary that does not provide a potentially unlimited source of water to the cross-section below the wall. The effect of the DRAIN conductance simulated the drain in the cutoff trench should be tested with sensitivity analysis. A proper analysis would give a range of capture efficiency that would allow the FEIS to better assess the potential flows from the tails. Failing to do that, the FEIS fails to adequately disclose the potential impacts of seepage from the tails.

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[2] The model report shows flow paths only commencing at the upstream end of the section. Initiating flow paths in the river boundaries would allow the reviewer to assess the role played by that boundary in preventing flow from passing the French drain.

The FEIS claims that Goldsim modeled the containment system conservatively by allowing “10 percent of the surficial groundwater” (FEIS, p 5-76) to bypass the system and enter pathways toward the Embarrass River. Considering the bias inherent in the modeling, this could be grossly too low.

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Technical Memorandum

To: Kevin Lee, Minnesota Center for Environmental Advocacy
From: Ann Maest, PhD; Buka Environmental
Date: 27 February 2018
Re: Comments on PolyMet Mining's Permit to Mine: Water quality and geochemical issues at the proposed NorthMet Mining Site

Introduction

The comments contained in this technical memorandum are presented on behalf of the Minnesota Center for Environmental Advocacy and are in response to the Permit to Mine Application for the NorthMet Project (PolyMet Mining, 2017a). I present a summary of my major findings and then discuss technical comments, including errors in mine waste characterization, assumptions about acid drainage and contaminant leaching, the quality of water impacted by the waste stockpiles at the mine site, the reactivity of tailings, and state-of-the-art tailings management. Recommendations are presented at the end of each section. The documents relied on for my evaluation are listed in the References section of the memorandum.

Summary of Major Findings

- The number of samples analyzed for acid-base accounting, whole rock chemistry, and mineralogy is inadequate for the waste rock and ore that will be generated for this project. Only 84 samples were analyzed, and the total should have been over 250. The low number of samples indicates that the possible range, especially the upper range, of sulfide and metal content is not known and likely underestimated. Statements that Category 1 wastes will have a sulfide content under 0.12% are therefore unreliable.
- Waste rock and ore samples were not analyzed for neutralization potential (NP), which, in combination with the acid production potential (AP), is used to estimate the acid generation potential of a waste. An NP surrogate, percent total carbon, was measured but did not reflect the carbonate content of the materials. Neutralization potential measurements were conducted on all other mined materials (flotation tailings, LTVSMC tailings, metallurgical residue, overburden, and saturated overburden). The NP values of the waste rock and ore are important to know for internal consistency. The limited mineralogic results indicate that waste rock has

nearly no ability to neutralize acidic leachate, should it develop in the stockpiles or the pit.

- The consistent separation of Category 1 wastes from wastes and ore with higher sulfide content during operations will be difficult, if not impossible, leading to a greater potential for pollutants to be generated in the unlined Category 1 storage pile than PolyMet assumes.
- No adaptive management plan (AMP) exists for waste rock management. Given the uncertainties associated with separating the different waste categories and ore, and the potential adverse environmental consequences if more reactive materials are included in lower category wastes, an AMP is especially important for wastes reporting to the Category 1 stockpile, which has the lowest neutralizing potential of any waste and will sit on the land surface in perpetuity.
- Incorrect assumptions about acid drainage and contaminant leaching have led PolyMet to underestimate the potential impact of mine water on the environment at and around the mine and plant sites. The assumptions include that once wastes go acidic, the pH will "recover." In addition, the repeated and seasonal contribution of secondary salts to waste and ore leaching has been ignored, and release rates and concentration caps rely on incorrect conceptual models. For example, if the measured pH values of Category 1 HCT leachate were used to estimate the concentration cap for nickel, maximum nickel concentrations would be approximately 10 times higher than predicted by the site water quality model.
- If the pH range between 6.0 and 7.0 is considered, the maximum measured nickel concentration is 120 mg/L, almost 10 times higher than the maximum concentration cap.
- Mitigation measures for the Category 1 stockpile are unlikely to prevent the movement of contaminants to mine site groundwater and surface water. An alternative modeling effort shows that sulfate plumes from the Category 1 and 2/3 stockpiles will be created during operations and reach groundwater under the Partridge River. A synthetic liner and segmented leachate collection system should be installed under the Category 1 stockpile to minimize the release of contaminants to groundwater and help identify the location of leaks that do develop.
- The waste characterization results for the flotation and LTVSMC tailings demonstrate that they are reactive according to the Minnesota definition, which includes any waste that is shown through characterization studies to release substances that adversely impact natural resources. Based on this finding, the tailings facility should be lined with a geomembrane and leachate collection system, and alternative, state-of-the-art methods of tailings management should be considered, including removal of the LTVSMC tailings and the use of dry tailings deposition methods. Improved techniques for desulfurization of the tailings should be examined, and mineralogic analysis should be used to determine their effectiveness.

Technical Comments

1. Errors in Mine Waste Characterization

a. Inadequate Number of Characterization Samples

PolyMet has not characterized a sufficient number of samples to determine the project's potential to generate acid or leach other contaminants. Characterization samples should include waste rock, ore, tailings (flotation and LTVSMC), hydrometallurgical residue, and overburden, at a minimum. The total number of waste rock samples is just 82, and only three ore composite samples and 33 flotation tailings samples have been analyzed as part of the mine waste characterization program (PolyMet Mining, 2017b, p. 4 and 5).

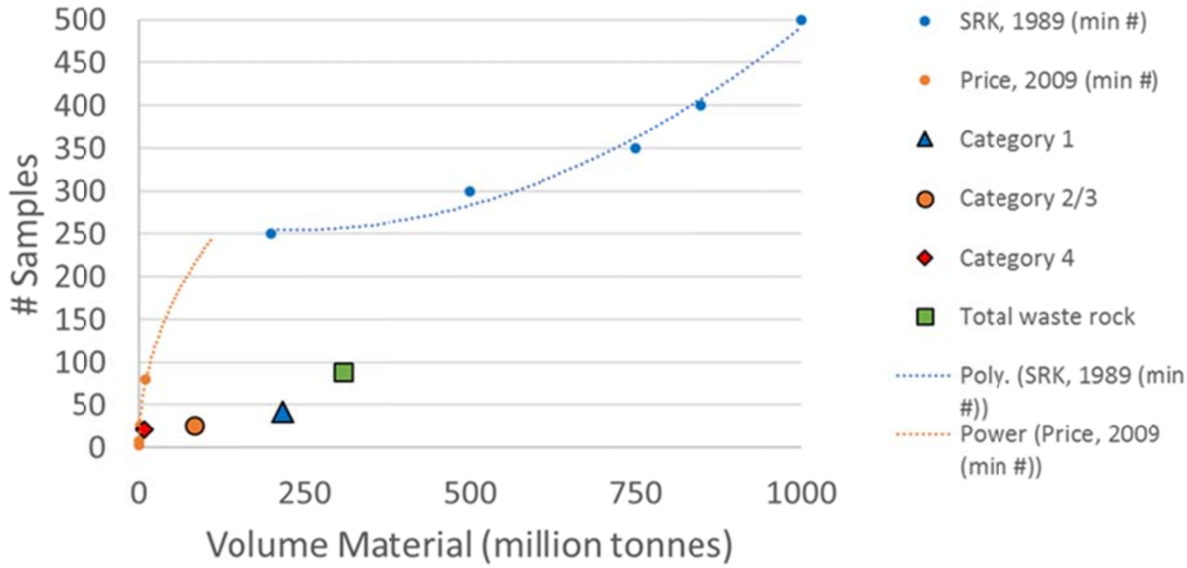
The volumes of waste rock are large (PolyMet Mining, 2017b, Table 2-1), especially for Category 1 wastes:

- Category 1 = 216,694,717 tons, 70.3% of all waste rock
- Category 2/3 = 82,782,343 tons, 26.7% of all waste rock
- Category 4 = 8,636,630 tons, 2.8% of all waste rock
- Total waste rock, all categories = 308,113,690 tons.

Figure 1 shows the recommended minimum number of geochemical characterization samples from two literature sources and the actual number of samples analyzed for each waste category and for the total amount of waste rock. Although no hard and fast rules exist, the number of samples analyzed for the NorthMet Project are well below recommended minimum values. Each sample should be run through the suite of geochemical tests, including acid-base accounting (ABA) and whole rock analysis, at a minimum. In addition, a smaller number of short-term leach tests, long-term kinetic tests, and mineralogy should be conducted on each sample.

PolyMet has chosen to sacrifice quantity for detail. Because of the involvement of the Minnesota Department of Natural Resources, in particular Kim Lapakko, an impressive number of very long-duration humidity cell tests (HCTs) have been run. Where the Project falls short is the number of ABA, whole rock, and mineralogic analyses. Instead of 84 samples, over 250 should have been tested for ABA and whole rock chemistry. Although the Rock and Overburden Management Plan touts its use of 38,000 assays to create the current mine site Block Model (PolyMet Mining, 2017c (Appendix 11.1, p. 39), the data for ore characterization are not publicly available. The block model is most commonly used to guide ore extraction and is built using target metal percentages (in the case of NorthMet, copper, nickel, cobalt, platinum, palladium, and gold) in the ore rather than the waste; this is

Figure 1. Recommended number of geochemical characterization samples vs. the actual number analyzed by PolyMet for each waste rock category and total waste.



Sources: For recommended minimum number of samples: SRK (1989), in Parbhakar-Fox, A. and Dominy, S.C. (2017) and Price (2009). For waste volumes: PolyMet Mining, 2017b, Table 2-1 and PolyMet Mining, 2015, Table 4-4. SRK (1989) points are fitted with a 2nd-order polynomial curve, and Price (2009) points are fitted with a power function and forecasted forward for 100 periods using Excel.

referred to as an *economic* block model. The NorthMet deposit block model is described in PolyMet Mining, 2017c, Appendix 11.1, Attachment A. In addition to ore assays, the NorthMet block model includes waste categories, waste units, %S, and whole rock metal concentrations. The block model has 133,000 blocks for ore and waste, and each block is given a metal concentration. However, only 82 waste rock samples were analyzed for metal content, as noted previously in this memorandum, so the accuracy of the block model for contaminant leaching of the wastes is quite limited. In addition, the total metal concentration in the rock does not necessarily relate directly to metal concentrations in waste leachate. Further, no information on neutralization potential is included in the block model. The decision on waste vs. ore is based on the metal content, and the separation of different waste categories is based on %S values. Because so few waste rock samples were analyzed for %S and metal content (a total of 82) and the only leach test results (HCTs) are not used to predict contaminant generation potential, the block model is a blunt tool for separating different waste categories according to their contaminant leaching or acid generation potential.

The available waste rock geochemical characterization data for whole rock chemistry and %S are included in SRK Consulting (2007a), Appendix D.4. But the results are categorized using the old definitions of reactive and nonreactive rather than the revised waste rock categories (1, 2/3, 4). To determine which results are for Category 1 waste rock, for example, one has to cross-reference the sample identifiers with those in Large Table 1 in

Polymet Mining (2015a), create a new table, and conduct statistical analyses. The summary statistics for whole rock chemistry of the revised waste rock categories are provided in PolyMet Mining, 2017b (Table 2-2), but the raw data are not. The lack of relevant raw data is a transparency issue and should be remedied.

b. Missing Analyses

In addition to analyzing an inadequate number of waste rock and ore samples, PolyMet failed to analyze the samples for their ability to neutralize acid. It appears that no measure of neutralizing ability was conducted for the waste rock or ore samples. This is a major shortcoming of the characterization program. Acid production potential (AP) and neutralization potential (NP) are two separate measures that are considered together to provide an indication of the potential for the development of low pH conditions.
During operations, mines commonly use static tests such as ABA to identify and separate potentially acid-generating (PAG) from uncertain or non-acid-generating materials quickly. The NP of a mined material is important to know because it provides an estimate of the amount of acid-neutralizing ability of a sample. Taken together, they are used to estimate the acid generation potential of the samples, using the NP:AP ratio, or NPR. The industry-sponsored GARD Guide (INAP, 2009) recommends that if the NPR is <1, the sample is potentially acid generating.

The reason PolyMet provides for analyzing the ore and waste rock samples for "carbonate" rather than NP was (SRK, 2007a, p. 28) is:

> Carbonate rather than neutralization potential was determined because neutralization potential determinations on rocks containing reactive silicates are ambiguous (Lapakko 1994a) and do not reflect field capacity to neutralize acid.

The method used to determine "carbonate" was not mentioned. PolyMet Mining (2017b, pgs. 4-7) lists "carbon" rather than carbonate as an analysis for all sample types, and I suspect this is what SRK, 2007a was referring to when they discussed "carbonate." Carbon measurements are a shortcut to estimating NP. A simple measurement from a Leco instrument will give a total carbon value, and equation (1) is given to convert to NP (INAP, 2009, Chapter 5b):

$$\text{NP (total C)} = \%\text{C} \times 83.3 \qquad (1)$$

This equation assumes that all the carbon is present as calcite (INAP, 2009, Chapter 5b). Although total carbon can be used as a surrogate for NP (INAP, 2009), the results are meaningless if they are not linked with mineralogic analyses showing that the carbon is associated with a neutralizing carbonate mineral such as calcite or dolomite. The percent total carbon (% Total C) results in SRK (2007a, Table 2-4) are low for all waste and ore samples, suggesting that the method was run to analyze samples for organic carbon rather than carbonate. I have found no documentation of any attempt to use carbon or "carbonate" to estimate the neutralizing potential of the waste rock or the ore.

Essentially all rocks associated with metal mines contain silicates, but their reaction rates are much slower than those for carbonates or sulfides (Sherlock et al., 1995). The Permit and associated documents repeatedly state that acid is neutralized by the dissolution of silicate minerals, but these minerals will only provide limited pH buffering near neutral pH and will not be able to keep up with the acid production once the pH drops. No method exists, short of detailed analysis of HCT results, to estimate the neutralizing ability of silicate minerals in mine waste. Although challenges exist with the measurement of NP, it is important to have internal consistency at a site for comparison of the relative ability to generate and neutralize acidity (INAP, 2009). While all other samples types were analyzed for NP (tailings, overburden, metallurgical residue, and saturated overburden; PolyMet Mining, 2017b, pgs. 4-7), the ore and waste rock were not, so internal consistency across waste types is not possible.

The lack of NP measurements for Category 1 wastes is important because these are the wastes that will remain on the surface in perpetuity. Although the sulfide content of Category 1 wastes is supposed to be ≤0.12%, the carbonate content is also very low. The mineralogy of the waste categories is summarized in PolyMet Mining (2017b, Table 2-4). It shows that Category 1 wastes have a maximum carbonate content of 2% (no minimum or average values are provided). All other waste categories (2/3, 4, and Virginia Formation) have maximum carbonate contents of 25%, with average values of 2, 5, and 10%, respectively. These results show that Category 1 waste rock has the lowest neutralizing ability of any of the waste categories.

c. Inability to Separate Category 1 from Ore and Category 2/3 and Wastes and Reactivity of Wastes

The consistent separation of Category 1 wastes from wastes and ore with higher sulfide content will be difficult, if not impossible, and this waste management challenge has important implications for water pollution at the mine site.

Category 1 and 2 wastes were previously combined in the waste management schemes described for the project; in fact, PolyMet originally considered waste rock “reactive” if the sulfide content was greater than only 0.05% S (discussed in SRK Consulting, 2007a, p. 23). According to SRK Consulting (2007a, p. ii), currently all waste categories are considered “reactive,” including what is now defined as Category 1 wastes:

> All of these categories are defined as “reactive” because drainage would be unsuitable for direct discharge. The concept of a category for which drainage would be suitable for direct discharge was evaluated but not found to be achievable because hardness-based water quality discharges standards for copper may not be met.

As noted in Section 1b of this memorandum, Category 1 waste rock has a very low neutralizing ability. If wastes with a higher sulfide content, or ore, are inadvertently included in the Category 1 stockpile, the Category 1 waste will not be able to neutralize the acid produced. In fact, although PolyMet states that the maximum %S for Category 1 waste rock is 0.12%, the maximum percent sulfide in the mineralogy summary table is 4% (PolyMet Mining, 2017b, Table 2-4 – average and minimum values are not provided). Table 2-5 in the same document shows that the most common sulfides in Category 1 wastes are either chalcopyrite or pyrrhotite. Using the formula weights for these minerals, a sample with 4% chalcopyrite would have a sulfur value of 1.4%, and one with 4% pyrite would have a sulfur value of 2.3% - both of which are much higher than the 0.12%S assumed for Category 1 wastes. This discrepancy is not explained in the text and suggests that higher sulfide values could be present in Category 1 wastes. In addition, an inadequate number of samples were analyzed for Category 1 wastes, and if more samples were analyzed, it is likely that the %S range would expand. The conclusion from these results is that if acid is generated from Category 1 wastes, it will not be neutralized and will instead be available to leach metals from sulfides and other minerals in the waste. In addition, oxyanions such as arsenic can leach from mine wastes under neutral and alkaline pH conditions (see, e.g., Al-Abed et al., 2006).

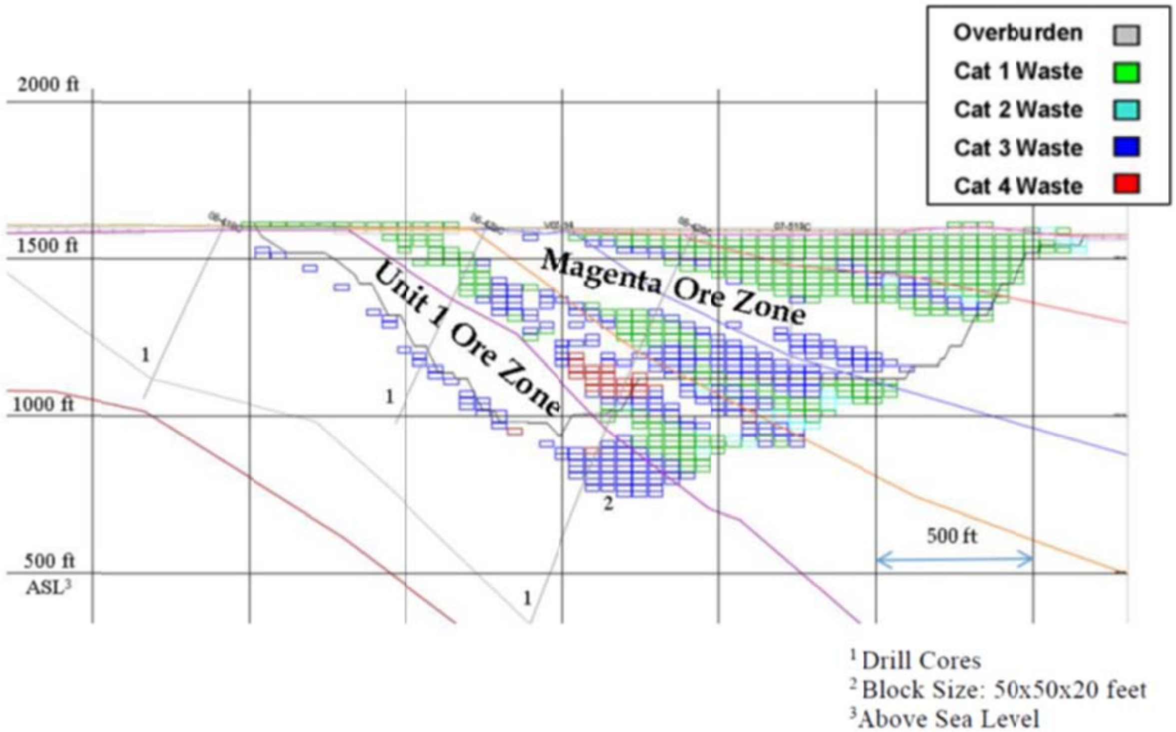
The Rock and Overburden Management Plan (PolyMet Mining, 2017c, Appendix 11.1, p. 40) discusses the plan for separating waste categories. In the beginning of operations, each blast hole will be assayed, but as mining progresses assaying will be conducted "less frequently." As the assaying becomes less frequent, errors in categorizing wastes in the field are bound to occur.

SRK Consulting (2007a, p. 92) discusses the difficulty in separating rocks with similar sulfur contents and the implications for environmental behavior in the field:

> Predictions of drainage chemistry from Category 2 rock are susceptible to the assumption that the overall conditions within the waste rock will remain non-acidic and the composition will reflect rock classified as Category 2 in the block model. Under operational conditions, these assumptions may be affected by the accidental inclusion of small amounts of Category 3 and 4 rock that could become localized sources of acidic water and leaching metals. The effect of these inclusions could be to contribute to metal leaching and lowering of pH resulting in higher concentrations of metals in the drainage. Category 3 and 4 rock could become incorporated into Category 2 rock by a number of routes which could include waste heterogeneity (i.e. small-scale inclusions of Category 3 and 4 rock in Category 2 rock) and operational errors. The latter are factors such as mistakes at the operating face and dumping location. These errors will be minimized by management practices but some level of operational mishaps can be expected.

Figure 2 shows that Category 1 waste in this example cross-section is most often close to Category 3 wastes and ore, especially along the upper edge of the Magenta Ore Zone. Ore has a higher sulfide content, and inclusion of ore, or any other waste category, will increase the acid drainage potential of the Category 1 stockpile.

Figure 2. Example cross-section through deposit showing waste rock categories.



Source: PolyMet Mining, 2017c, Appendix 11.1, Figure 4-2.

The categorization of wastes for the NorthMet Project is based solely on sulfide content. In the past, copper concentrations in the wastes were also considered, but they are not currently. Descriptions of the pollution potential of mine wastes often focus solely on their acid generation potential, and acidity does increase the leaching of metals and other contaminants. However, the metal content of the waste rock is also a major concern. The total metal content of Category 1 wastes is not notably different than that of the other waste categories or ore, and in some cases, the concentrations are higher in Category 1 wastes.

As shown in Table 1, the mean nickel concentration in Category 1 wastes is similar to that in the other waste rock categories, and the maximum concentration is higher. Nickel is one of the major contaminants of concern for the NorthMet Project. Mean and maximum cobalt and manganese concentrations are higher in Category 1 than in the other waste categories. Category 1 zinc concentrations are similar to those in Category 2/3 wastes and higher than those in the ore. The %S content of Category 1 wastes, as proposed, is lower than the other wastes and ore, and Category 1 wastes have the lowest copper content, with the exception of the Virginia Formation, which is only 2.8% of all waste rock (see pg. 3). The whole rock data show that the potential exists to leach elevated concentrations of toxic metals from Category 1 wastes by themselves. The inadvertent mixing in of other wastes will only increase metal concentrations and acidity in the Category 1 stockpile leachate.

Table 1. Whole rock and %S summary results for some key constituents in waste rock and ore.

Constituent	Units	Category 1 (n=38) Mean	Category 1 (n=38) Range	Category 2/3 (n=25) Mean	Category 2/3 (n=25) Range	Category 4 (Duluth Complex; n=16) Mean	Category 4 (Duluth Complex; n=16) Range	Virginia Formation (n=3) Mean	Virginia Formation (n=3) Range	Ore (n=3) Mean	Ore (n=3) Range
Copper	%	0.025	0.005-0.095	0.084	0.010-0.295	0.088	0.020-0.152	0.017	0.015-0.021	0.360	0.323-0.422
Nickel	%	0.032	0.000-0.095	0.035	0.000-0.072	0.034	0.013-0.071	0.017	0.013-0.020	0.106	0.088-0.139
Cobalt	ppm	57	21-117	51	11-94	60	21-119	29	24-36	83	76-94
Manganese	ppm	864	351-1545	702	331-1325	451	151-1130	227	125-377	717	705-739
Zinc	ppm	78	33-136	84	33-200	120	47-324	575	252-918	74	71-76
Total Sulfur	%	0.05	0.02-0.12	0.29	0.14-0.59	1.44	0.68-4.46	3.82	2.00-5.68	0.87	0.86-0.90

Source: PolyMet Mining, 2017b, Table 2-2.

Given the uncertainties associated with separating the different waste categories and ore, and the potential adverse environmental consequences if more reactive materials are included in lower category wastes, it is critical to have an adaptive management plan (AMP) for waste rock. This is especially true for wastes reporting to the Category 1 stockpile, which will sit on the land surface in perpetuity. The only AMPs discussed in the Permit to Mine Application are for water quality and quantity and tailings dam stability (PolyMet Mining, 2017a, Section 3.6). An AMP for waste rock management should be similarly included and defined at this stage of the project. PolyMet Mining, 2017c, Appendix 11.1 (Section 6.0, p. 46) vaguely discusses adaptive management, but it does not appear to be related to stockpile composition. Section 6.2, although it is titled Adaptive Management, only discusses the capacity of the pits and the temporary stockpiles to hold waste rock. An AMP for waste rock management should include actions required if testing results indicate that wastes have been mixed, an evaluation of the impacts based on monitoring results, mitigation measures to be employed, mine company and agency responsibilities, timelines for actions, and an evaluation of the effectiveness of the mitigation measures employed.

Recommendations: Conduct ABA testing for more waste rock and ore samples, including NP, especially for samples identified as Category 1 wastes. Re-examine the assumption that the %S in Category 1 wastes will be ≤0.12%. Rerun the water quality predictions for discharge from the Category 1 stockpile assuming that a certain percentage of Category 2/3 wastes and ore will be included in the pile (use a range of percentages). Create an adaptive management plan for waste rock management.

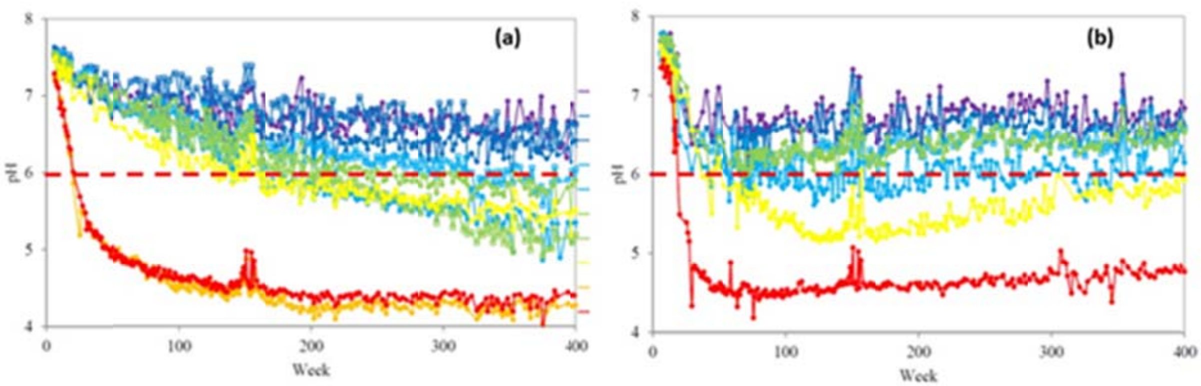
2. Assumptions about Acid Drainage and Contaminant Leaching

a. The pH recovers in samples that have gone acidic

SRK Consulting (2007a) and PolyMet Mining (2015a) have stated that in some cases, once the pH becomes acidic, the pH "recovers." SRK Consulting (2007a, p. i) stated that "the transition to acidic pHs takes many years" and the recovery occurred after "depletion of sulfide minerals." The Minnesota Department of Natural Resources (MDNR) reactor kinetic tests did show some recovery of pH values after the onset of acidification, as shown in Figure 3b for the samples with higher %S values. However, pH values were still acidic (pH<6) throughout the test. The minimal recovery was only seen in the MDNR reactor tests, where the sample and particles sizes were smaller than in the conventional HCTs (Figure 3a).

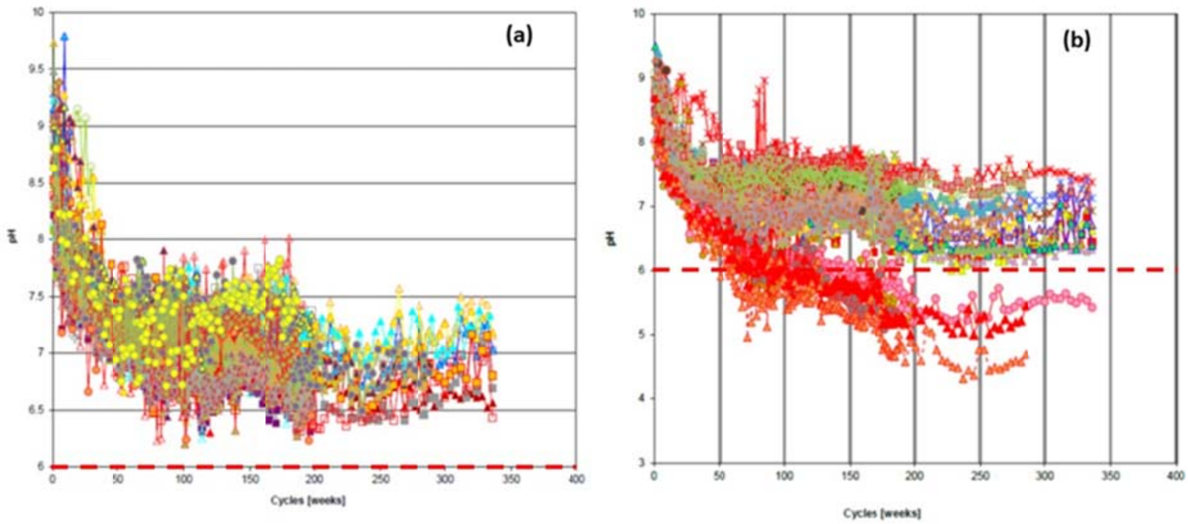
PolyMet Mining (2015a; Attachment 2, p. 2) stated that in some cases the pH recovered as oxidation rates decreased. Category 1 waste rock HCTs (Figure 3a) did not produce acidic conditions, but Category 2/3 waste rock did (Figure 4b). Some pH recovery occurred in the Category 4 waste rock HCTs (PolyMet Mining 2015a, Attachment 2, Figure 3; not shown), but in no case did pH values increase above 6.

Figure 3. The pH of long-term kinetic testing using (a) HCTs and (b) MDNR reactors. HCT=1000g, d<6.35mm; MDNR reactors=75g, 0.053<d<0.149mm. Red=0.94%S, yellow=0.64%S.



Source: MDNR, 2013, Figure 7.

Figure 4. The pH of HCTs for (a) Category 1 and (b) Category 2/3 waste rock.



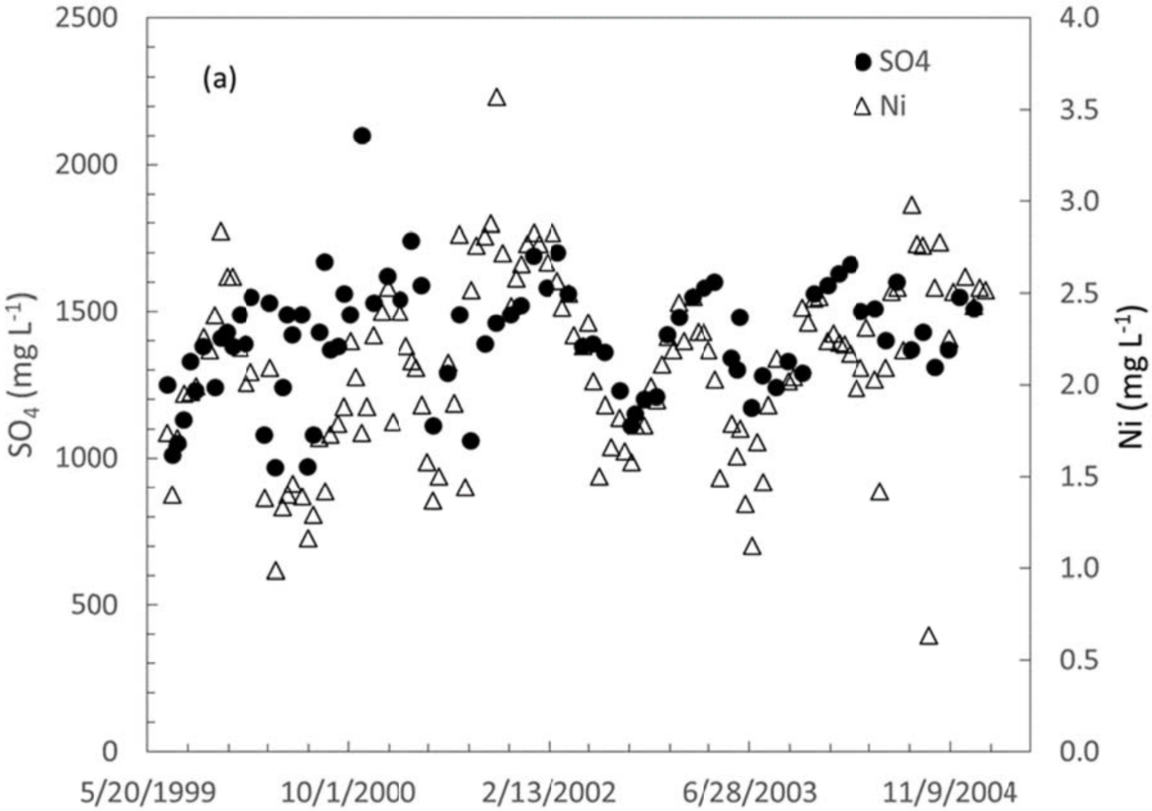
Source: PolyMet Mining, 2015a. Attachment C, Figures 1 and 2. Line at pH 6 added.

b. Release from secondary salts

One important distinction between HCTs and field conditions is the formation of secondary salts seasonally in aerially deposited waste rock piles. These hydrated metal-sulfate salts form from the oxidation of sulfide minerals and create crusts on the surface of mine wastes during periods of evaporation (Jambor et al., 2000). Under field conditions, some of these secondary salts (especially hydrated iron sulfate salts) can store acidity – and all store metals and sulfate – that can be readily released during rain or snowmelt events; the secondary minerals can form again as interstitial waters in the waste pile evaporate under drier conditions (Nordstrom, 1982; Hammarstrom et al., 2005). Under laboratory conditions, the dissolution of secondary salts occurs most notably during the first few weeks of kinetic testing, but these results are uniformly ignored (Maest and Nordstrom, 2017). In HCTs, the secondary salts are typically rinsed out during the first few weeks of testing – sometime purposefully – and these weeks often show the highest concentrations and release rates. The PolyMet HCTs used a higher volume of rinsate for the first week of testing (750 mL) than subsequent weeks (500 mL), so the first flush from the dissolution of soluble salts is diminished in the HCT results.

PolyMet took a different approach with the tailings and the waste rock regarding incorporating this "first flush" into release rates for water quality predictions at the NorthMet site. It is included for the tailings but excluded for the waste rock. This process clearly applies to waste rock, as seen in Figure 5 for the Dunka Road test piles. In the spring, concentrations of nickel and sulfate spike and then decrease as the sulfate salts that built up over the winter are dissolved.

Figure 5. Duluth Formation field leachate results. Sulfate and nickel concentrations over a 4.5-year period from 1999 to 2005 in Duluth Formation waste rock seeps, Dunka Road stockpile 8011.



Data source: Minnesota Division of Natural Resources, Division of Ecological & Water Resources. Electronic data deliverable. March 2014.

c. Release Rates and Concentration Caps

Overview

The methods used to build the GoldSim water quality model are described in PolyMet Mining, 2017b, Section 2.4. The results from the waste characterization program and other sources were used to develop the geochemical parameter inputs to the model. The primary reference for the inputs to the model is SRK Consulting (2011). The focus in this section will be on the development of model parameters for Category 1 waste rock because it is the only waste material that will remain on the surface forever.

SRK Consulting (2011) distinguishes between “release” and “leaching” as follows:

- Solute release = movement of the contaminant from the mineral or solid material source to solid, secondary weathering products
- Leaching = dissolution of weathering products by contact water and release to the environment.

Weathering products can be thought of as the metal sulfate salts produced from the oxidation and dissolution of primary minerals in the wastes or ore. For example, when sulfide minerals weather, they produce metal-sulfate salts. To estimate release rates, SRK used measured rates from the HCTs and metal:sulfur ratios in pyrrhotite[1] or olivine.[2]

One of the fallacies associated with this distinction is that HCT results actually include both processes, yet HCT results were only used for developing release rates. In addition, SRK (2011, p. 1) makes the following statement in their first paragraph: "The finite solubility of secondary minerals typically limits their dissolution so that leaching rates are lower than release rates on average." While this statement could be true for hydroxides, the opposite is the case for secondary metal-sulfate salts. Sulfate salts forming on weathered waste dissolve rapidly when contacted by rain water or snowmelt; in contrast, primary sulfide and aluminosilicate minerals weather relatively slowly (Maest and Nordstrom, 2017 and references contained therein). This assumption leads to underestimation of release rates that are used as inputs to the NorthMet water quality model.

To estimate leaching, SRK's main focus was on limiting concentrations (concentration caps) that could be present in leachate from waste rock. SRK used concentrations from short-term leach tests (SMWMP), theoretical mineral solubilities, and data from the AMAX test piles (only for nickel, and only from pH 7 to 8). These concentrations are the maximum values allowed to reach the environment after the contaminant is released from the weathering products by contact water (e.g., rain or snowmelt). Once in the environment, concentrations are limited further by adsorption onto soils or aquifer materials.

The approaches used by SRK to develop inputs to the water quality model are unnecessarily convoluted, inconsistent, unsupported, and opaque. Some of the limitations to SRK's development and use of release rates and leachate concentration limits (concentration caps) are discussed below.

Release Rates

Final methods for developing model distribution parameters for ore and waste rock release are shown in Tables 2-19 to 2-23 (PolyMet Mining, 2017b).

Method 1: Fit to HCT Data. For many constituents, release rates are based on *average* non-acidic release rates from HCTs.[3] Release rates for waste rock were initially developed as shown in Table 1 in SRK (2011). Discrepancies between this table and Large Table 2 in PolyMet Mining (2015a), which contains and relies upon the SRK (2011) memorandum, suggest that using whole rock or microprobe metal:S ratios for silver, arsenic, beryllium, lead, antimony, selenium, and vanadium and multiplying by the sulfate release rate was

[1] Pyrrhotite, $Fe_{1-x}S$, is the primary iron sulfide mineral in the NorthMet deposit that is responsible for acid drainage formation.
[2] A rock-forming mineral containing iron, magnesium, and, in the case of the NorthMet deposit, trace amounts of nickel.
[3] For Category 1 waste rock this includes Ag, alkalinity, As, B, Be, Ca, Cr, F, K, Mg, Na, Pb, Sb, Tl, and V.

abandoned. Instead, average HCT release rates from non-acidic conditions earlier in the tests (referred to as Conditions 1 & 2) were used.

Although this approach seems reasonable on the face of it, there are two issues that will underestimate release rates for constituents using Method 1. First, the initial releases of contaminants ("first flush," referred to as Condition 0) are never included (see SRK, 2011, pg. 7). Second, using average release rates dampens the higher release rates that should be considered for environmental protection. Figure 6a shows that the highest arsenic release rates for Category 1 samples occurred very early in the tests – in fact, some rates are so high they are excluded from the graph; however, these "Condition 0" first flush rates were excluded from the water quality model. Figure 3a also shows how using average release rates for the entire series of Category 1 HCTs (Category 1 HCT results were only labeled as Condition 1 or 2) would minimize release rates, especially by inclusion of rates beyond week 200.

A variation on Method 1 was used for sulfate. The HCT data from Conditions 1 & 2 were used, but the results were regressed against the %S values. Again, this approach eliminates the higher rates seen in Condition 0, or first flush, times in the tests, as shown in Figure 6b.

Method 2: Use element ratios from solids – either using whole rock chemistry (aka aqua regia) or individual mineral results. This approach was used for many of the important contaminant of concern, including copper, zinc, and nickel for Category 1 and 2/3 wastes and arsenic in Category 2/3 wastes.

A very brief description of the approach is given in SRK (2011, Section 2.4), but no data are provided to confirm that the approach makes sense for the constituents and samples evaluated. The following equations are provided in Section 2.1 of the same document; equation (2) is for metal and sulfur concentrations in pyrrhotite, and equation (3) is for metal and magnesium concentrations in olivine. Taken together, the implication is that to arrive at a release rate for metals using Method 2, the sulfate, magnesium, or potassium release rate from the HCTs is multiplied by the metal:major anion or cation concentration ratio in the solid. No information is given on the release rates used for sulfate, magnesium, or potassium. Is it an average of all the rates in the HCT? Is it the average of rates in a certain Condition (1, 2, or 3, for example)? Section 8.1.2.3 in PolyMet Mining (2015a) states that for metals using ratios from whole rock data (aqua regia results), 18,800 samples were used to develop distributions. However, those data are tied to HCT release rates from a limited number of samples (just those in a given waste Category). Are the metal:S ratios varying wildly, but the sulfate release rate from the HCTs is not? Samples with different metal and sulfur concentrations in the solid will presumably produce different sulfate and metal release rates, but this does not seem to be accounted for in the approach. No examples are provided to show how the results from this method relate to results, for example, from the AMAX test piles. We are apparently to take this on faith.

Figure 6a. HCT release rates for arsenic in Category 1 waste rock samples.

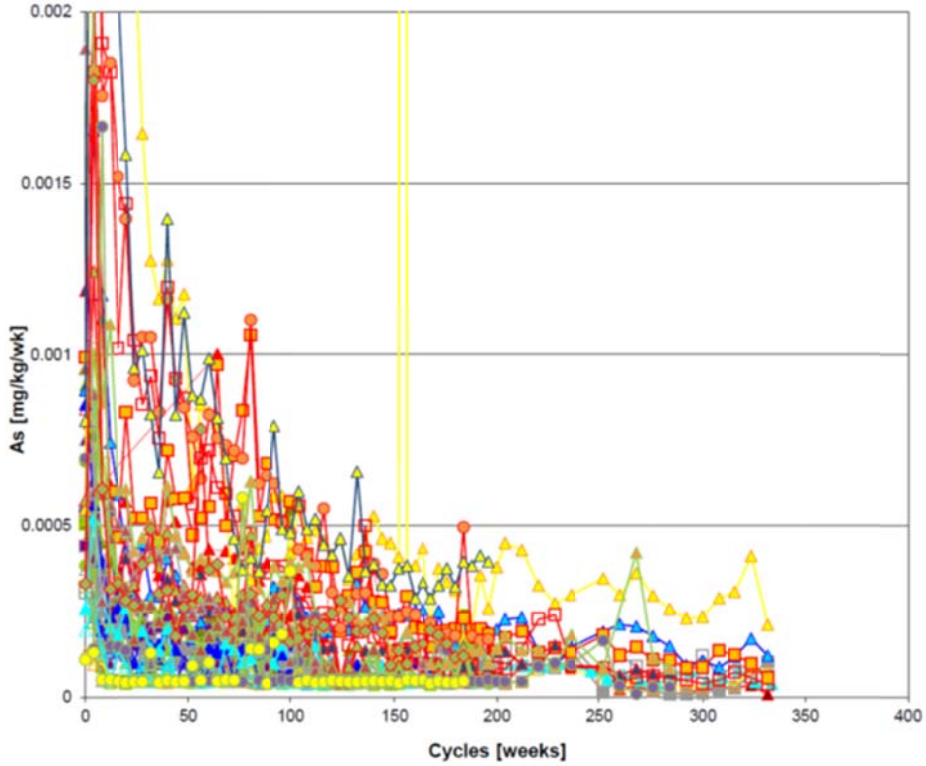
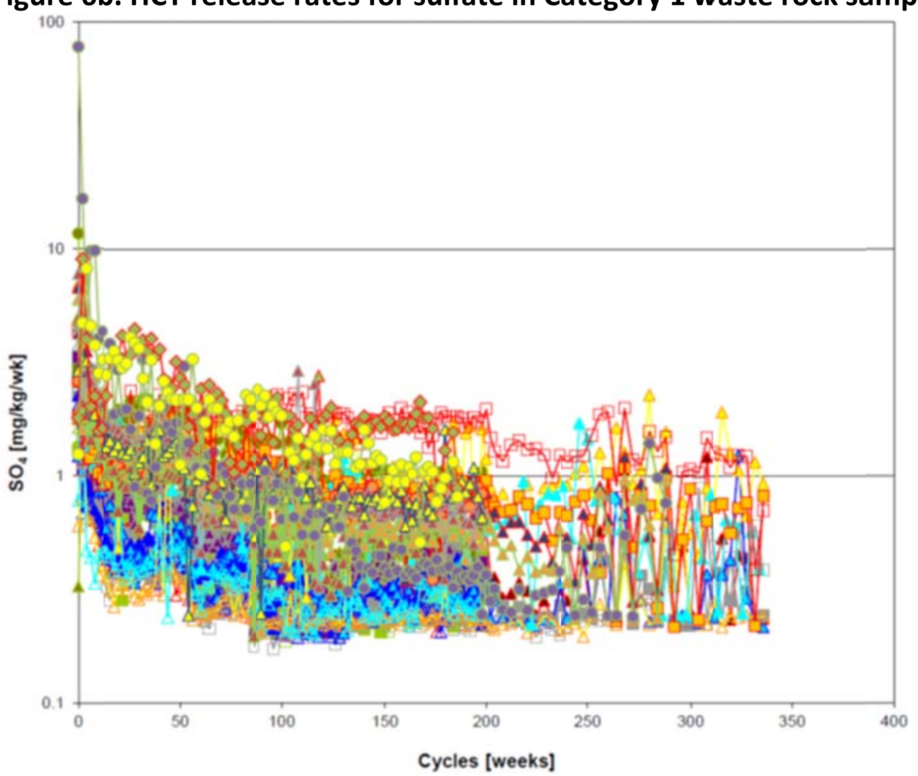


Figure 6b. HCT release rates for sulfate in Category 1 waste rock samples.



Source: PolyMet Mining, 2015a, Attachment C, Figure 1.

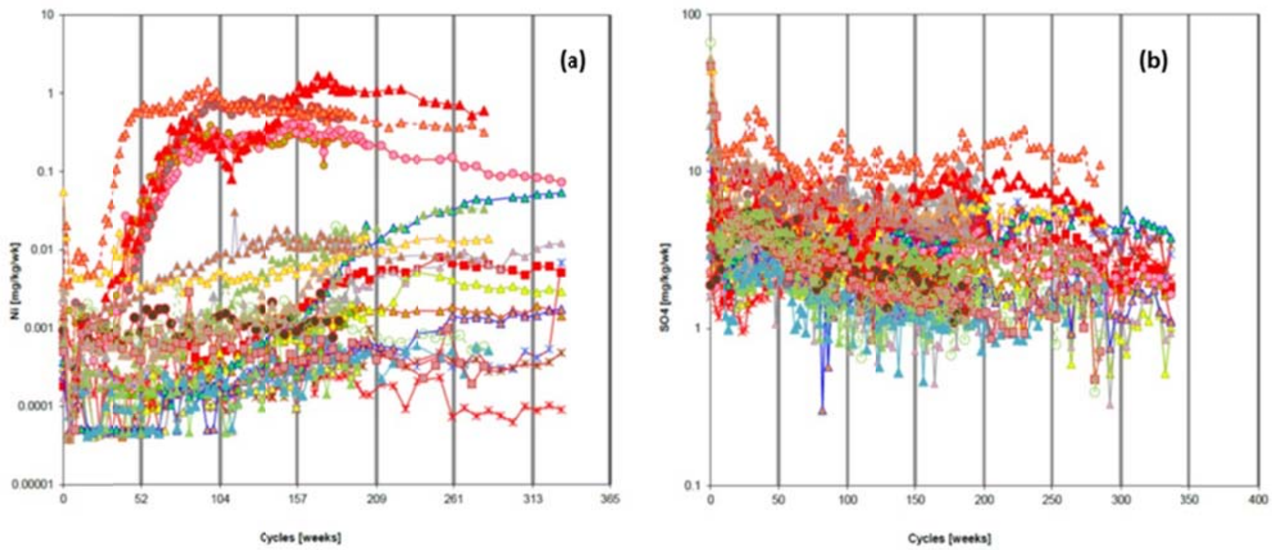
The math implied in equations (2) and (3) requires that the metal release rate will always be in lock step with the sulfate, magnesium or potassium release rate. However, we can see by looking at the HCT results that this is not the case. For example, the HCT release rate for nickel is tied to the HCT release rate for sulfate for Category 1 and 2/3 wastes. Figure 7 shows that trends in rates for these two contaminants do not mirror each other.

$$R_M = R_S \cdot \frac{[M]_{solid}}{[S]_{solid}} \tag{2}$$

$$R_{metal} = R_{Mg} \cdot \frac{[M]_{solid}}{[Mg]_{solid}} \tag{3}$$

The methods used to develop release rates for wastes and ore often underestimate potential release rates in the environment and do not hold true to the available data. In addition, the theories are unconvincing because they are not supported by comparison to actual laboratory or environmental data.

Figure 7. Comparison of rate trends for nickel (a) and sulfate (b) in Category 2/3 waste rock HCTs.



Source: PolyMet Mining, 2015a, Attachment C. Figure 2.

Scaling Factors and Concentration Caps

Scaling factors and concentration caps were used to limit input concentrations in the water quality model. Scaling factors will be discussed only briefly for Category 1 waste rock. The approaches have changed over the different versions, but the current approach for scaling laboratory to field results for Category 1 waste rock is to compare sulfate release rates from the Dunka Road stockpiles to sulfate release rates from MDNR reactor tests using rock from the Dunka Mine blast holes. For the laboratory tests, the first 71 weeks of testing were used, but results from the first five weeks were excluded (PolyMet Mining, 2017b, p. 13 and PolyMet Mining, 2015a, Section 8.2.8). This resulted in 17 *average* sulfate release rates as a function of sulfur content. The fact that results from the first five weeks were removed from the leach tests means that any "first flush" effects were also removed. In contrast, all flow and concentration data from the Dunka Mine stockpiles were used, which likely includes first flush data, as shown by the peaks in sulfate concentrations each spring (see Figure 4). However, the first flush concentrations and the high values during the remainder of the leach tests were essentially removed by using average annual sulfate release rates as a function of sulfur content.

A more protective approach to scaling for Category 1 waste rock would be to use the full range of non-acidic AMAX leachate data without averaging (i.e., using a scaling factor of 1.0) to account for uncertainties in the sulfur content of the stockpile (discussed in Section 1c of this memorandum). It is also important to keep in mind that the AMAX leachate data are from filtered samples, which ignores the potential for particulate metals to dissolve and increase mobile concentrations under varying field conditions.

Concentration caps are important because the Mine Site water quality model assumes that contaminants in the stockpile leachate will be entering the environmental at no higher than these concentrations. Concentration caps for Category 1 were used for nearly every constituent: alkalinity, aluminum, antimony, arsenic, beryllium, cadmium, cobalt, copper, iron, lead, manganese, nickel, potassium, selenium, silver, sodium, thallium, vanadium, and zinc (PolyMet Mining, 2017b, p. 15). Release rates units are mg/kg/wk, and concentration cap units are in mg/L.

In addition to the use of averaging and elimination of first flush values, a further shortcoming of the Category 1 concentration cap conceptual model is that pH values below 7.0 and above 8.1 are not considered; apparently this narrow range was based on results from short-term leach tests (SMWMP; SRK, 2011, p. 15), which are not reflective of longer term leaching. The entire Category 1 HCT pH range should instead be used. The pH range used for Category 1 metal concentration cap distribution values is 7.0 to 8.1 (PolyMet Mining, 2017b, Table 2-30), yet many Category 1 HCT pH values are below 7.0, including values from early in the tests (starting at ~25 weeks) to the end of the tests (~350 weeks), as shown in Figure 8a. When the pH drops, most metal concentrations increase, so the caps will underestimate leachate metal concentrations at pH values <7 for the Category 1 stockpile. Similarly, the higher pH values in Category 1 HCTs are between 9.5 and 10 (see Figure 7a). Concentrations of elements that form oxyanions such as arsenic, antimony, molybdenum, selenium and vanadium can increase at higher pH values, and higher arsenic concentrations are associated with higher pH values in Category 1 leachate (see Figures 6a, which shows arsenic rates that reflect concentration trends) and 8a (for pH). Examples of this behavior are shown for some of the oxyanions listed above in SRK's porphyry database (2011b, Attachment 3).

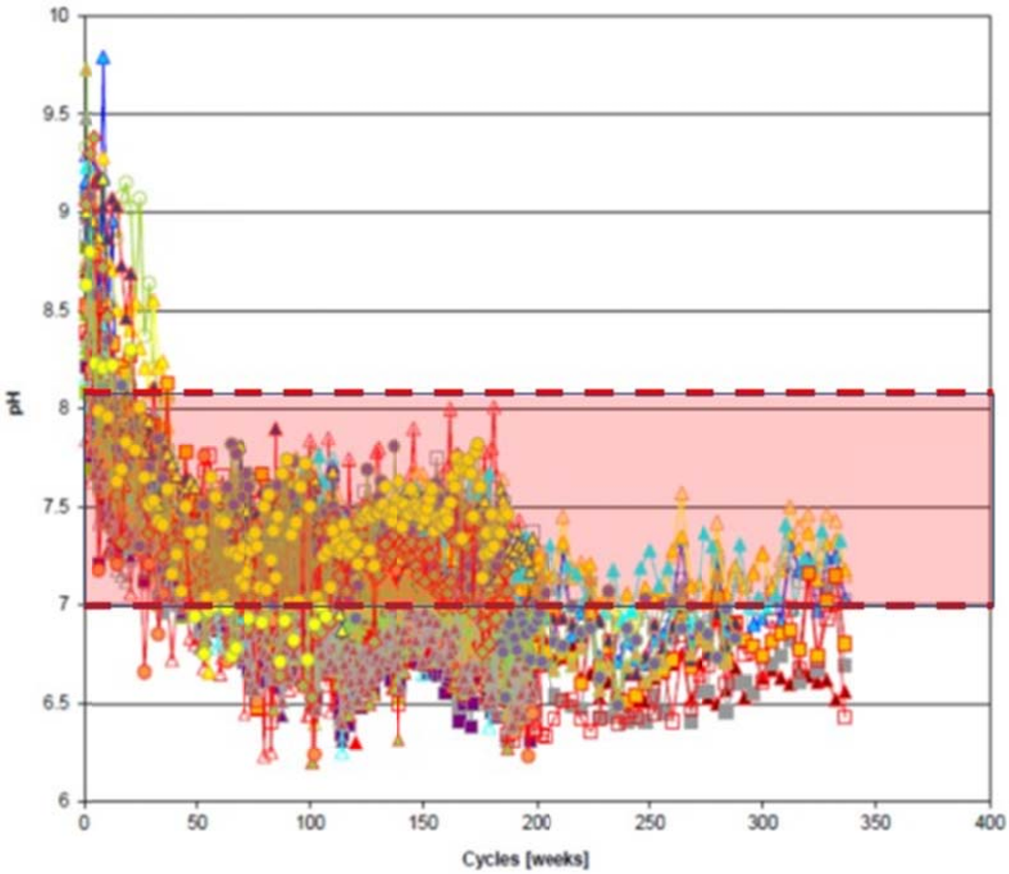
The AMAX test pile data were used to develop the concentration caps for most metals and for alkalinity (PolyMet Mining, 2017b, Table 2-30). Figure 8b shows the AMAX data for nickel as a function of pH. In the pH range considered for Category 1 waste rock concentration caps, the maximum measured nickel concentration is 67 mg/L. However, the maximum concentration cap allowed for nickel in Category 1 wastes is only 13 mg/L (PolyMet Mining, 2017b, Table 2-30). If the pH range between 6.0 and 7.0 is considered, the maximum measured nickel concentration is 120 mg/L, almost 10 times higher than the maximum concentration cap. Similar results are likely for other metals. For comparison, the cap for non-acidic leaching of Category 2/3, 4, and ore materials is only 32 mg/L at pH 6.0 (PolyMet Mining, 2017b, Table 2-31). These results show that the concentration caps for nickel and possibly other metals in all mined materials are too low and that their use in the mine site water quality model will underestimate concentrations of metals in leachate that reaches the environment.

These alternative results are based on a different conceptual model for the development of concentration caps:

- Concentration caps are unnecessary in a water quality model that could use a geochemical code to limit concentrations based on mineral solubility.
- If caps are to be used, they should include upper concentration values that were excluded by using averages and eliminating first flush concentrations.
- The full range of potential Category 1 pH values should be used, including values above 8 and below 7. Considering that the Category 1 stockpile will likely include higher %S wastes, acidic conditions could develop. Limiting pH values to 6.0 on the low end could underestimate maximum possible contaminant concentrations in Category 1 leachate. As an initial estimate, the pH range from Category 1 HCTs could be used (approximately pH 6-9.5)
- Using "median" sulfate concentration for gypsum solubility, estimated at 2,700 mg/L (SRK, 2011, pg. 11) and based on HCT results for a time in the test when gypsum is not likely dissolving (Condition 2), will underestimate possible sulfate concentrations for the Category 1 stockpile. A better approach would be to base limits on first flush HCT values or, even better, use a geochemical code that will take complexation into account.
- Concentrations of many elements, including sulfate, copper, nickel, selenium, iron and others are likely limited by the solubility of secondary sulfate salts, and a geochemical code with thermodynamic data for these phases should be employed. Inverse modeling could be used to evaluate potential phases (Maest and Nordstrom, 2017). SRK (2011b, pg. 9) notes that concentrations of sulfate, barium, selenium, and copper were likely limited by secondary mineral solubilities in the sequential short-term leach tests conducted on Category 1 wastes.

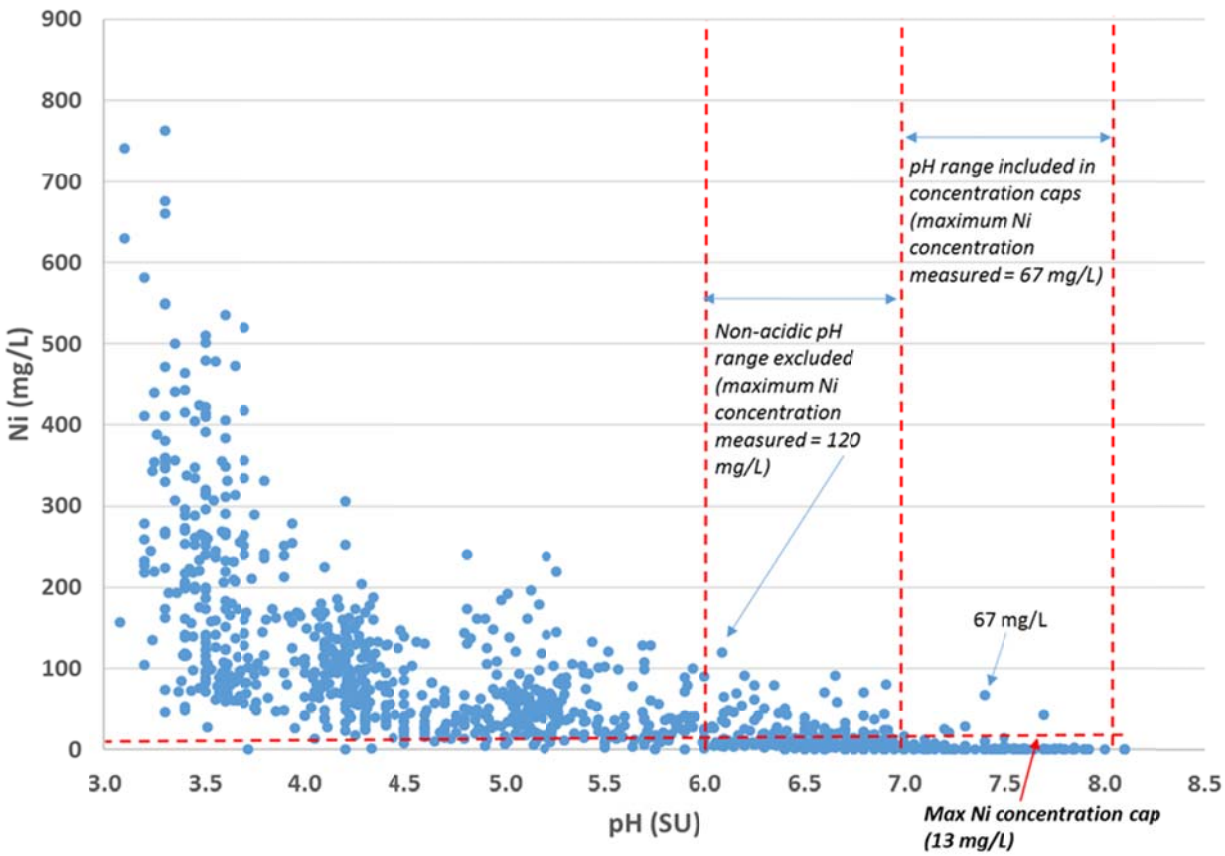
Recommendations: Incorporate the release of metals, acidity, and sulfate from secondary salts into release rates for waste rock and ore and then into water quality predictions. The release of contaminants from secondary salts has been ignored in water quality modeling for the mine site, yet these are important long-term, soluble sources. Using averages and ignoring inputs from secondary salts will underestimate the extent of contaminant plumes in the environment, and the use of a proprietary code (GoldSim) decreases transparency. Use the information to create seasonal changes in released concentrations that better mimic the releases observed from the Dunka Road/AMAX piles.

Figure 8a. Category 1 HCT pH values and the pH range considered for development of concentration caps.



Source: PolyMet Mining, 2015a, Attachment C, Figure 1.

Figure 8b. Nickel concentrations vs. pH in AMAX test pile, showing pH range considered for Category 1 concentration caps with maximum measured value (67 mg/L) and non-acidic pH range excluded (pH 6.0 to 7.0) and maximum measured value (120 mg/L) between pH 6.0 to 7.0. The maximum concentration cap for nickel in Category 1 waste rock is only 13 mg/L.

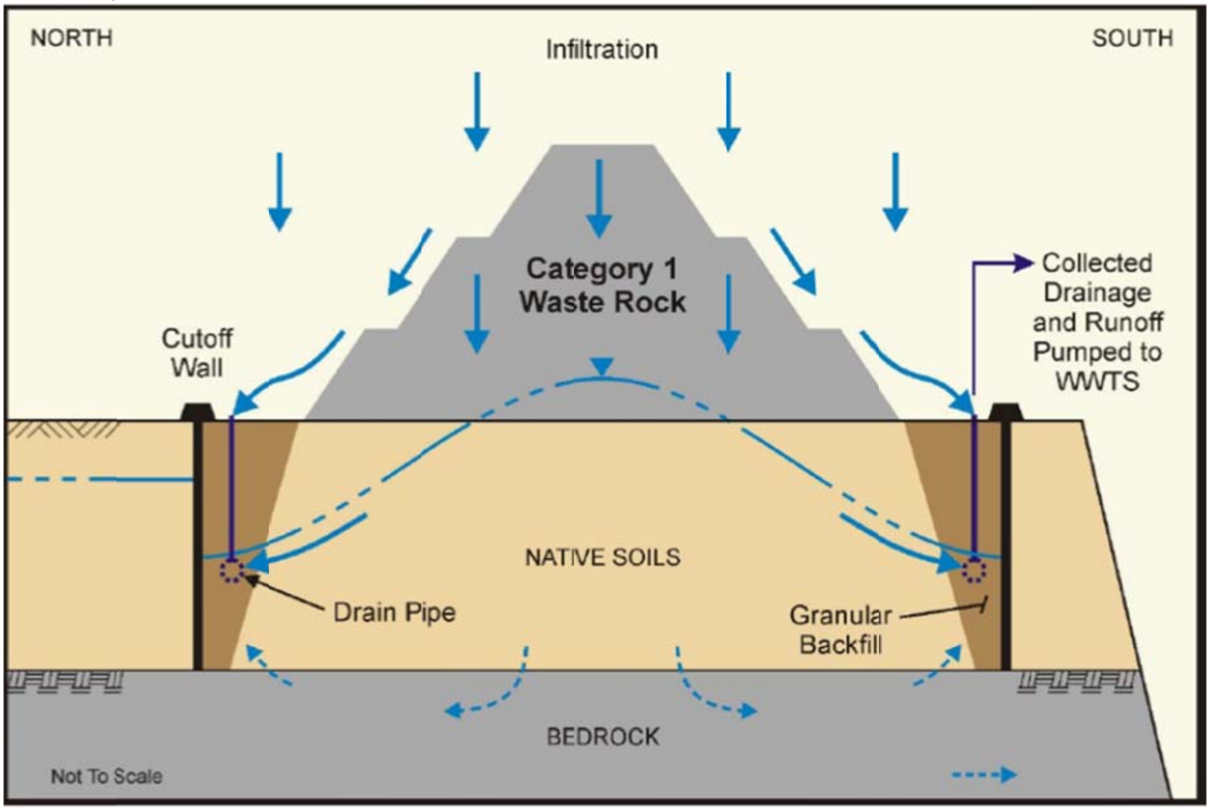


Data source: Minnesota Division of Natural Resources, Division of Ecological & Water Resources. Electronic data deliverable. March 2014.

3. The Quality of Water Impacted by Category 1 and Category 2/3 Stockpiles

If seepage collection from the waste rock stockpiles doesn't work as well as predicted during operations and closure, nearby groundwater and surface water resources will be threatened. Figure 9 shows the plan for management of seepage from the Category 1 stockpile. No liner is proposed for the facility, the groundwater between the cutoff walls is expected to contact the wastes, and contaminated drainage has the potential to escape capture and infiltrate to the bedrock aquifer. The stockpile cap is assumed to limit the infiltration of precipitation falling on the stockpile (although not the ingress of oxygen), but the cover will not be installed until Mine Year 14 and will take eight years to complete (PolyMet Mining, 2017c, Appendix 11.4, p. 20 and 39). This leaves one to two decades of weathering and leaching for contaminants in the stockpile.

Figure 9. Conceptual cross-sectional model of Category 1 stockpile drainage and containment system during operations. Note that no liner is proposed for the facility, the groundwater surface (blue dashed line with blue triangle at high point) between the cutoff walls is expected to contact the wastes, and contaminated drainage has the potential to escape capture and infiltrate to the bedrock aquifer (dashed blue lines with arrows in bedrock).



Source: PolyMet Mining, 2017c, Appendix 11.1, Figure 2-2.

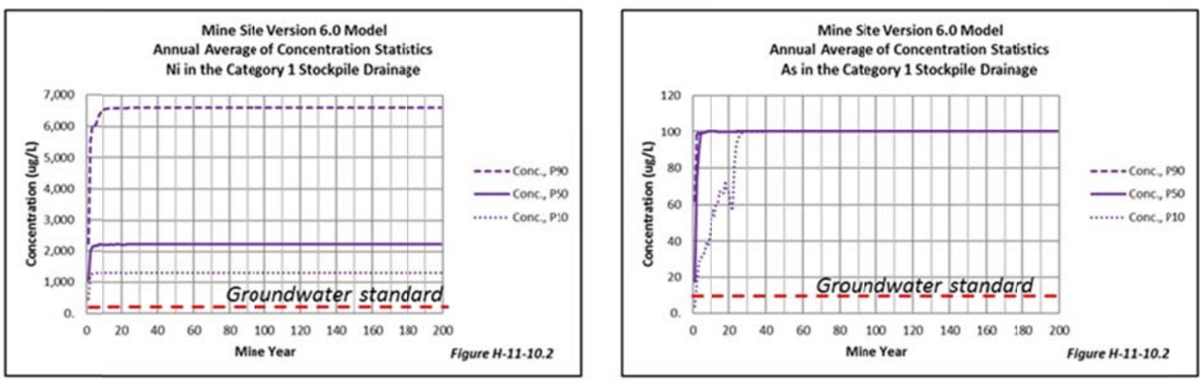
The Rock and Overburden Management Plan (PolyMet Mining, 2017c, Appendix 11.1, p. 15) states that groundwater could flow under the cutoff wall on all sides of the stockpile but the south side, but that groundwater recovery wells could be installed if this occurs. Allowing pollution and attempting to remediate the situation does not reflect a pollution prevention approach. Instead, the stockpile should be lined with a segmented leachate collection system (to help pinpoint the source of leaks) installed directly under the pile instead of in native soils that drain to bedrock.

Annual average (not maximum) nickel concentrations in the drainage are predicted to be at least 10 times higher than groundwater standards, and arsenic concentrations are predicted to be up to 10 times higher than the groundwater standard, as shown in Figure 10a. According to modeling conducted by Myers (2018, p. 17), Category 1 drainage will not be captured by dewatering of the West Pit but will instead flow toward the Partridge River south of the mine site (Figure 11a).

Similar results are found for drainage from the temporary Category 2/3 stockpile, which is predicted to have much higher copper and nickel concentrations than Category 1 drainage. Figure 10b shows that predicted concentrations of nickel and copper in the Category 2/3 stockpile drainage are up to 3,500 and 160 times higher than groundwater standards, respectively, during the 20-year life of the stockpile (groundwater standards for nickel and copper are 0.1 and 1 mg/L, respectively).

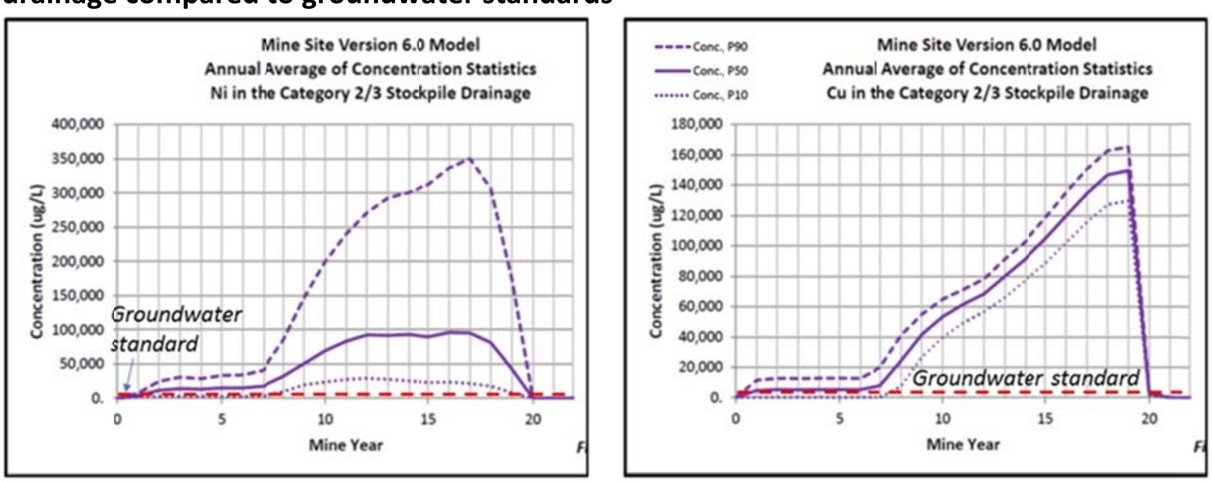
Discharge from the Category 2/3 stockpile will flow south a shorter distance than the predicted Category 1 plume toward the Partridge River (Figure 11b; Myers, 2018, p. 17). Surface water standards for nickel and copper are 0.158 and 0.0098 mg/L, respectively (using a hardness of 100 mg/L as $CaCO_3$, which is close to average values for points close to the mine site); predicted peak copper concentrations in Category 2/3 stockpile discharge are over 17,000 times higher than water quality standards for the Partridge River.

Figure 10a. Predicted concentrations of nickel and arsenic in Category 1 stockpile drainage compared to groundwater standards



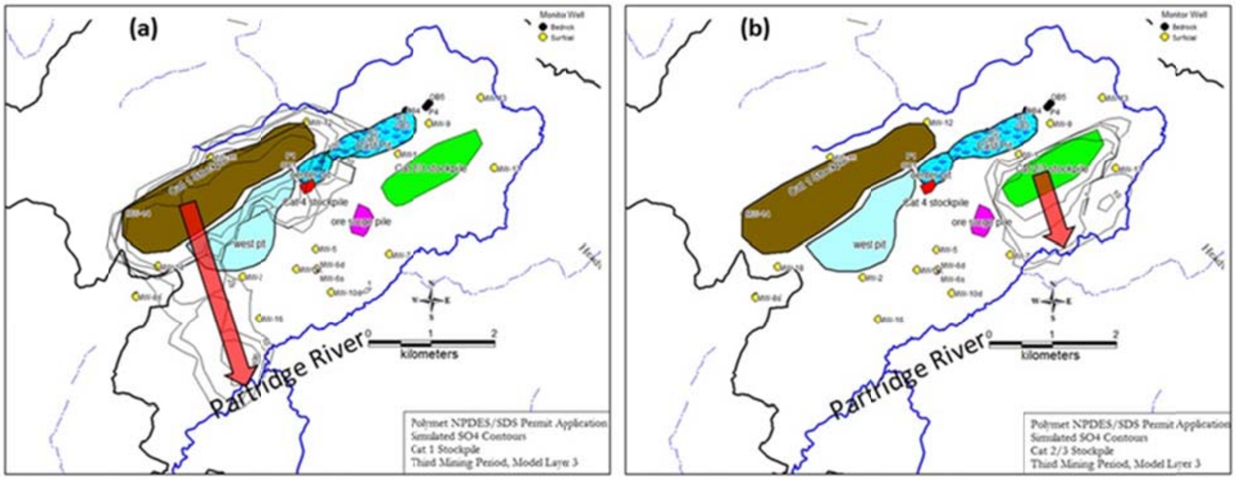
Source: Excel file received from MN DNR, GW_Conc_Timeseries_MineSite.xls (Note: these graphs were not included in PolyMet Mining, 2015b).

Figure 10b. Predicted concentrations of nickel and copper in Category 2/3 stockpile drainage compared to groundwater standards



Source: PolyMet Mining, 2015b, Fig. G-01-13.2 (Cu) and G-01-20.2 (Ni).

Figure 11. Predicted sulfate plumes and flow directions in groundwater for the (a) Category 1 and (b) Category 2/3 stockpiles during Mine Year 11



Source: Myers, 2018, Figures 21 and 22. Flow directions added.

PolyMet does not estimate the pH of stockpile drainage, but the HCT results suggest that pH values for the Category 1 stockpile will be between 6.5 and 7.5, and values for the Category 2/3 drainage will be acidic. If the Category 1 drainage does become acidic as a result of mixing with higher-sulfide materials (see Section 1c of this memorandum), the silicate minerals will not be able to buffer the acidity (see, e.g., King and McSween, 2005). A detailed examination of a PolyMet sample that did go acidic shows that when pH values are low and aluminosilicate minerals such as olivine are dissolving, the pH remained low (~pH 4) (Maest and Nordstrom, 2017).

The available information on stockpile drainage quality and groundwater flow directions strongly suggests that groundwater and the Partridge River will exceed water quality standards as a result of drainage transport. The Permit to Mine Application predicts that all metals and sulfate will be attenuated at the mine site before it reaches compliance locations. Nonconservative assumptions about contaminant fate and transport in groundwater result in this conclusion.

Modeling by SRK Consulting predicts that no mine-related contaminants will exceed water quality standards at the surface water and groundwater locations examined (Dunka Road, SW005, etc.). However, closer-in monitoring wells were not but should have been examined.

Recommendations: Commit to lining the Category 1 stockpile using a geomembrane and underlying it with a sectional leachate collection system. Rerun the water quality model for Category 1 releases using this new mitigation approach and assuming no adsorption onto aquifer materials as one end-member of the prediction.

4. *Reactivity of Flotation and LTVSMC Tailings*

The State of Minnesota defines "reactive" mine waste as follows (Minn. R. 6132.0100, subp. 28):

> "Reactive mine waste" means waste that is shown through characterization studies to release substances that adversely impact natural resources.

The definition implies that the "substances" refers to those that could potentially have an adverse impact on natural resources. For example, if the waste rock releases only magnesium, the waste rock would likely not be considered reactive, but if the waste rock releases copper, which has known adverse effects to aquatic biota, it would be. The goal of the definition is to prevent or minimize the effect of the releases on natural resources, so the definition of reactivity addresses the <u>potential</u> of the material to release contaminants. If a potential to release substances that could adversely affect natural resources exists, the mitigation measures in Minn. R. 6132.2200, subpart 2.B must be put in place to avoid the negative impact.

The characteristics of the NorthMet tailings, and all sulfidic tailings for that matter, are such that the "oxidation of residual sulfide minerals resulting in release of acidity, iron, sulfate and trace elements (copper and nickel)" is expected to occur, and an oxidation front is expected to develop and move through the tailings (SRK, 2007b; p. 15). This statement from PolyMet's consultants, and the available data, clearly show that the tailings are reactive, will remain reactive for a long time, and need best practice mitigation measures to prevent an adverse effect on natural resources.

In addition to the NorthMet flotation tailings, pre-existing tailings from former iron ore processing, known as LTVSMC tailings, are also at the Plant Site. PolyMet plans to put NorthMet tailings on top of the LTVSMC tailings. Some of the LTVSMC tailings are saturated with water, and groundwater levels are currently above the former ground level (PolyMet Mining, 2017a, p. 83). The LTVSMC tailings were also examined using characterization methods that were similar to those used for the NorthMet flotation tailings.

A report on the NorthMet flotation tailings and hydrometallurgical residues is actually called "Reactive Residues Progress Report" (SRK, 2006a) suggesting that as early as 2006, PolyMet considered the tailings reactive. The primary iron sulfide mineral in the NorthMet ore, tailings, and waste rock is pyrrhotite, which is known to be more reactive than even pyrite (Nicholson and Scharer, 1994).

a. LTVSMC Tailings

Unlike the NorthMet tailings, the LTVSMC tailings currently exist, and water quality data from groundwater and seeps in and around the tailings basin are available (Barr Engineering, 2006). The description of the releases from these tailings limits the constituents to calcium, magnesium, iron, manganese, and alkalinity (SRK, 2007b, p. 15). However, the tailings area groundwater and seep quality data show that fluoride, manganese, and sulfate exceed state water quality standards applicable to the project in groundwater affected by the LTVSMC tailings (SRK, 2007b, Table 4-1). The elevated fluoride is believed to be related to the use of wet scrubbers for control of particulate emissions from the induration furnaces (SRK, 2007b. p. 12).

Leaching experiments with LTVSMC tailings show that the leachate exceeded NorthMet Project groundwater quality standards for fluoride, sulfate, and arsenic and had higher concentrations of these constituents and chloride, cobalt, copper, and manganese than leachate from the NorthMet tailings (SRK, 2007b, Appendix C.3). The LTVSMC tailings leachate also generally had higher pH and alkalinity and higher calcium and magnesium concentrations than the leachate from the NorthMet tailings. However, nickel concentrations were almost always higher in the NorthMet tailings leachate, indicating that nickel is a major contaminant of concern for the new project.

Several of the constituents in the LTVSMC tailings (SRK, 2007b, Appendix C.3) showed a flushing effect (initial higher concentrations), including sulfate, fluoride, chloride, cobalt, copper, nickel; sulfate, arsenic, boron, chloride, copper, lithium, magnesium, potassium, sodium, strontium, and molybdenum showed a flushing effect in the NorthMet tailings.[4] The results indicate that these constituents are associated with soluble salts in the tailings and could be released fairly rapidly upon contact with infiltrating waters.

b. NorthMet Flotation Tailings

The NorthMet tailings have sulfur values ranging from 0.09 to 0.24 %S (SRK, 2007b, Table 5-2), and eight of 13 samples had %S values higher than those for Category 1 wastes (0.12 %S). SRK (2007b, p. 39) predicts that tailings with sulfur values < 0.2% S would not produce acid. Only 13 tailings samples were analyzed for ABA, and three of 13 samples had sulfur values ≥0.2 %S (SRK, 2007b, Appendix B.3). However, as noted in the following paragraphs, leaching even under neutral conditions will increase the release of nickel and other metals. Results from only 13 tailings samples are presented in SRK (2007b), but PolyMet, 2017b (p. 5) states that 33 tailings samples were analyzed for total sulfur and NP. The complete results are not presented in any available document. According to sulfur testing of NorthMet flotation tailings, the average sulfur content of the tailings was 0.19 %S, and the composite tailings sample had a sulfur content of 0.2%, “closely representing the average” (SRK, 2006b, p. 1). These results indicate that, over time, the NorthMet tailings will likely produce acid.

SRK (2007b) uses geochemical modeling on the results from tailings kinetic tests and concludes that the leaching of nickel from secondary minerals in the tailings could generate concentrations of nickel from 2.2 to 2.4 mg/L at neutral pH (pH 6.5) under field conditions. SRK further concludes that the coarser NorthMet tailings can be expected to leach nickel after several months when the pH drops below 7, and that nickel concentrations below pH 7

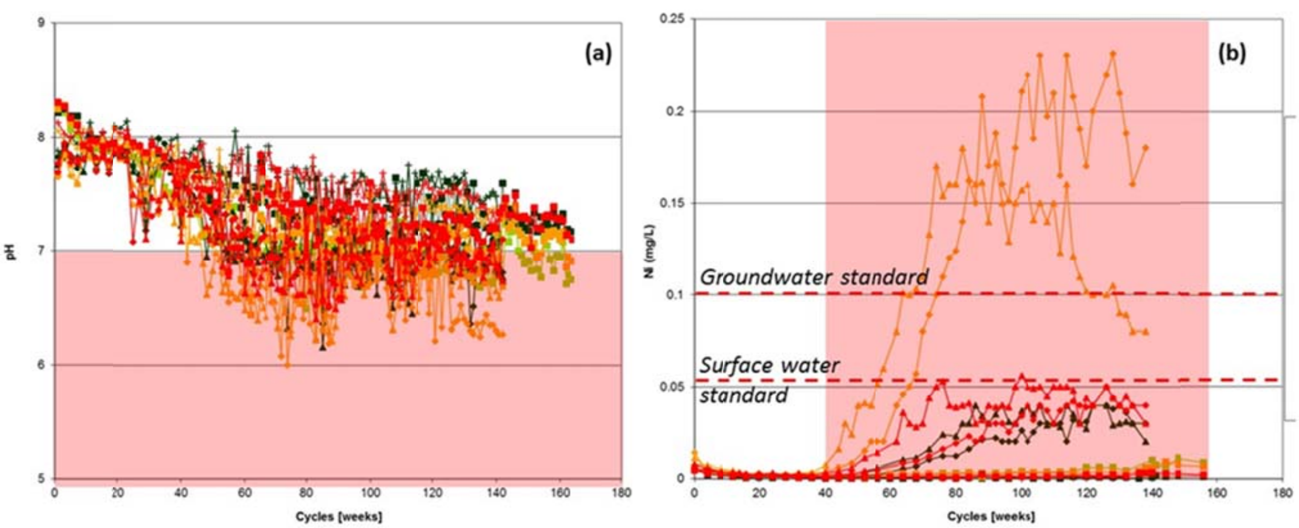
[4] Source: Minnesota Division of Natural Resources, Division of Ecological & Water Resources. Electronic data deliverable. March 2014. Excel file of tailings graphs, concentrations_Tailings_graphs.xls.

will be higher under field conditions than indicated in the kinetic testing results (SRK, 2007b, p. 46). The predicted leachate nickel concentrations are over 20 times higher than applicable groundwater quality standards, indicating that the NorthMet tailings do pose a water quality threat to underlying groundwater, and effective, best practice mitigation measures must be installed.

In terms of pH, a discrepancy exists between statements in reports and the leach test results. PolyMet Mining, 2017b (p. 10), which contains mine waste characterization summaries, states that the kinetic testing results for the flotation tailings show "no indication of trends below pH 7" or "with lowest pHs typically above 7." As shown in Figure 12a, many pH values are below 7, with values as low as pH 6.

Samples with pH values below 7 also show enhanced nickel leaching (Figure 12b) with cobalt and manganese concentrations following very similar trends. SRK (2007b, p. i) notes that kinetic testing by MDNR and PolyMet "on coarse (>200 mesh fraction) tailings has shown that nickel and cobalt leaching accelerates when pH falls below 7 due to re-leaching of weathering products formed at higher pH." These results indicate that the tailings are reactive even under non-acidic leaching conditions. According to PolyMet, 2017b (p. 10), the mineralogy of the flotation tailings is similar to that of Category 1 waste rock. If that is the case, Category 1 waste rock could also activate the release of nickel and cobalt if the pH drops below 7.

Figure 12. Flotation tailings humidity cell results for pH and nickel; (a) tests with pH values <7 in pink shading, (b) enhanced nickel leaching when pH values are <7 (pink shading) and applicable groundwater and surface water quality standards.



Source: Minnesota Division of Natural Resources, Division of Ecological & Water Resources. Electronic data deliverable. March 2014. Excel file of tailings graphs, concentrations_Tailings_graphs.xls.

The geochemical characterization results for the LTVSMC and NorthMet flotation tailings strongly indicate that these wastes are reactive and best management measures are needed to avoid environmental impacts at the Plant Site.

Recommendations: Commit to lining the entire tailings facility based on the reactivity of the new flotation and the older LTVSMC tailings. Consider removing the LTVSMC tailings and using for alternative purposes, potentially pit backfill.

5. State-of-the-Art Tailings Management

The NorthMet flotation tailings are reactive, especially in terms of their ability to leach metals that threaten surface water and groundwater quality. According to Minnesota regulation, reactive mine waste must be mined, disposed of, and reclaimed to prevent the release of substances that result in the adverse impacts on natural resources (Minn. R. 6132.2200, subpart 1.). The facility design must meet the following requirements (Minn. R. 6132.2200, subpart 2):

> B. A reactive mine waste storage facility must be designed by professional engineers registered in Minnesota proficient in the design, construction, operation, and reclamation of facilities for the storage of reactive mine waste, to either:
> (1) modify the physical or chemical characteristics of the mine waste, or store it in an environment, such that the waste is no longer reactive; or
> (2) during construction to the extent practicable, and at closure, permanently prevent substantially all water from moving through or over the mine waste and provide for the collection and disposal of any remaining residual waters that drain from the mine waste in compliance with federal and state standards.

The results from LTVSMC tailings area groundwater and seep samples (Barr Engineering, 2006) demonstrate that water is “moving through or over the mine waste” at the existing tailings basin and that the “remaining residual waters that drain from the mine waste” have not been adequately collected. PolyMet’s plan is to deposit the NorthMet flotation tailings on top of the existing LTVSMC tailings at the Plant Site without the addition of a liner. PolyMet has stated publicly that the NorthMet Project will be a state-of-the-art mine, but their plan for tailings management does not comport with their statements.

Several recent governmental or industry organization documents have addressed the repeated failure of tailings dams around the world and recommended best practices for tailings management. In addition to addressing tailings dam breaches, these reports recommend innovative tailings management approaches that minimize environmental releases of contaminated leachate (see, e.g., Mining Association of Canada, 2017; United Nations Environment Programme and GRID-Arendal, 2017; INAP, 2009 (GARDGuide, Chapter 6, which is regularly updated); and European Commission, 2009).

The design of the flotation tailings basin (FTB) is described in PolyMet Mining (2017, Section 10.2.3). PolyMet plans to use the reactive coarse LTVSMC tailings to construct the FTB dam and maximize subaqueous disposal of tailings; Polymet is not considering adding a tailings impoundment liner or alternative use or management of the existing tailings.

In the past, PolyMet was considering using the LTVSMC tailings for pit backfill, and that is one of the best practice approaches recommended in INAP (2009, Chapter 6). Dry stacking or tailings filtration and dry closure are also recommended; dry closure is especially recommended for existing wet tailings facilities (UNEP and GRID-Arendal, 2017; IIERP, 2015). Tailings desulfurization is recommended to minimize the long-term acid drainage potential of tailings (INAP, 2009, Section 6.6.3.3). PolyMet has used copper sulfate to remove pyrrhotite (e.g., SRK, 2007b, p. 23), but the method only decreased the %S from 0.2 and 0.23% to 0.1 and 0.15%. The reduced percentages are still above the cutoff for Category 1 wastes, and both are above the former reactive values of 0.05 %S. In addition, no mineralogic analyses were conducted to examine if pyrrhotite had actually been removed. Desulfurization is also recommended by the Nordic Council of Ministers (2014, p. 56).

PolyMet should take a fresh look at its plans for tailings management for both the LTVSMC and the NorthMet materials to consider more protective options that are needed to effectively manage and meet the requirements for reactive wastes.

Recommendations: Re-evaluate the management of the flotation tailings to include lining the facility and an underlying, segmented leachate collection system. Evaluate alternative methods for removal of sulfides, especially pyrrhotite, from the tailings that will improve sulfide removal over that seen from the addition of copper sulfate. Examine the mineralogy of the tests, not just the %S. Consider using paste tailings or dry stack tailings to minimize the potential for leaching of contaminants from the facility.

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NYSE AMERICAN: PLM $3.07 -4.66% | TSX: POM $3.85 -5.87% | CU $4.19 2.53% | NI $8.22 -0.3%

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NOVEMBER 19, 2019

PolyMet drilling program results in additions to NorthMet Mineral Resources and Reserves

St. Paul, Minn., November 19, 2019 – Poly Met Mining, Inc., a wholly-owned subsidiary of PolyMet Mining Corp. (together "PolyMet" or the "company") TSX: POM; NYSE American: PLM, today announced updated Mineral Resources and Reserves for the NorthMet deposit based on results of its 2018-19 drilling program. Highlights include:

- Proven and Probable Reserves increased by 14% to 290 million tons;
- Measured and Indicated Resources increased by 22% to 795 million tons.

"We are pleased with the improvements the drilling program delivered to our mineral resource, with an additional 177 million pounds of copper, 53 million pounds of nickel and 322,000 ounces of precious metals added to the Proven and Probable Reserve category," said Jon Cherry, president and CEO.

"The drilling program outcomes are indicative of our tremendous NorthMet asset and the progress we continue to make with the project," Cherry said. "With a fully permitted project, we remain in ongoing discussions with potential lenders about financing while we also continue to identify opportunities to optimize and deliver the project in the most economic way possible."

The results of drilling that commenced in the fourth quarter of 2018 and concluded in 2019 were used to convert material from the Inferred category into the Measured and Indicated Resource classifications. Subsequently, the Reserve was updated under NI 43-101 guidelines.

Updated NorthMet Mineral Resources and Mineral Reserves

Mineral reserves

The 2018-19 drilling program increased the Proven and Probable Mineral Reserve by 35.7 million tons, or 14%. The January 2018 and September 2019 reserve statements are shown in Table 1. Metal prices used for the reserve calculations are shown in Table 2.

Table 1. Mineral Reserves Statement – January 2018 and September 2019

Class	Tonnage	2018 Grades (Diluted)							
	(x 1,000)	Copper	Nickel	Platinum	Palladium	Gold	Cobalt	Silver	NSR
		(%)	(%)	(ppb)	(ppb)	(ppb)	(ppm)	(ppm)	$/t
Proven	121,849	0.308	0.087	82	282	41	74.81	1.11	19.87
Probable	132,820	0.281	0.081	78	256	37	74.06	1.02	18.02
Total	**254,669**	**0.294**	**0.084**	**80**	**268**	**39**	**74.42**	**1.06**	**18.90**
Contained Metal		**1.497 Blb**	**427 Mlb**	**0.59 Moz**	**2.00 Moz**	**0.29 Moz**	**37.9 Mlb**	**7.91 Moz**	
Class	**Tonnage**	**2019 Grades (Diluted)**							
	(x 1,000)	**Copper**	**Nickel**	**Platinum**	**Palladium**	**Gold**	**Cobalt**	**Silver**	**NSR**
		(%)	**(%)**	**(ppb)**	**(ppb)**	**(ppb)**	**(ppm)**	**(ppm)**	**$/t**
Proven	173,495	0.288	0.083	75	270	39	74.21	1.05	19.84
Probable	116,904	0.288	0.081	76	256	37	73.56	1.08	19.60
Total	**290,399**	**0.288**	**0.083**	**75**	**264**	**39**	**73.95**	**1.06**	**19.74**
Contained Metal		**1.674 Blb**	**480 Mlb**	**0.64 Moz**	**2.24 Moz**	**0.33 Moz**	**42.9 Mlb**	**8.96 Moz**	

Notes:

1. *Mineral Reserves tonnage and contained metal are rounded to reflect the accuracy of the estimate; numbers may not add due to rounding.*
2. *The 2019 Mineral Reserves estimate is effective as of September 2019. The QP for the estimate is Herb Welhener, RM-SME, of Independent Mining Consultants, Inc. The mineral reserves statement for*

*January 2018 is extracted from the company's March 26, 2018 technical report titled "NorthMet Project" (the "**NorthMet Technical Report**").*

3. *All reserves are stated above a $7.98 Net Smelter Return (NSR) cutoff and bound within the final pit design.*
4. *Net Smelter Return includes payable metal values less concentrate transportation and smelting and refining costs.*
5. *January 2018 pit; average waste: ore ratio = 1.47. September 2019 pit; average waste: ore ratio = 1.43*
6. *Tonnage and grade estimates are in Imperial units. Estimation methodology has not changed from the NorthMet Technical Report.*
7. *The risks that could materially affect the development of the NorthMet asset are set out under the heading "Risk Factors" in the company's Annual Information Form dated March 28, 2019.*

Table 2. Reserve metal prices from 2018 and 2019

All Metal Prices In US Dollars	Copper per lb	Nickel per lb	Platinum per oz	Palladium per oz	Gold per oz	Cobalt per lb	Silver per oz
2018	2.93	6.50	1286	734	1263	13.28	19.06
2019	2.91	5.54	889	1058	1274	28.82	16.19

Mineral resources

Mineral Resources statements from 2018 and 2019 are shown in Table 3. The additional drilling increased Measured and Indicated Mineral Resources by 146 million tons while decreasing the Inferred Mineral Resources by 51 million tons. The 2019 Mineral Resources prices are based on a 15% increase from the prices used in the 2019 Mineral Reserves estimates. Metal price assumptions are shown in Table 4.

Table 3. Measured, Indicated and Inferred Mineral Resources from 2018 and 2019

2018 Grades (Undiluted)									
Class	**Tonnage (X1000)**	**Copper (%)**	**Nickel (%)**	**Platinum (ppt)**	**Palladium (ppt)**	**Gold (ppt)**	**Cobalt (ppm)**	**Silver (ppm)**	**NSR (US$/t)**
Measured	237,200	0.270	0.080	69	241	35	72	0.97	19.67
Indicated	412,200	0.230	0.070	63	210	32	70	0.87	16.95
M+I	**649,400**	**0.245**	**0.074**	**65**	**221**	**33**	**71**	**0.91**	**17.94**
Inferred	508,900	0.240	0.070	72	234	37	66	0.93	17.66
2019 Grades (Undiluted)									
Class	**Tonnage (X1000)**	**Copper (%)**	**Nickel (%)**	**Platinum (ppt)**	**Palladium (ppt)**	**Gold (ppt)**	**Cobalt (ppm)**	**Silver (ppm)**	**NSR (US$/t)**
Measured	351,500	0.240	0.073	64	222	33	71	0.88	19.01
Indicated	443,700	0.230	0.069	61	207	30	68	0.87	17.91
M+I	**795,200**	**0.234**	**0.071**	**62**	**214**	**31**	**69**	**0.87**	**18.40**
Inferred	457,700	0.236	0.067	63	225	32	56	0.87	18.07

Notes:

1. *Mineral Resources tonnage and grades are rounded to reflect the accuracy of the estimate, and numbers may not add due to rounding.*
2. *The 2019 Mineral Resources estimate is effective as of July 2019. The QP for the estimate is Zachary J. Black, RM-SME, of Hard Rock Consulting, LLC. The mineral resources statement for 2018 is extracted from the NorthMet Technical Report*
3. *Mineral Resources are not Mineral Reserves and do not have demonstrated economic viability.*
4. *Mineral Resources are reported inclusive of Mineral Reserves at $6.34 Net Smelter Return (NSR) cut-off. The Mineral Resources are considered amenable to open pit mining and are reported within an optimized pit shell. Pit optimization is based on total ore costs of $5.49/ton processed, mining costs of $1.15/ton at surface and increasing $0.02/ton for every 50 feet of depth, and pit slope angles of 48 degrees. Tonnages are reported in short tons (2000lbs)*
5. *The Mineral Resources estimation methodology has not changed from the NorthMet Technical Report.*
6. *The risks that could materially affect the development of the NorthMet asset are set out under the heading "Risk Factors" in the company's Annual Information Form dated March 28, 2019.*

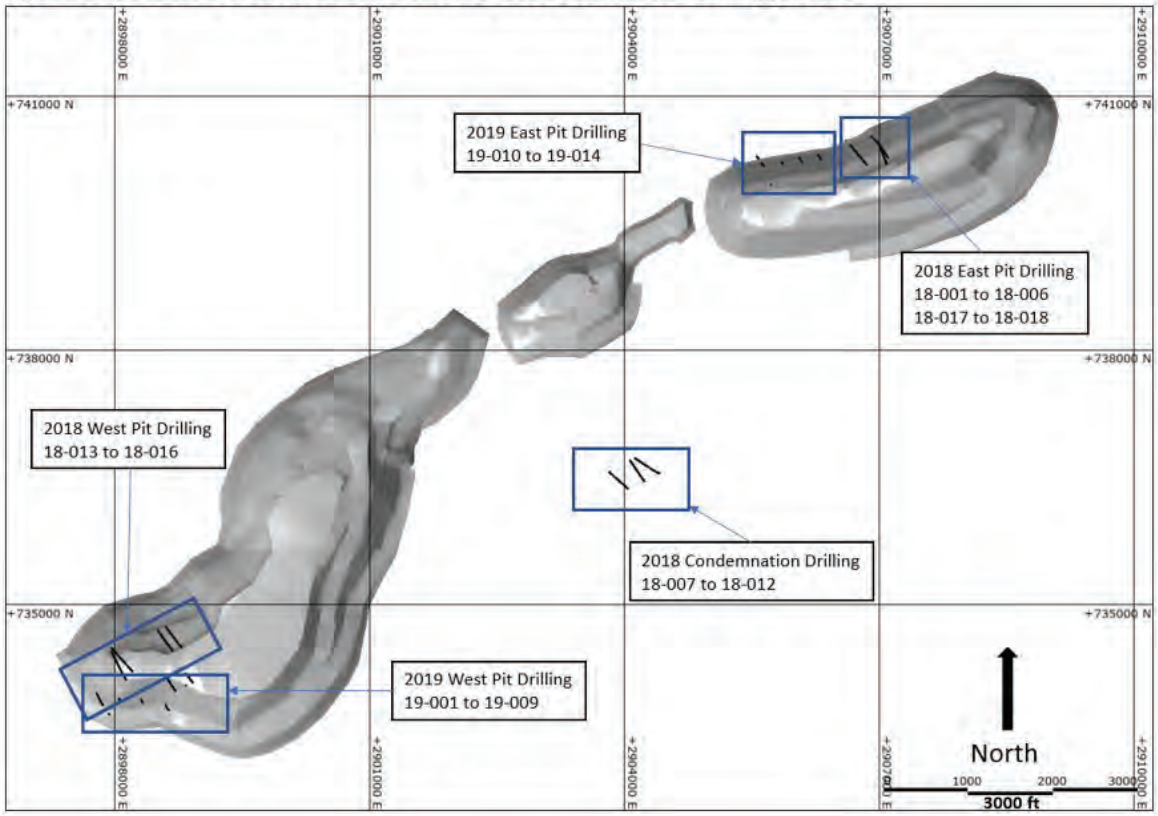
Table 4. Resource metal prices from 2018 and 2019

All Metal Prices In US Dollars	Copper per lb	Nickel per lb	Platinum per oz	Palladium per oz	Gold per oz	Cobalt per lb	Silver per oz
2018	3.30	8.50	1286	734	1263	13.28	19.06
2019	3.34	6.37	1023	1216	1465	33.14	18.62

Drill hole locations

Drill hole locations from the 2018 and 2019 drilling program in the east and west pit, are shown in Figure 1. Table 5 contains a summary of all 2018 and 2019 drilling assay results. Table 6 contains the drill hole locations.

Figure 1. Location of drill holes from the 2018 and 2019 drilling program



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POLYMET MINING

Investor Presentation

Minnesota Commitment | Global Opportunity

November 2021

Cautionary Statements

The reserve and resource estimates included in this presentation were prepared in accordance with National Instrument 43-101 – Standards of Disclosure for Mineral Projects (“NI43-101) and the Canadian Institute of Mining, Metallurgy and Petroleum Standards on Mineral Resources and Reserves: Definitions and Guidelines.

Readers are referred to the technical report prepared under NI 43-101 for PolyMet entitled “NorthMet Project – Form NI 43-101 F1 Technical Report” dated March 26, 2018 (“2018 Technical Report”) as filed under the Company’s SEDAR and EDGAR profiles.

Proven & Probable Reserves are from Table 1 of November 19, 2019 PolyMet News Release. Measured, Indicated, Measured & Indicated, inclusive of Mineral Reserves, and Inferred resources are from Table 3 of that same news release. Mineral resources are not mineral reserves and do not have demonstrated economic viability. There is no certainty that all or any part of the mineral resources estimated will be converted into mineral reserves.

A copper price of $2.93 per pound, a nickel price of $6.50 per pound, a cobalt price of $13.28 per pound, a palladium price of $734 per ounce, a platinum price of $1,286 per ounce, a gold price of $1,263 per ounce and a silver price of $19.06 per ounce was used to estimate mineral reserves at the NorthMet Project.

A copper price of $3.30 per pound, a nickel price of $8.50 per pound, a cobalt price of $13.28 per pound, a palladium price of $734 per ounce, a platinum price of $1,286 per ounce, a gold price of $1,263 per ounce and a silver price of $19.06 per ounce was used to estimate mineral resources at the NorthMet Project.

Mineral reserves are estimated at an NSR cut-off of $7.98 per ton inside of the final pit design which includes the estimated plant operating costs (including rail handling costs), all G&A costs and the water treatment costs during pit operation.

According to NI 43-101 definitions, a PEA implies a study that does or does not include an economic analysis of the potential viability of all mineral resources. NI 43-101 also states that an issuer may disclose the results of a preliminary assessment that includes or is based on inferred mineralized materials. For greater certainty, the pursuit of the expansion scenarios referred to herein would be subject to additional engineering and environmental review and permitting. The inferred mineral resources included in these expansion scenarios would have to be successfully converted to Measured and Indicated before any prefeasibility studies could commence. For greater certainty, the PEAs for these two upside cases are preliminary in nature, include inferred mineral resources that are considered too speculative geologically to have the economic considerations applied to them that would enable them to be categorized as mineral reserves, and there is no certainty that the results of these preliminary economic assessments will be realized. Mineral resources that are not mineral reserves do not have demonstrated economic viability and there is no certainty that mineral resources will become mineral reserves.

For a description of the key assumptions, parameters and methods used to estimate mineral reserves and resources, as well as data verification procedures and a general discussion of the extent to which the estimates of scientific and technical information may be affected by any known environmental, permitting, legal title, taxation, sociopolitical, marketing or other relevant factors, please see the: “2018 Technical Report”.

The scientific and technical information contained in this presentation has been reviewed and approved by: Zachary Black, SME-RM, Hard Rock Consulting, Jennifer Brown, P.G., Hard Rock Consulting; Nicholas Dempers, Pr.Eng., SAIMM, Senet; Thomas Drielick, P.E. M3 Engineering; Art Ibrado, P.E. M3 Engineering; Erin Patterson, P.E., M3 Engineering; Thomas Radue, P.E., Barr Engineering Co.; Jeff S. Ubl, P.E., Barr Engineering Co.; and, Herbert Welhener, SME registered member, Independent Mining Consultants; who are all Independent Qualified Persons within the meaning of National Instrument 43-101 (“NI 43-101”).

Cautionary Statements

This presentation contains certain forward-looking statements and forward-looking information concerning anticipated developments in the operations of PolyMet Mining Corp. (“PolyMet”) in the future, including, without limitation, the statements regarding the ongoing development of PolyMet’s NorthMet Project and the results of the feasibility study on the permitted base case for the NorthMet Project as well as results of the preliminary economic assessments (“PEA”) on two expansion cases for the NorthMet Project. Forward-looking statements are frequently, but not always, identified by words such as “expects,” “anticipates,” “believes,” “intends,” “estimates,” “potential,” “possible,” “projects,” “plans,” and similar expressions, or statements that events, conditions or results “will,” “may,” “could,” or “should” occur or be achieved or their negatives or other comparable words. These forward-looking statements may include statements regarding our beliefs related to the expected project development timelines, exploration results and budgets, reserve estimates, mineral resource estimates, continued relationships with current strategic partners, work programs, estimated capital and operating costs and expenditures, actions by government authorities, including changes in government regulation, the market price of natural resources, estimated production rates, ability to receive and timing of environmental and operating permits, estimated construction costs, job creation and other economic benefits, or other statements that are not a statement of fact. In addition, and for greater certainty, the results of (i) the feasibility study on the permitted base case of the NorthMet Project, and (ii) the PEAs on the two expansion cases for the NorthMet Project, constitute forward-looking information, and include future estimates of internal rates of return, net present value, future production, estimates of cash cost, proposed mining plans and methods, mine life estimates, cash flow forecasts, metal recoveries, and estimates of capital and operating costs.

Forward-looking statements and forward-looking information address future events and conditions and therefore involve inherent known and unknown risks and uncertainties. These risks, uncertainties and other factors include, but are not limited to, adverse general economic conditions, operating hazards, inherent uncertainties in interpreting engineering and geologic data, fluctuations in commodity prices and prices for operational services, government regulation and foreign political risks, fluctuations in the exchange rate between Canadian and US dollars and other currencies, as well as other risks commonly associated with the mining industry. Actual results may differ materially from those in the forward-looking statements and forward-looking information due to risks facing PolyMet or due to actual facts differing from the assumptions underlying its predictions.

In connection with the forward-looking information contained in this presentation, PolyMet has made numerous assumptions, regarding, among other things, that the geological, metallurgical, engineering, financial and economic advice that PolyMet has received is reliable and is based upon practices and methodologies which are consistent with industry standards, that PolyMet will be able to obtain additional financing on satisfactory terms to fund the development and construction of the NorthMet Project and that the market prices for relevant commodities remain at levels that justify construction and/or operation of the NorthMet Project. While PolyMet considers these assumptions to be reasonable, these assumptions are inherently subject to significant uncertainties and contingencies.

PolyMet’s forward-looking statements are based on the beliefs, expectations and opinions of management on the date the statements are made, and PolyMet does not assume any obligation to update forward-looking statements if circumstances or management’s beliefs, expectations and opinions should change.

Specific reference is made to risk factors and other considerations underlying forward-looking statements discussed in PolyMet’s most recent Annual Report on Form 40-F for the fiscal year ended December 31, 2020, and in our other filings with Canadian securities authorities and the U.S. Securities and Exchange Commission. PolyMet’s financial statements have been prepared in accordance with International Financial Reporting Standards (“IFRS”).

All amounts are in U.S. funds.

Executive Summary

First mover along world-class Duluth Complex

Permitted for construction and operations (subject to litigation)

Global decarbonization efforts create strong demand for our products

Low-cost, long-life operation with attractive economics

Significant expansion and exploration opportunities

Glencore is our principal partner, a premier global mining company


PolyMet
MINING
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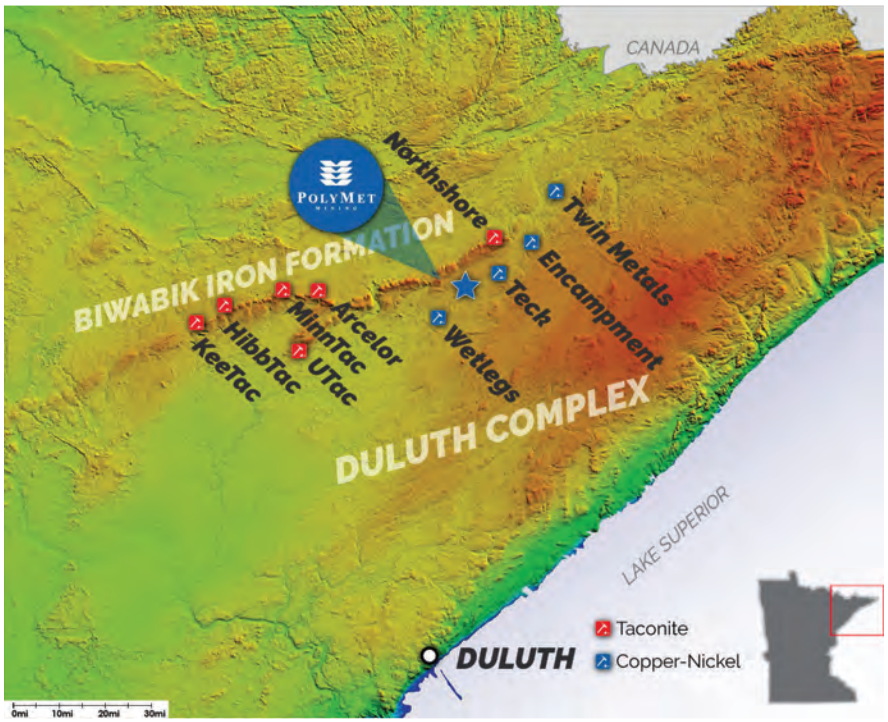
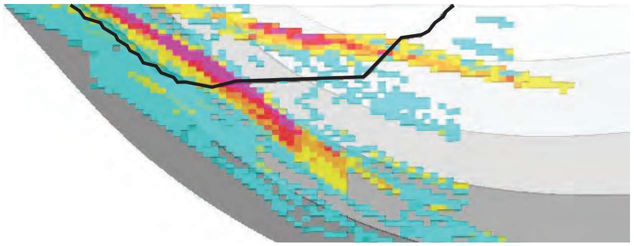
Ideally located



World-class copper, nickel, PGM resources located in the Duluth Complex

Attractive Assets



NorthMet Deposit [1]

- Proven & Probable Reserve: 290Mt
- Measured & Indicated Resource: 795Mt
- Inferred Resource: 458Mt
- Revenue distribution [2]:
  Cu 61%, Ni 18%, PGM 18%, Co 2%, Au 1%

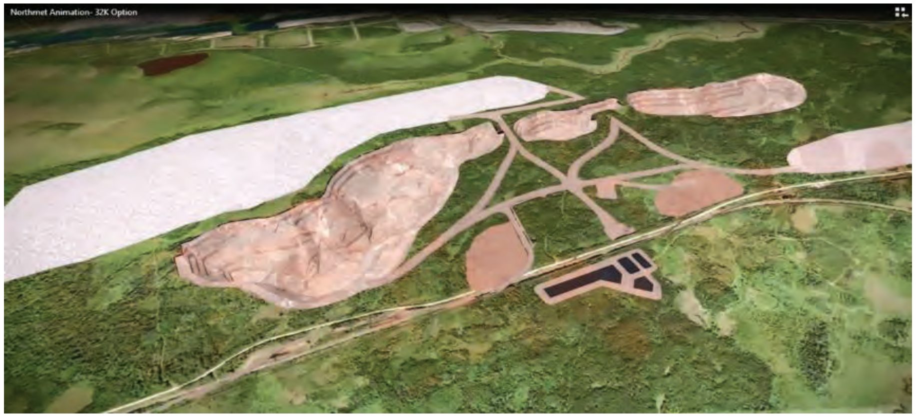
Plant Site

- Previously processed 100k tpd taconite
- Primary crusher, ore transfer facilities and buildings will be refurbished
- Installed industrial electric power
- Tailings basin with over 300Mt capacity

Associated Infrastructure

- Rail connecting mine and plant
- Onsite access to class one rail carrier
- Plentiful water sources
- Established supplier network

Phased Development



- Develop 225M ton ore body
- LOM strip ratio 1.6
- Refurbish existing plant facilities
- Install new 40' SAG, ball and flotation circuit
- Upgrade existing tailings basin
- Produce copper and nickel concentrates

Phase II – Hydromet

- Construct 1,000 tpd hydromet facility
- Finance with operating cash flows
- Improve metal recoveries
- Value-added products
  - Nickel-cobalt hydroxide
  - PGM precipitate
  - Higher copper concentrate quality

Source: "2018 Technical Report" as filed under the Company's SEDAR and EDGAR profile. Additional resource and reserve information, including grades is included on slide 17.

POLYMET MINING

Leverage Existing Plant

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Responsible Mining

ENVIRONMENTAL STEWARDSHIP

Design safeguards water, air and other natural resources

Repurposes idled plant and addresses legacy water quality

Among highest EPA rating of EIS of any mine in U.S.

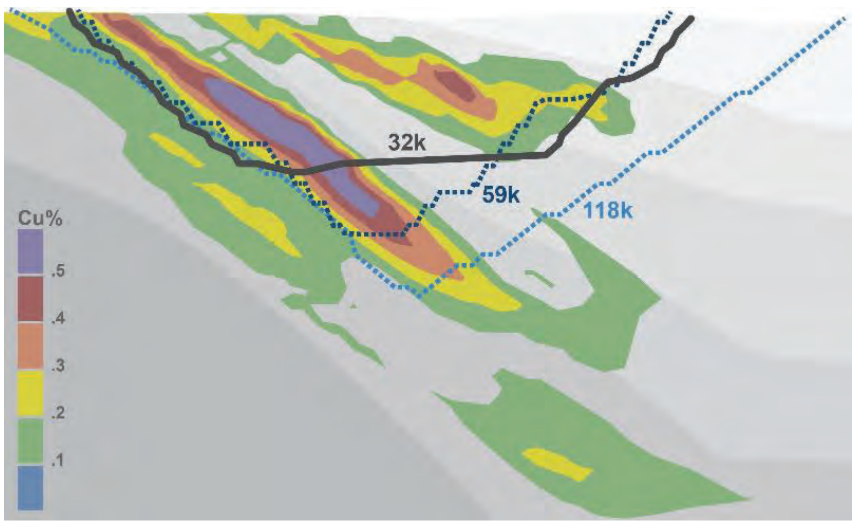
COMMUNITY COMMITTMENT

Vested partner in Iron Range communities

Aligned company and community values

Strong support across business, labor and community spectrum

NorthMet Upside Production Scenarios



Phase I	Permit	Opportunity[1]	Expansion[1]
Mine life	20 yrs	15 yrs	19 yrs
Mill feed[2]	225m tons	293m tons	730m tons
Processing rate	32k tpd	59k tpd	118k tpd
Annual CuEq prod.[3]	91m lbs	155m lbs	276m lbs
Cash costs[4]	106 c/lb	72 c/lb	85 c/lb
Project capital	$945M	$1.1B	$1.6B
NPV_7 / IRR	$173M / 10%	$751M / 18%	$1.7B / 22%
Phase I & II			
Annual CuEq prod.[3]	106m lbs	180m lbs	310m lbs
Cash costs[4]	59 c/lb	23 c/lb	39 c/lb
Hydromet capital	$259M	$259M	$259M
NPV_7 / IRR	$271M / 10%	$963M / 19%	$2.2B / 24%

Principal Shareholder – Glencore

Experts in mine and processing operations	Long-term source for Canadian smelters
Industry-wide support network	Geographically positioned for trading
Global scale and marketing capabilities	Offtake agreement

Strong Financial Partner – Investments totaling more than $400M


PolyMet
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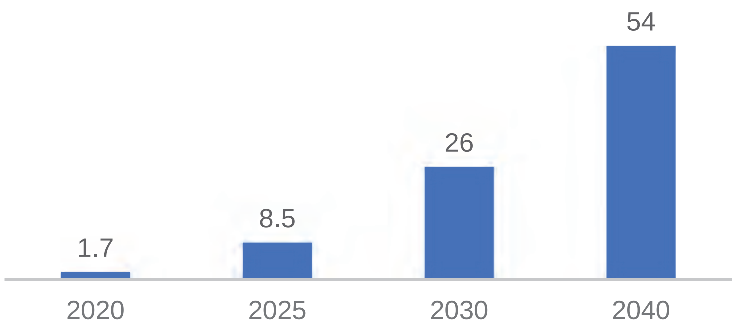
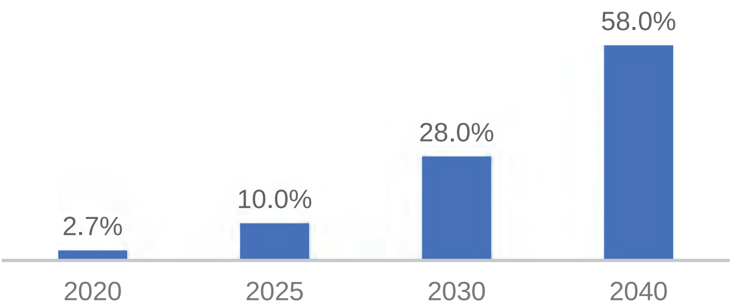
Global Growth In Electric Vehicles



Electric Vehicle Share of New Car Sales



Global EV Fleet

2020
8.5M

2030
116M

Global Vehicle Fleet

2020
1.2B

2030
1.4B

Source: Bloomberg New Energy Finance estimates

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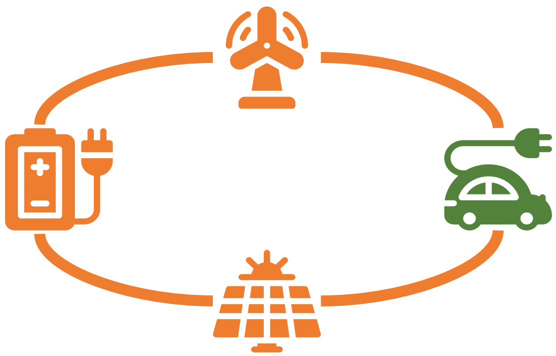
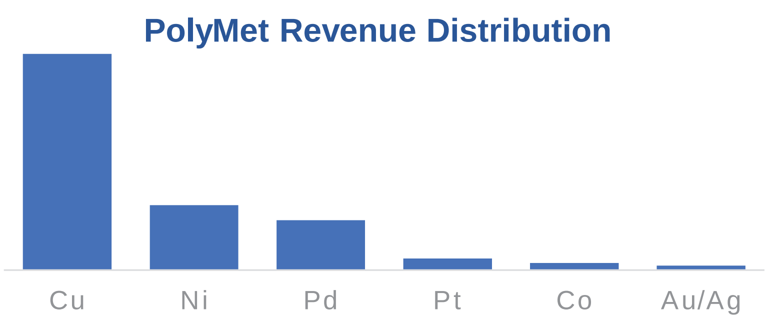
Clean & Renewable Energy





Meeting The EV Target Of 30 Million

- Generation and grid infrastructure
- Grid storage
- Charging infrastructure
- Non-ICE vehicles

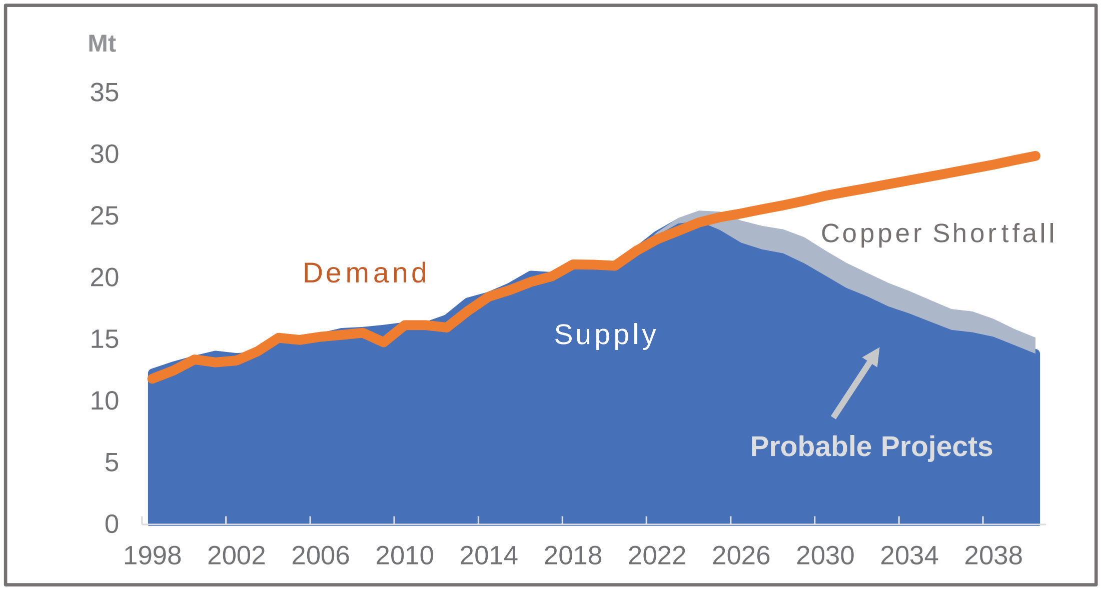
New metal requirement for 30 million electric vehicles [2]

- 4.1Mt copper (18% of global supply)
- 1.1Mt nickel (56% of global supply)
- 314Kt cobalt (314% of global supply)

1 The Electric Vehicles Initiative is a multi-government policy forum comprising Canada, China, Finland, France, Germany, India, Japan, Korea, Mexico, Netherlands, Norway, Portugal, South Africa, Sweden, UK and USA.
2 CRU International

Bright Copper Outlook

Estimated Global Copper Supply/Demand Imbalance



Demand projected to exceed global production in 2023 onward

Urbanization, electric vehicle growth and decarbonization efforts drive demand

Supply gap due to reserve depletion, falling head grades and long lead times

Our commodity mix is essential to building zero-carbon technologies

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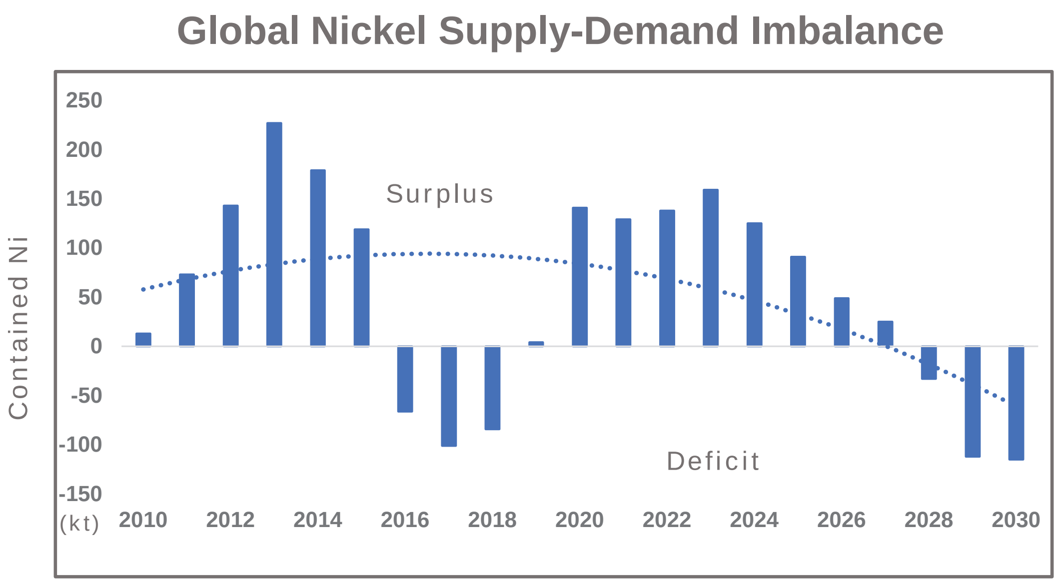
Shortfall in Long-Term Nickel Supply



Source: Wood Mackenzie, Global Nickel Long-Term Outlook 2020

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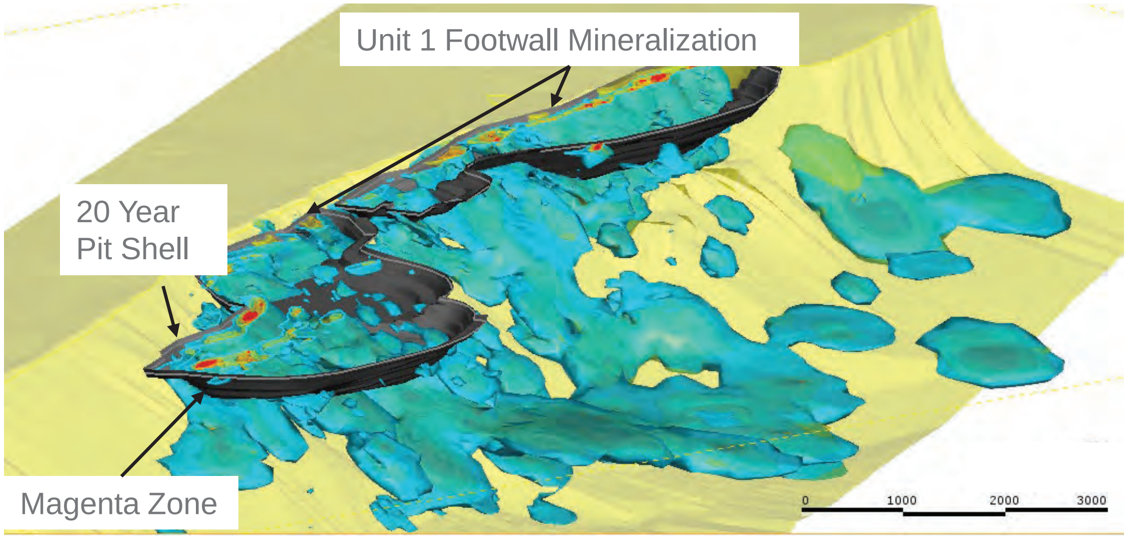
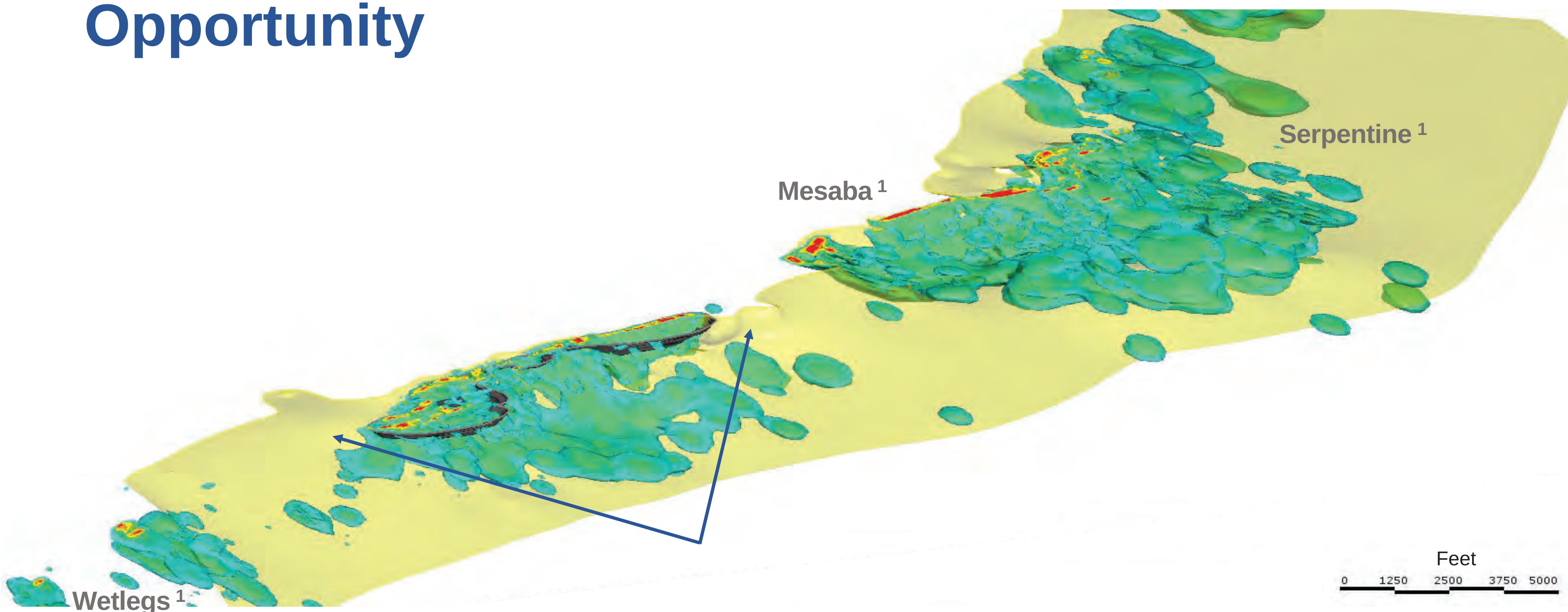
Abundant Resource



Mineral Resource [1,2]	Short Tons (Millions)	Copper (%)	Nickel (%)	Palladium (ppb)	Platinum (ppb)	Gold (ppb)	Cobalt (ppm)
Measured	351	0.240	0.073	221	64	33	71
Indicated	444	0.230	0.069	207	61	30	68
Measured & Indicated	795	0.234	0.071	214	62	31	69
Inferred	458	0.236	0.067	225	63	32	56
Proven & Probable [3]	290	0.288	0.083	264	75	39	73.95

Regional Exploration Opportunity



1 Unclassified Mineral Resources: Non NorthMet mineralization solids based on public file information from MN Natural Resources Research Institute TR 2003/21.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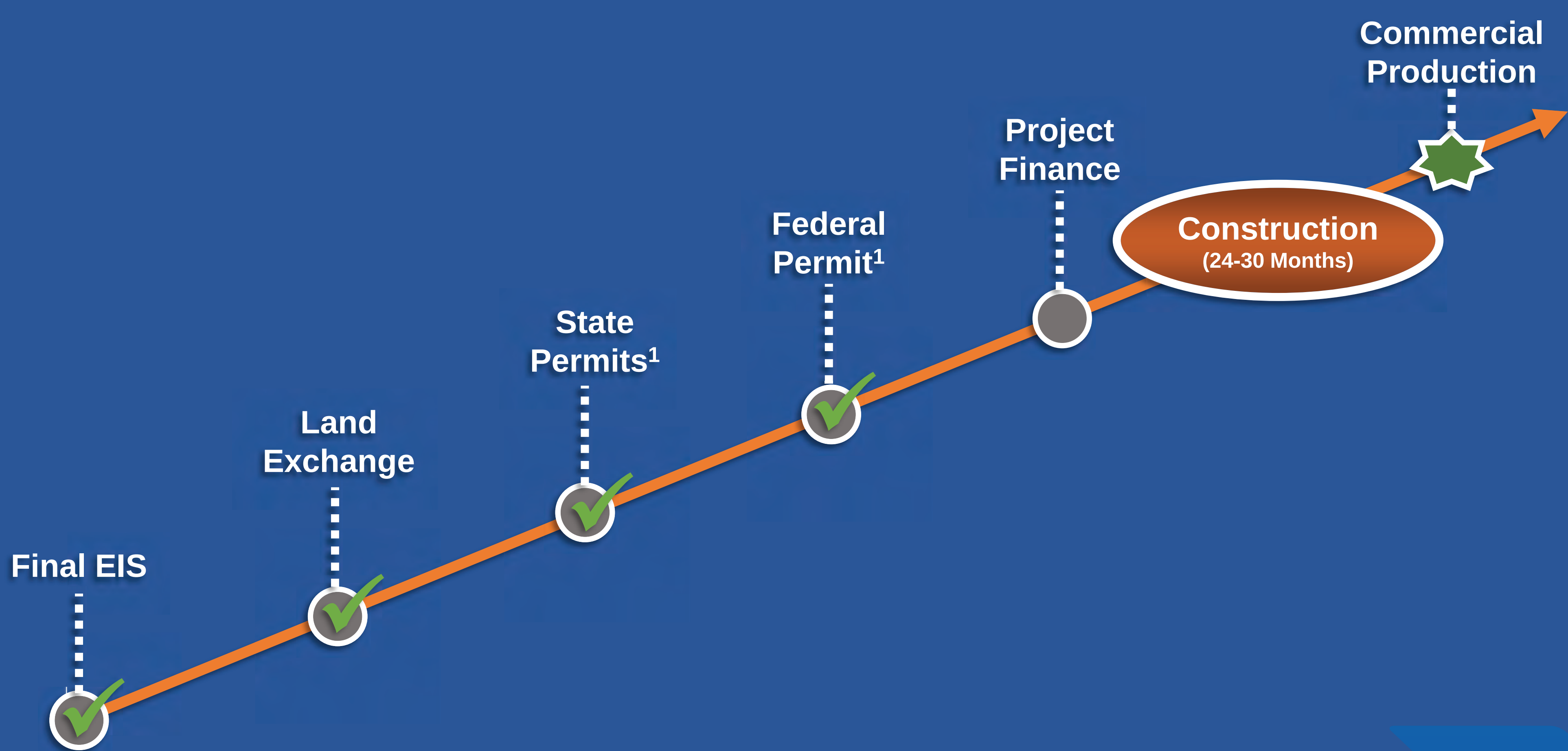
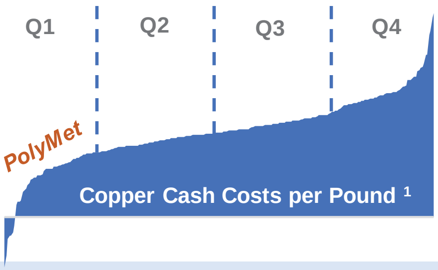


[1]Subject to litigation

Project Highlights



Attractive Economics

- Robust demand for products
- Timed to meet supply deficit
- Long life, low cost asset

Expansion Opportunity

- Existing infrastructure supports higher volumes
- Mine plan represents 1/3rd of existing M&I resource
- 458M tons inferred material

Exploration Potential

- High grade, near mine, legacy intercepts
- Untested strike to NE and SW of ore body

First Mover in Duluth Complex

- All key state and federal permits (subj. to litigation)
- +6B tons of mineralized material in complex [2]

Glencore Strategic Alliance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POLYMET
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Executive Leadership

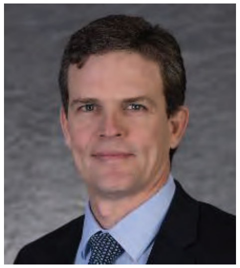
Jon Cherry
President & CEO

Leader in new mine development and environmental policy

Executive roles in 20-year Rio Tinto career

Permitted and developed Eagle Mine

+25 years experience



Pat Keenan
Chief Financial Officer

Extensive finance and executive leadership with major global mining operations

Finance executive at Rio Tinto and Newmont

+25 years experience

Extensive development and construction experience at major mining projects globally

Executive at Arizona Mining, Canadian Natural Resources Ltd, Diavik Diamond Mines

+25 years experience

Andrew Ware
Chief Geologist

Authority on the Duluth Complex and Mid-Continent Rift

Principal geologist with Rio Tinto developing projects in SE Asia and the Americas

+25 years experience

Shares Outstanding (TSX: POM, NYSE American: PLM)	100.9 million
Market Capitalization	US$307.7 million
Cash	US$7.5 million
Stock Price (Sept. 30, 2021)	US$3.05
Stock Price 52-week range (reverse-split adjusted)	US$2.69 - $5.41

Financial information as of September 30, 2021