Nutrient Reductions as Co-Benefit of Acid Mine Drainage (AMD) Treatment: Quantifying Nutrient Load Reductions for Restored Stream Segments in AMD-impacted Watersheds

Benjamin Hayes[1], Weixing Zhu[2], R. John Dawes[3], Charles A. Cravotta[4], Robert Hughes[5], Gregory Moyer[6], Travis Tasker[7], James Shallenberger[8], Michael A. Hewitt[9] and John Dawes[10]

[1]Bucknell University, [2]SUNY Binghamton, [3]Consultant, Foundation for Pennsylvania Watersheds, [4]Geochemical Consulting, [5]Eastern Pennsylvania Coalition for Abandoned Mine Reclamation, [6]Mansfield University PA, [7]Saint Francis University, [8] Susquehanna River Basin Commission, [9]Eastern Pennsylvania Coalition for Abandoned Mine Reclamation, and [10]The Chesapeake Commons

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The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

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Contributors

Robert Hughes (Eastern Pennsylvania Coalition for Abandoned Mine Reclamation): Analysis, Investigation, Writing - original draft; **Gregory Moyer** (Mansfield University of PA): Analysis, Investigation, Writing - original draft; **Travis Tasker** (Saint Francis University): Analysis, Investigation, Writing - original draft; **Charles A. Cravotta III** (Cravotta Geochemical Consulting): Analysis, Investigation, Writing - original draft; **James Shallenberger** (Susquehanna River Basin Commission): Writing - original draft; **Benjamin R. Hayes*** **(**Bucknell University): Writing - review and editing; **Weixing Zhu*** (SUNY Binghamton): Writing - review and editing; **R. John Dawes*** (The Chesapeake Commons); **Michael A. Hewitt** (Eastern Pennsylvania Coalition for Abandoned Mine Reclamation): Analysis, Investigation; **John Dawes** (Consultant, Foundation for Pennsylvania Watersheds): Writing - review and editing. **** denotes STAC member***

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STAC Administrative Support Provided by:
Chesapeake Research Consortium, Inc.
645 Contees Wharf Road
Edgewater, MD 21037
Telephone: 410-798-1283; 301-261-4500
Fax: 410-798-0816
http://www.chesapeake.org

Contents

Executive Summary......................................*4*

Background: AMD's Role in Chesapeake Bay Nutrient Dynamics......................................*6*

The AMD-Nutrient Paradox......................................**6**

Data and Management Context......................................**6**

Synthesis of Technical Review Responses......................................*7*

Question 1. What is the rate of nutrient and sediment assimilation in a healthy watershed?......................................**7**

Question 2. How can nutrient load reductions as a co-benefit of AMD treatment and watershed restoration be quantified?......................................**7**

Question 3: Which social science considerations for working with landowners who have contaminated potable water sources and impaired local streams should be considered?......................................**9**

Question 4: Can AMD cause a nutrient-situation?......................................**9**

Question 5: What data needs to be collected and at what stages?......................................**10**

Question 6: Literature review of the benefits of resource recovery: Can a material be used outside of the plant for other means? If possible, should we be handling it differently?......................................**10**

Characterizing the Fate of Nutrients in AMD Streams......................................*11*

How AMD Alters Nutrient Spiraling......................................**11**

Rates of Nutrients and Sediment Assimilation in Healthy Streams......................................*13*

Quantifying Nutrient Load Reductions as Co-Benefits of AMD Treatment and Watershed Restoration......................................*14*

Assessing the Extent of Stream Miles Impacted by AMD......................................**17**

Key Geographic Patterns......................................**18**

Tracking the Restoration of AMD-Impacted Stream Miles: Progress and Ongoing Efforts......................................*19*

Case Study Opportunities......................................**20**

Social Science Considerations for Engaging with Landowners......................................*22*

Evaluating Incidental Nutrient Additions from AMD Treatment Systems......................................*24*

Identifying Data Collection Needs and Timing for Planned AMD Restoration Projects......................................*27*

Resource Recovery Benefits: Potential Uses and Handling of Materials Beyond Treatment Facilities......................................*29*

Recommendations......................................*32*

Enhanced Monitoring and Data Collection......................................**32**

Modeling and Decision Support Tools Geochemical Modeling......................................**32**

Strategic Funding and Innovation......................................**32**

Policy and Collaboration......................................**32**

Conclusion......................................*33*

References......................................*34*

APPENDIX A: STAC Technical Review Request......................................*39*

APPENDIX B: Acronym List and Glossary of Terms......................................*40*

APPENDIX C: List of Figures......................................*43*

APPENDIX D: List of Tables......................................*44*

Executive Summary

Abandoned mine drainage (AMD) has long-lasting impacts on water quality and stream health in the Chesapeake Bay Watershed (Figure 1). Nutrient reductions have been proposed as a co-benefit of AMD treatment and watershed restoration. Yet, nutrient load reductions have not been sufficiently quantified for restored stream segments and in AMD-impacted watersheds. To address such knowledge gaps, the STAC team solicited input from AMD experts working within the Chesapeake watershed, specifically asking them to respond to a set of six technical review questions (hereafter referred to as "Q1" through "Q6" and summarized in Sections 3-9). Collectively, their responses point to information and data gaps, as well as provide a framework that could lead to improvements in the Bay Watershed Model accounting for possible nutrient reductions that are attributable to AMD remediation.

All healthy watersheds assimilate nitrogen (N) and phosphorus (P) in lands, riparian zones/floodplains, and in streams and rivers, through biological activities commonly described in the "nutrient spiraling" model (Q1). AMD-impaired streams have limited biological activities but iron and aluminum hydroxide adsorption removes phosphorus from the water column; therefore, quantifying the net difference in nutrient assimilation between healthy and AMD-impaired streams is crucial. Extensive abandoned mined land (AML), if restored, can accommodate the application of manure N and P from the same or nearby watersheds for plant growth, but this topic was not explicitly stated and addressed by the review panelists. Extensive AMD waterway impairment exists in parts of the Chesapeake Bay watershed. In Pennsylvania, approximately 5,500 linear stream miles were impaired due to AMD but less than 5% had been restored (Shull 2024). Therefore, AMD and AML restoration should be a priority for the healthy Chesapeake Bay Watershed. In terms of nutrient load reductions as a co-benefit of AMD treatment (Q2), several panelists cautioned that AMD treatment could curtail P adsorption by metallic hydroxides, but a healthy stream segment should increase N removal through biological uptake and denitrification. Quantifying nutrient load reductions can be accomplished by measuring total nitrogen (TN) and total phosphorus (TP) while sampling for typical AMD parameters, with flow measurements also taken to calculate loading from the measured concentrations. Several reviewers stated that untreated AMD, enriched in iron and aluminum, diminishes phosphorus (bio-) availability through geochemical sorption. The reviewers indicated AMD treatment: (i) would effectively curtail interference with P by metals; and, (ii) could result in re-release (desorption) of P into the water column by shifting the geochemical regime (Q4). The consensus among reviewers was that data collection should span pre- and post-treatment (Q5). Most reviewers recommended grab samples collected with a frequency of at least quarterly, the need for samples that represent flow and seasonal variability, and multiple years sampling. Several reviewers discussed potential co-benefits of using AMD treatment residuals for P removal in Wastewater Treatment Plants (WWTPs), fish rearing facilities, and manure management (Q6).

Restoring streams in AMD-impacted watersheds is critically important for the Chesapeake Bay watershed and impacted states. Exploring nutrient reduction co-benefits and others, including social benefits to affected landowners (Q3) and Rare Earth Elements (REE) extraction (Q6), will help to achieve that goal.

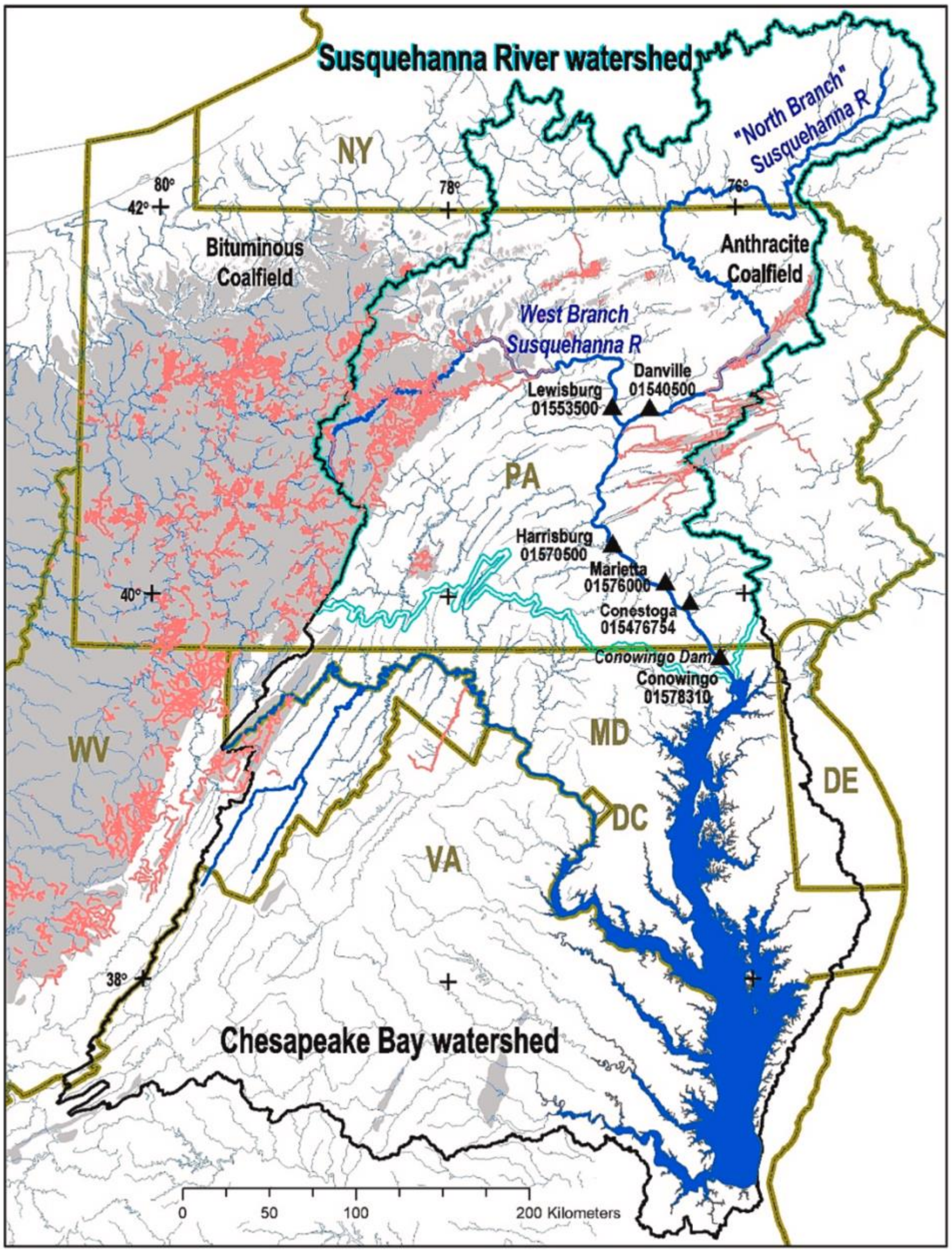

Figure 1. Map showing the distribution of streams impaired by acid mine drainage (AMD)* from legacy coal mines (orange-red) within the Chesapeake Bay Watershed, specifically, Pennsylvania, West Virginia, and Virginia. In the eastern area, anthracite coal mines discharge AMD to numerous tributaries of the Susquehanna River, whereas in the western area, bituminous coal mines discharge AMD to tributaries of the West Branch Susquehanna River. Selected U.S. Geological Survey (USGS) streamgage locations on the Susquehanna River (triangle symbol) considered in this paper are part of the Chesapeake Bay Program nontidal monitoring network (Mason et al., 2022). [From Cravotta and others (2024)].

Background: AMD's Role in Chesapeake Bay Nutrient Dynamics

Nutrient pollution is among the United States' most widespread, costly, and ecologically damaging environmental challenges. In the Chesapeake Bay watershed, it drives both the 2010 TMDL and thousands of miles of stream impairments. AMD compounds these impacts by disrupting aquatic life and altering nutrient cycling through two paradoxical mechanisms: (1) impairing biological uptake (lengthening nutrient spirals), while (2) sequestering phosphorus via geochemical reactions. This section examines AMD's dual role in watershed health.

The AMD-Nutrient Paradox

Water discharged from legacy mining features damages aquatic life through acidic conditions created when sulfur-bearing minerals react with oxygen and water. Minerals in undisturbed rock are stable, but mining activities (excavation, tunneling, blasting, de-watering) upset geologic stability, enabling sulfide minerals to react with air/water. This generates acids that leach toxic concentrations of aluminum, iron, and manganese. These reactions leach aluminum, iron, manganese, and other substances at concentrations toxic to aquatic organisms. Crucially, AMD alters key ecosystem functions governing nutrient transport:

- Disrupted Nutrient Spiraling**:** In healthy streams, nitrogen (N) and phosphorus (P) are repeatedly assimilated into biomass and released back into the water column, a process called "nutrient spiraling" that slows downstream nutrient transport. AMD-impaired streams exhibit diminished uptake, elongating spirals and potentially increasing N/P accumulation downstream (Ensign and Doyle 2006).
- Phosphate Sequestration: Paradoxically, AMD’s geochemistry (low pH, high metals) can reduce P bioavailability. Iron in AMD reacts with phosphate to form iron-hydroxyphosphate precipitates, while other P forms adsorb to organic matter or iron-rich colloids.

Data and Management Context

The CBP framework tracks land management practices through pollutant-reduction 'credits' in its Chesapeake Assessment Scenario Tool (CAST), used for planning and progress-tracking. While this system effectively tracks conventional practices, it currently lacks AMD-specific metrics. Understanding how AMD remediation affects nutrient loads requires:

1. Comparing pre/post-treatment conditions in streams (healthy, AMD-impaired, and restored); and
2. Leveraging Pennsylvania's comprehensive monitoring infrastructure:
    a. PADEP's eMapPA digital interface for spatially explicit water quality data;
    b. SRBC's publicly accessible tools including: the Mine Drainage Portal; Water Quality Portal; Continuous Instream Monitoring Program, and Water Quality and Biological Index; and
    c. USGS SPARROW models for watershed-scale nutrient loading.

These resources enable detailed analysis of AMD's dual outcomes: aquatic life restoration and potential phosphorus mobilization. Effective protocols must monitor both ecological recovery and geochemical changes.

Synthesis of Technical Review Responses

Question 1. What is the rate of nutrient (TN and TP) and sediment assimilation in a healthy watershed?

Two reviewers opted not to address Q1; two other reviewers invoked the tenet that biological processes rely on nitrogen (N) and phosphorus (P) for metabolic functions; ipso facto, healthy watersheds exhibit intrinsically higher rates of nutrient assimilation relative to AMD-impaired waterways. While it is well-known that severe AMD impairment depletes aquatic taxa overall, it is anticipated that certain aquatic life may persist or even thrive in such settings; therefore, estimating the net difference in nutrient assimilation between healthy and AMD-impaired streams is crucial.

One reviewer referenced the Chesapeake the Program's (CBP) Approved Expert Panel Report(s) on Stream Restoration practices as an information source(s) for nutrient and sediment assimilation rates in healthy/restored waterways.

Another reviewer invoked the concept of "nutrient spiraling;" i.e., a term that describes the cycling of nutrients as they are assimilated from the water column into benthic biomass, temporarily retained, and mineralized back into the water column (Newbold et al., 1982). Nutrient spiraling rates are influenced by a variety of abiotic (e.g., channel size and the surface area-to-channel volume ratio) and biotic factors (e.g., bacteria, fungi, algae, and macrophyte abundance; Gomez and Harvey 2014). A meta-analysis by Newcomer Johnson et al. (2016) compared nutrient spiraling metrics for restored, degraded and reference (healthy) streams; therefore, metrics from their reference streams can be used as estimates for nutrient assimilation rates in healthy watersheds.

Question 2. How can nutrient load reductions as a co-benefit of AMD treatment and watershed restoration be quantified?

The consensus among reviewers was that quantifying nutrient load dynamics as a consequence of AMD remediation warrants the following general data collection framework:

- Characterize flow and water quality conditions in a physical project setting that is defined by up, within, and downstream locations of prominent/all relevant sources of nutrient loads and AMD inputs;
- Collect data set measurements that capture sufficient (e.g., multiple years before and after) pre- and post-AMD remediation to reflect magnitude ranges; and
- Conduct an evaluation that compares nutrient load and/or assimilation rates before and after treatment to evaluate net differences.

It was noteworthy that multiple reviewers emphasized the expectation that AMD treatment could result in higher phosphorus loads due to geochemical interaction (phosphate sorption to iron oxide solids) that occurs where low pH AMD mixes with phosphate-containing waters. The reviewers cautioned that where pH becomes sufficiently elevated (~ >8), then phosphate desorption from accumulated iron oxide may increase downstream P loads.

Building from the nutrient spiral concept invoked in response to Question 1, there are approaches to estimate whole stream metabolic rates. Stream metabolism indicates total biotic activity and affects water quality via basic ecosystem properties, such as nutrient uptake rates, carbon flux into the food web, and trophic status (heterotrophic/"consumer" and autotrophic/"producer" state

(Dodds, 2007). Diel trends in dissolved O_2 have been used to measure whole-system metabolism since Odum (1956) introduced the method. Gross primary production (GPP), community respiration (R), and aeration rates (k) drive changes in O_2 concentration over time. Stream metabolic rates are estimated by measuring how each factor changes O_2 over distance or time. Net ecosystem production (NEP) is the sum of GPP and R, and NEP, GPP, and R, are fundamental indicators of organism-mediated carbon gain or loss in an ecosystem. As a potential converging "line-of-evidence," estimating NEP in addition to estimating the terms in a nutrient budget model would add insight about the mechanisms of nutrient dynamics.

Question 2A. How many stream miles are impacted by AMD?

All of the reviewers who responded to this question did so through a Pennsylvania-only perspective; while Pennsylvania is likely to dominate the AMD impairment category, it is not the only Bay jurisdiction facing abandoned (or acid) mine discharge, as may be inferred from the coalfields map below (Figure 2).

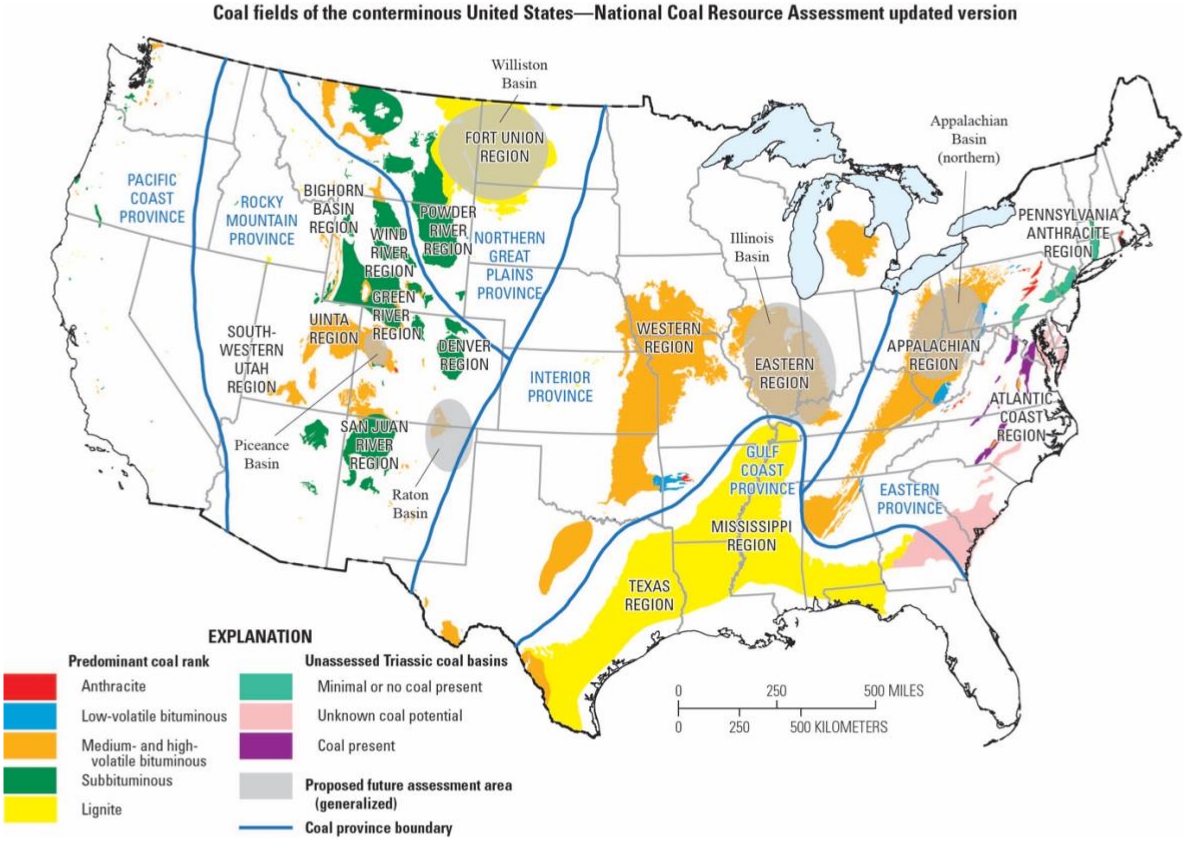
Coal fields of the conterminous United States—National Coal Resource Assessment updated version

Figure 2. A map of the various coal fields of the conterminous United States. Source: US Geological Survey, 2017.

To answer the question, "How many stream miles are impacted by AMD?" requires analysis of the federal Clean Water Act Integrated Reports (IR) for 305(b)/assessed waters and 303(d)/list of waters with total maximum daily loads (TMDLs) because current pollution control technologies cannot meet water quality standards, as developed for each of the Bay jurisdictions. The compilation of synchronous IR information, spatially extracted to the Bay watershed, will answer the question.

Schull (2024) reports that within Pennsylvania, 5,500 linear stream miles are impaired due to AMD. The Eastern Pennsylvania Coalition for Abandoned Mine Reclamation (EPCAMR) estimates that 1,900 linear stream miles within the Chesapeake Bay watershed are impaired due to AMD (Hughes, 2025). According to the 2024 Pennsylvania IR, most of these 1,900 miles are in the bituminous region (1,272), with a smaller amount in the anthracite region (597 miles). Although AMD impaired streams in Pennsylvania, West Virginia, and Virginia are displayed on Figure 1, the total length of those segments has not been computed for this question. It is imperative to note that the Bay region extends this far west.

Question 2B. How many miles of stream have been/are being restored?

A similar approach to that used to answer Question 2a—e.g., compilation of IR for 305(b) and 303(d) reporting as developed for each of the Bay jurisdictions—will answer the question of how many stream miles have been/are being restored. The compilation of synchronous IR information, spatially extracted to the Bay watershed and compared across discrete points in time, will answer the question.

A comparison of Pennsylvania's share of the Bay watershed from 2004-2022 indicated that approximately 178 linear stream miles of former AMD impairments were restored (Shull, 2024).

Question 3: Which social science considerations for working with landowners who have contaminated potable water sources and impaired local streams should be considered?

Several reviewers did not address Question 3; two reviewers alluded to rational choice theory, i.e., the economic concept that individuals are expected to select outcomes that maximize their own benefit and satisfaction. EPCAMR's research identifies eight complementary social science lenses for AMD remediation engagement listed in this report on page 25. Through rational choice theory, it is important to consider, in dialogue with stakeholders, the importance of cleaning up their own potable water sources and streams that are impacted by AMD to improve water resource health and safety, recreation, property values, and downstream benefits that such projects can provide to neighbors and communities (e.g., social welfare, writ large).

Question 4: Can acid mine drainage treatment cause a nutrient-situation? (incidental)

Several reviewers stated that untreated AMD, where enriched in iron and/or aluminum, diminishes phosphorus (bio-) availability through geochemical sorption to iron and aluminum hydroxide solids. The reviewers indicated treating such AMD: (i) could effectively curtail with the attenuation of P by iron oxides at low pH; and (ii) could result in re-release (desorption) of P into the water column by increasing the pH and shifting the geochemical regime. It is worth noting that in Pennsylvania, AMD settings tend to exhibit low-level nutrient (N and P) status.

One reviewer stated that certain types of passive AMD treatment utilize compost media that can release nutrients (and carbon). This reviewer also observed that waters in various legacy mine features, especially below-ground mine pools and flooded surface pits, behave as conduits for coalescing nutrient load sources from the landscape such as agriculture waste, runoff from manure/fertilizer/biosolids applications, atmospheric deposition, and leaky/failing septic and sewage infrastructure. Under such circumstances, AMD may become nutrient-enriched.

A reviewer stressed the view that AMD treatment can cause a positive nutrient situation downstream that is not only incidental, but purposeful and planned. Specifically, if nutrient limitations impair productivity in AMD-impaired streams, AMD treatment could help to reverse this limitation.

Question 5: What data needs to be collected (grab sample or continuous) and at what stages of these projects that are currently being planned?

Several reviewers emphasized study designs to address particular questions/site-specific considerations; that is, if designing for nutrient budget, data collection must include relevant sources.

The consensus among reviewers was that data collection should span pre- and post-treatment phases and that at least one full year of data collection is warranted pre- and post-treatment (a minimum of two years total). Owing to inter-annual variability of precipitation and temperature conditions, more than a single year of pre- and post-treatment data collection is sensible to account for the natural range of variation that is inherent in complex, open settings.

Most reviewers recommended grab samples collected with a frequency of at least quarterly. Most reviewers also stressed the need for samples that represent flow and seasonal variability, i.e., a recommendation that infers frequency greater than quarterly. Several reviewers favored continuous data collection for pH, dissolved oxygen (DO), temperature, specific conductance, and discharge.

All reviewers recommended analyzing some combination of metals (especially aluminum, iron, and manganese), nutrients (especially nitrate, nitrite, phosphate, total nitrogen, and total phosphorus), acidity, alkalinity, and sulfate.

Reviewers were unanimous in recommending discharge measurements be obtained in conjunction with all water quality samples. The discharge data are needed to compute loads of nutrients and other constituents.

Question 6: Literature review of the benefits of resource recovery: Can a material be used outside of the plant for other means? If possible, should we be handling it differently?

a. Evaluate the benefit of chemical reactions like absorbance (USGS work in fisheries; Hedin Environmental funded by DEP to look at mixing AMD sludge with manure to stabilize phosphorus).
b. Evaluate certain treatment designs that could be considered for resource recovery to meet nutrient management objectives.

Most reviewers cited familiarity with at least the concept of incorporating AMD residue with wastewater effluent (e.g., sewage, fish hatchery effluent) as an approach to sequester phosphorus, particularly owing to iron and aluminum oxides in AMD residue. Similarly, most reviewers cited the conceptual potential to extract rare earth elements (REE) from AMD treatment residue, although one reviewer cautioned that REE separation techniques available to date are not economically viable. One reviewer remarked that certain extractable compounds of AMD residue are used as pigments in ceramic glazes and fabric dyes. See examples at Clean Creek Pottery and EPCAMR and The International Interdependence Hexagon Art Project.

Characterizing the Fate of Nutrients in Acid Mine Drainage (AMD) Streams

Characterizing the fate of nutrients in AMD streams is complex but can be conceptualized by two general models.

The first model is characterized by a non-remediated AMD site or sites. In this instance, the non-treated AMD water mixes with alkaline stream water from various inputs in the watershed – these inputs are typically of greater pH as well. The dissolved iron (Fe^{3+}) and aluminum (Al^{3+}) ions from the AMD bind with hydroxyl ions found in the more alkaline/higher pH waters resulting in a precipitate covering the aquatic substrate (Simmons, 2010). The precipitate also has a high affinity for phosphorus (McBride, 1994; Oelkers and Valsami-Jones, 2008; Denver et al., 2010). Thus, any dissolved phosphorus is sequestered to the substrate and unavailable for use by aquatic life (e.g., bacteria, fungi, and algae; Simmons, 2010; DeNicola and Lellock, 2015). In contrast, nitrogen (in the form of nitrate, nitrite or ammonia/ammonium) uptake is minimized due to the lack of aquatic life; therefore, instead of aquatic life removing anthropogenic nitrogen from the aquatic ecosystem, nitrogen is transported downstream (Bott et al., 2012). Conceptually, these abiotic processes occur along a continuum downstream, where at first the stream is impaired (low pH and high dissolved metals), then there is a transition zone as alkalinity and pH increase and metals precipitate, and finally an improved zone where basic ecological functions are reestablished.

The second model is characterized by a *remediated* AMD site or sites. In this model, the AMD is typically treated by raising alkalinity and pH in a contained area so that iron/aluminum hydroxide is precipitated prior to being discharged to receiving waters. The assumption here is that most, if not all, heavy metals are precipitated in the treatment site, and few are released to the receiving stream. If this assumption holds, then little to no phosphorus is sequestered downstream of the AMD site, making it available for microbial and plant uptake. Available phosphorus should increase microbe, algal, and plant growth; thereby increasing nitrogen uptake by microbes, algae and plants as well. It is often assumed then that aquatic ecosystem functions are restored (or in the process of being restored); however, see Bott et al. (2012).

How AMD Alters Nutrient Spiraling

AMD mixtures harm aquatic life communities, thereby altering a suite of ecosystem functions that govern the transport and fate of water-borne nutrients in fluvial settings. As nutrient substances enter the stream channel, bioavailable forms become assimilated from the water column into aquatic biomass, get released through excretion and decomposition and re-mineralize back into the water column, and so on in a repetitive manner known as “nutrient spiraling” in which individual nitrogen and phosphorus atoms are recycled/reused many times over. The very processes of biologic uptake, metabolism, sequestration, and turn-over create delays to downstream nutrient transport and thereby slows the movement of nitrogen and phosphorus between terrestrial and aquatic settings and from “headwaters to sea”. In streams with aquatic life impairment due to AMD, nutrient uptake is diminished, nutrient spiraling is interrupted, and there is the potential for nitrogen and phosphorus to progressively accumulate/increase in downstream parts of the ecosystem as nutrient spirals effectively become elongated (in time and distance) (Ensign and Doyle 2006).

Due to the dramatically contrasting geochemical traits between AMD and receiving waters (notably pH and/or dissolved oxygen disparities, elevated metals concentrations in AMD, and differences in the availability of organic matter), AMD also has the potential to reduce bioavailability or even sequester phosphorus. In particular, iron in AMD reacts with phosphate in stream or groundwater to form *iron – hydroxyphosphate* mineral phase precipitates. Additionally, certain forms of phosphorus may adsorb to organic matter and/or iron-rich colloid surfaces in manners that limit biological uptake.

Rates of Nutrient (Total Nitrogen and Total Phosphorus) and Sediment Assimilation in Healthy Streams

"Nutrient spiraling" is a term that describes the cycling of nutrients as they are assimilated from the water column into benthic biomass, temporarily retained, and mineralized back into the water column (Newbold et al., 1981). Nutrient spiraling rates are influenced by a variety of abiotic (e.g., channel size and the surface area-to-channel volume ratio) and biotic factors (e.g., bacteria, fungi, algae, and macrophyte abundance; Gomez and Harvey 2014).

Nutrient spiraling is typically described by four terms (Newcomer Johnson et al., 2016) as follows:

1. The uptake rate coefficient (k), which describes assimilation of nutrients on a volumetric basis;
2. The uptake length (S_W), which is the average downstream distance that a nutrient atom travels in its dissolved form in the water column before it is consumed by biota or sorbed onto sediments;
3. The areal uptake (U), which is the nutrient uptake rate per unit area of stream bottom; and,
4. The uptake velocity (V_f) which is the vertical velocity of nutrient molecules through the water column toward the benthos in mm/min.

Therefore, understanding nutrient assimilation in healthy watersheds requires an understanding of these metrics for a variety of healthy streams. A meta-analysis by Newcomer Johnson et al. (2016) compared nutrient spiraling metrics for restored, degraded, and reference (healthy) streams; therefore, metrics from their reference streams can be used as estimates for nutrient assimilation rates in healthy watersheds. Table 1 summarizes their findings[1].

Nutrient	Metric (units)	Mean	Median	Range	Sample size
NO_3	S_w (m)	3107	1341	108–18,632	13
	U (ug/m^2/s)	5.3	0.42	0.01–33.6	12
	V_f (mm/min)	3	1	0.02–38.2	24
NH_4	S_w (m)	609.5	789.5	197–842	3
	U (ug/m^2/s)	0.7	0.6	0.0–2.2	17
	V_f (mm/min)	3.5	1	0.0–22.8	23
SRP	S_w (m)		1403		1
	U (ug/m^2/s)				0
	V_f (mm/min)	19.9	11.8	1.4–87.4	8

Table 1. Nutrient spiraling metrics for nitrate (NO_3), ammonium (NH_4), and soluble reactive phosphorus (SRP) reported by Newcomer Johnson et al. (2016) for reference (healthy) streams. Metrics abbreviations are as follows: S_W = uptake length, U = areal uptake, and V_f = uptake velocity.

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[1] Note related to Table 1: the sample size is limited and increasing the number of samples will improve the accuracy of nutrient assimilation rates for healthy aquatic ecosystems

Quantifying Nutrient Load Reductions as Co-Benefits of AMD Treatment and Watershed Restoration

This is a difficult and complex question to address accurately. The expectation is that AMD treatment could initially increase phosphorus concentrations and decrease nitrogen concentrations; however, this is contingent on the amount of external inputs of these nutrients. AMD-affected waters, high in iron and aluminum, can bind phosphorus to the substrate, making it unavailable for downstream use. Therefore, once treatment occurs, with consequent increases in pH, this legacy phosphorus may become readily available to freely spiral downstream—the extent of material floc movement and possible release of legacy phosphorus has not been well studied (Smyntek et al., 2022). Furthermore, the amount of phosphorus from external inputs to the system (e.g., agriculture and WWTPs) that is typically sorbed by heavy metals may now be readily available for downstream transport or uptake by microbes, algae, and plants. In this case, nutrient load reductions may not occur, highlighting the need for reductions in external phosphorus loadings to AMD-influenced streams.

In contrast, AMD-affected waters typically disrupt the nitrogen cycle of the influenced watershed; therefore, any external nitrogen source is not utilized or retained in the watershed, rather it freely moves downstream. Once AMD treatment occurs and the nitrogen cycle is established, nitrogen load reductions should occur as the nitrogen is now readily available for microbial, algal, and plant usage, as well as denitrification removal in the treated watershed.

The complexity of quantifying the load reduction of phosphorus and nitrogen stems from the typical lack of understanding of the influences of:

- Nutrient concentrations delivered by external inputs;
- The efficiency of heavy metal removal of AMD treatment; and
- Hydrogeochemical conditions of the watershed.

If this complexity could be summarized in geochemical models, then nutrient load reductions could be quantified. Geochemical modellings of heavy metals (Cravotta, 2015, 2021), phosphorus (Smyntek et al., 2022), and nitrogen (Acuna et al., 2019, Rutherford et al., 2020) appear promising as an emerging tool to predict the fate of nutrients post-AMD treatment (see Alam and Dutta, 2021 for a review of existing nutrient modelling tools).

While this technical review is focused on evaluating existing research and data to aid in the development of nutrient load reduction efficiencies for AMD treatment projects in the Chesapeake Bay watershed, it should be clear that **AMD treatment and remediation will not likely decrease phosphorous loads.** Rather, remediating AMD could increase the bioavailable dissolved phosphorus in our waterways.

There is an abundance of literature and scientific evidence to suggest that AMD treatment could increase dissolved phosphorus, and there was a consensus among the technical reviewers that this research should be further explored and supported financially. One suggested revenue stream to support this research would be through the Bipartisan Infrastructure Law (BIL) signed on November 15, 2021. This BIL provides a 500% increase in state agency annual budgets for AMD and AML remediation over the next 15 years. Without careful consideration, this large effort to remediate AMD could result in inadvertent increases in phosphate (PO_4) transport to downstream waterways.

Once in operation, AMD treatment systems can improve pH, metal, and alkalinity concentrations for miles downstream of the treated pollution source. Because many miles of stream can be restored by AMD treatment systems, this could make it challenging to determine the larger-scale impact of AMD reclamation on instream nutrient loads. However, there are several recommendations for how nutrient loading could be quantified before and after mine reclamation projects.

Recommendation 1: To adequately assess the impact that AMD treatment has on nutrient loads, water quality and flow rate must be quantified pre- and post-AMD treatment system construction. Sampling locations should be upstream and downstream of where the treated/non-treated AMD flows into the receiving stream. Collected samples should be analyzed for iron (Fe), aluminum (Al), manganese (Mn), sulfate (SO_4), acidity, alkalinity, DO, PO_4, total phosphorus (TP), total nitrogen (TN), nitrate (NO_3), total carbon (TC), and total organic carbon (TOC). Funding and resources could affect the frequency of sample collection before and after AMD treatment construction. At the very least, quarterly sampling is recommended to accurately quantify the impact of AMD reclamation on nutrient loads.

Recommendation 2: The downstream sampling locations (highlighted in Recommendation #1) are very important to consider when quantifying the impact that AMD could have on nutrient loads. For example, shortly after an AMD discharge contacts a stream, there could be a wastewater treatment plant discharge or agricultural runoff that also flows into the stream, providing a source of nutrients. Once the untreated/treated AMD mixes with these nutrient sources, the instream dissolved nutrient concentrations are likely sequestered (as explained in response to Question 4). This phenomenon has been observed in several places in Pennsylvania (Spellman et al., 2022; Smyntek et al., 2022; Spellman et al., 2020). Therefore, if a sample is collected at a location before the point of mixing between the AMD and nutrient source, it would be impossible to quantify how the treated/non-treated AMD interacts with the nutrient source and influences dissolved nutrient loads (Figure 3). In summary, the downstream sampling location is very important!

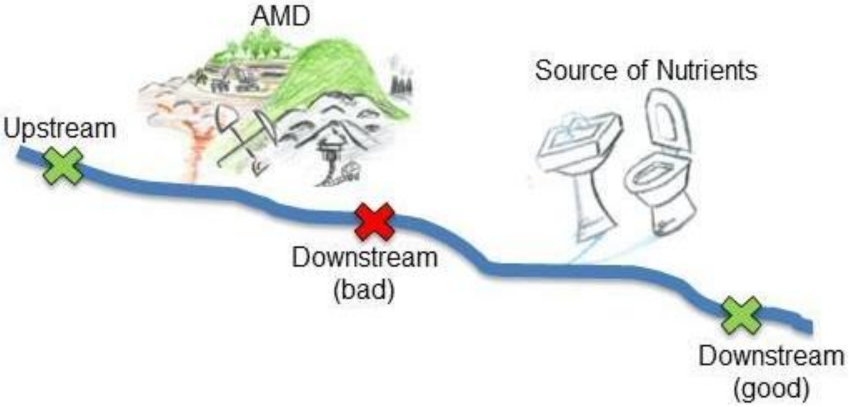


Figure 3. Example of good (shown in green) and bad sampling locations when considering how AMD may impact nutrient loads. [Source: Travis et. al.]

Recommendation 3: When collecting samples for water chemistry analysis, require flow measurements as well. Load calculations cannot be performed without concentration and flowrate.

Additional Considerations

Emerging research (e.g., Cravotta et. al., 2024) and field studies by EPCAMR completed for the Tri-County (Luzerne, Lackawanna, and Susquehanna) County Action Plan note that phosphate, in particular, binds to newly formed iron oxide particles in suspension and settles to the bottom of the stream as AMD “legacy sediments.”

Quantifying nutrient load reductions can be accomplished by taking samples of TN and TP while sampling for typical AMD parameters (e.g., iron, aluminum, pH, acidity, alkalinity, temperature, DO, conductivity, and Total Dissolved Solids (TDS)), in the field and/or the lab. Flow measurements must also be taken to calculate loadings from the measured concentrations. It is also important to note that sampling is needed not only at the inlet and outlet of the treatment system but also instream upstream and downstream to monitor chemistry and flow, demonstrating the impact on the receiving stream.

EPCAMR currently has several years of data from the Loyalsock Watershed and the Nanticoke Creek Watershed (in and out of AMD treatment systems and instream upstream and downstream of AMD treatment systems). The chemical makeup of mine drainage in these two watersheds is different (acidic aluminum-dominated vs. iron-dominated alkaline, respectively) and it is interesting to contrast the difference in how phosphates, in particular, move through the treatment systems. At the Askam Borehole Treatment System on Nanticoke Creek, observations show a reduction in phosphates from the input to the output when the treatment system is functioning well below the 2,000 gallons per minute (gpm) flow through. As this system was built directly into the creek channel, it accepts flow from upstream as well. Due to several site constraints, the settling pond is undersized and the baffles across the pond are configured to promote mixing rather than settling. There are many times throughout the year when flows over 2,000 gpm pass through the system. TP levels have measured lower at the input (in samples directly from the boreholes and upstream) and higher levels at the output. Robert Hughes, EPCAMR Executive Director, posed this question to Brent Means, OSMRE (Office of Surface Mining Reclamation and Enforcement) Hydrologist, when he visited the borehole site a few years ago. Means suggested filtering a sample to measure dissolved phosphates; the results seem to indicate a kind of flushing event when flows exceed 2,000 gpm. This can be visually observed by the orange sediment leaving the pond.

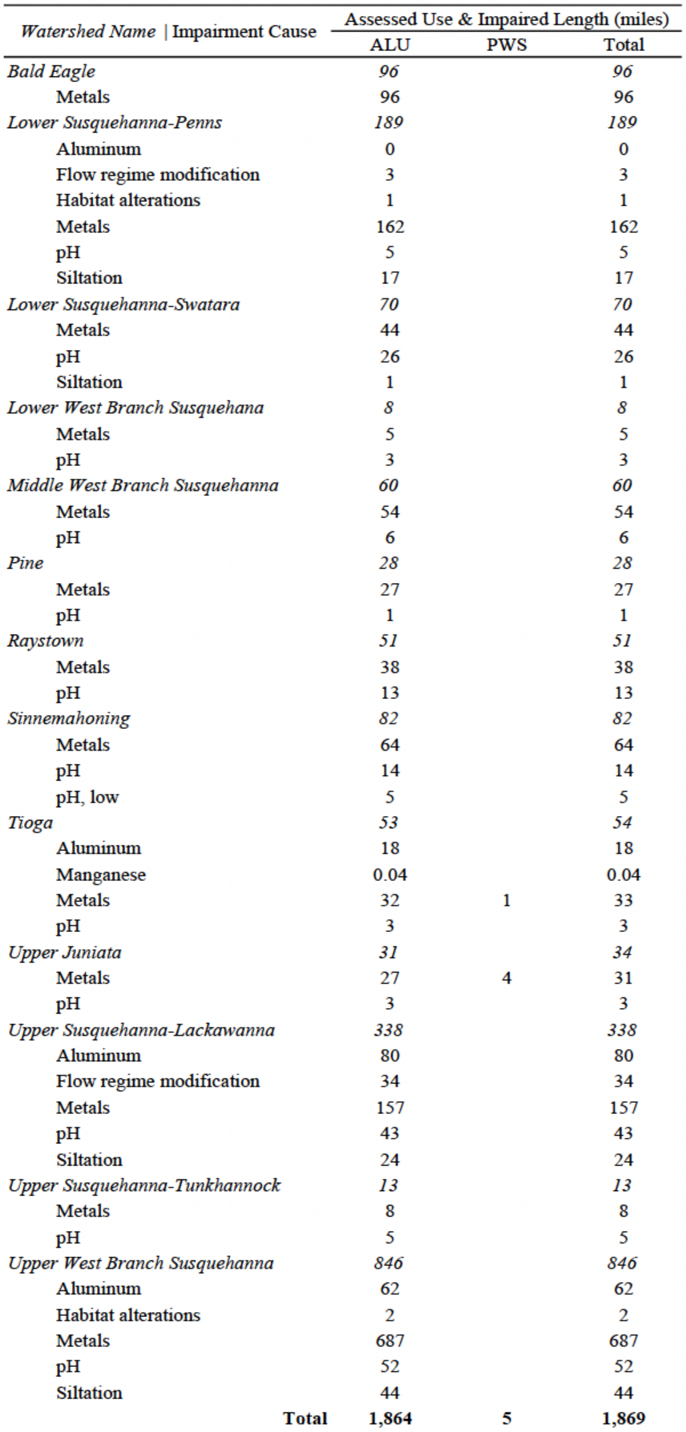
TN concentrations seem to pass through these systems relatively unchanged.

An aquatic biological survey of macroinvertebrates and/or a fish survey can be completed at each site sampled prior to any restoration work and removal of TN or TP through best management practices, green infrastructure projects, streambank stabilization, and/or floodplain restoration or riparian corridor restoration to determine if there is an increase in stream ecology and diversity of macroinvertebrates and fish species.

Sampling should be completed on existing AMD treatment systems for TN and TP to determine if they have already been removing TN and TP for decades since their installation and construction across the Chesapeake Bay and other major watersheds in the Commonwealth. This would help determine if TN and TP removal has historically been unaccounted for in the Chesapeake Bay Model (CBM).

Assessing the Extent of Stream Miles Impacted by Acid Mine Drainage (AMD)

The total impacted stream mileage varies by data source and reporting year. Based on the Pennsylvania Department of Environmental Protection's (PADEP) 2024 Integrated Water Quality Report, approximately 1,869 stream miles in the Susquehanna River watershed are impaired by AMD (PADEP, 2024; Table 2).



Watershed Name | Impairment Cause	Assessed Use & Impaired Length (miles)		
	ALU	PWS	Total
Bald Eagle	*96*		*96*
Metals	96		96
Lower Susquehanna-Penns	*189*		*189*
Aluminum	0		0
Flow regime modification	3		3
Habitat alterations	1		1
Metals	162		162
pH	5		5
Siltation	17		17
Lower Susquehanna-Swatara	*70*		*70*
Metals	44		44
pH	26		26
Siltation	1		1
Lower West Branch Susquehana	*8*		*8*
Metals	5		5
pH	3		3
Middle West Branch Susquehanna	*60*		*60*
Metals	54		54
pH	6		6
Pine	*28*		*28*
Metals	27		27
pH	1		1
Raystown	*51*		*51*
Metals	38		38
pH	13		13
Sinnemahoning	*82*		*82*
Metals	64		64
pH	14		14
pH, low	5		5
Tioga	*53*		*54*
Aluminum	18		18
Manganese	0.04		0.04
Metals	32	1	33
pH	3		3
Upper Juniata	*31*		*34*
Metals	27	4	31
pH	3		3
Upper Susquehanna-Lackawanna	*338*		*338*
Aluminum	80		80
Flow regime modification	34		34
Metals	157		157
pH	43		43
Siltation	24		24
Upper Susquehanna-Tunkhannock	*13*		*13*
Metals	8		8
pH	5		5
Upper West Branch Susquehanna	*846*		*846*
Aluminum	62		62
Habitat alterations	2		2
Metals	687		687
pH	52		52
Siltation	44		44
Total	**1,864**	**5**	**1,869**

Table 2. Acid Mine Drainage causes by 8-Digit Hydrologic Unit Code (HUC) in water ways of the Susquehanna River basin, Pennsylvania.

Key Geographic Patterns

Pennsylvania's AMD impacts show distinct spatial distributions tied to coal geology. The Susquehanna River Basin contains the majority of impaired miles, with Clearfield County (591 miles) as the most impacted county. The patchwork distribution of impaired and healthy subcatchments creates natural laboratories for studying nutrient dynamics, exemplified by Moshannon Creek (an 8-digit HUC tributary to Bald Eagle Creek that receives AMD-impaired flow) contrasting with its clean eastern tributaries. Regionally:

- Anthracite regions (NE Pennsylvania) produce the largest-volume AMD discharges, exemplified by high-flow sources like the Audenreid Tunnel impacting Catawissa Creek.
- Bituminous regions (W Central Pennsylvania) contain the greatest linear extent of impaired streams, particularly in the rural West Branch Susquehanna ("Pennsylvania Wilds") and Juniata River subbasins, where AMD affects longer stream segments despite lower discharge volumes compared to anthracite areas.

Within Pennsylvania’s Chesapeake Bay watershed specifically, AMD impairs 1,869 stream miles, while statewide, AMD affects 5,533 total stream miles (PADEP, 2024). Restoration progress has been limited, with just 178 miles restored to designated uses as of 2021. Notably, agricultural activities impair even more stream miles statewide than AMD, emphasizing the need for integrated watershed management approaches.

Tracking the Restoration of AMD-Impacted Stream Miles: Progress and Ongoing Efforts

For a number of reasons, estimates of the number of miles of AMD-impacted streams that have been or are being "restored" are difficult and varies.

For AMD-impaired segments, the delisted streams from the 2018 to 2022 datasets totaled 72 miles, compared to the dataset provided in 2018, which included 5,621 miles. The delisted streams totaled 246 miles when calculated by subtracting the 2008 dataset from the 2018 dataset (a 10-year statistic). Therefore, from 2008 to 2022, 318 miles of formerly listed AMD-impaired streams were delisted.

PADEP Bureau of Abandoned Mine Reclamation (BAMR) published a 2019 Fact Sheet entitled, "*Pennsylvania's Surface Mining Control and Reclamation Act Funded Abandoned Mine Lands Program: Past, Present, and Future.*" The document lists their program accomplishments, including some additional statistics, but the time period for several of their statements is unknown. More accurate assessments might be possible if the PADEP backdates when they began removing stream segments from the federal 303(d) List of Impaired Waters to provide an accurate reflection of the number of stream miles that have been restored. Data on AMD-related stream restoration projects may not go back as far as the Surface Mining Control and Reclamation Act (SMCRA) of 1977.

EPCAMR provided comments suggesting that the PADEP Bureau of Water Quality create a separate dataset of delisted streams in their Integrated Water Quality Report, as this very important question arises frequently and would be a great way to demonstrate progress. These reports are published every other year. In the PADEP 2022 Integrated Water Quality Report, there is now a section on 2022 Delistings, including a table. This table tallies stream miles removed from 2021 to 2022 (a 1-year period).

Based on Datashed, according to the Pennsylvania Integrated Water Quality Monitoring and Assessment Report (2022), these pollutive discharges, commonly referred to as acid mine drainage or abandoned mine drainage, are one of the largest sources of stream degradation in Pennsylvania, with over 5,600 miles of streams impacted. Furthermore, 45 of Pennsylvania's 67 counties are impacted, with over 250,000 acres of unreclaimed mine lands, 2.6 billion cubic yards of abandoned coal refuse, and about 7,800 abandoned underground mines. In many cases, entire watersheds have been completely decimated by AMD.

Over the last three decades, watershed organizations, nonprofits, and government agencies have been installing systems to treat abandoned mine drainage throughout Pennsylvania and the United States. According to an inventory of mine drainage treatment projects compiled by Datashed, over 325 passive and at least 15 active, publicly funded systems exist within Pennsylvania alone, treating billions of gallons of AMD and preventing millions of pounds of metal loadings from entering streams each year. Through land reclamation and the installation of treatment systems, many streams have been—or are in the process of being—restored. These restoration projects, however, must be properly maintained, including regularly scheduled site inspections and water monitoring, to allow for long-term treatment and sustained improvements in stream quality. To prevent streams from reverting to their polluted condition, these projects must continue to function effectively.

Volunteers, nonprofit organizations, and government agencies have spent numerous hours collecting valuable water quality data to determine the effectiveness of these treatment systems. Depending on the organization, this data has a variety of end uses. Some groups enter this data into a computer database and use it for reports, newsletters, etc. Other groups do not have a database and only keep paper records. Often, government and nonprofit agencies store their data in proprietary databases behind firewalls for security. As a result, the availability of this data to the general public and researchers is limited.

The County Conservation Districts that have completed Countywide Action Plans (CAPs) may have an individual number calculated for each county where the CAP was completed. These numbers can be added together based on the total number of counties where the CAP has been completed across the Commonwealth[2].

The definition of "restored" can vary among agencies and community organizations, with different measurable environmental outcomes. It is recommended to seek these definitions from the appropriate agencies and community organizations, as they often define what a comprehensive watershed restoration plan entails. PADEP BAMR has a Comprehensive Plan for Abandoned Mine Reclamation, which includes two tiers of restoration and was last updated in 1997. 100% of metals may not need to be removed from an impaired stream for it to be considered restored. For example, stocking trout in a once-impaired AMD stream might be considered a restoration success, while the return of native trout species, such as brook trout, might be considered an even greater success.

Given the availability of Geographic Information Systems (GIS) portals to the public, answering this question should be straightforward. However, none of the experts could locate a table, list, or GIS layer for ongoing AMD restoration activities that cross-references the number of river miles being restored. Efforts to query the Susquehanna River Basin Commission's (SRBC) mine drainage portal for AMD treatment projects in the Susquehanna Basin found only six active projects (Rausch Creek, Babb Creek, Hollywood, Cresson, Barnes and Tucker/Lancashire) and two pending projects (Tioga and Catawissa) included in the GIS database. Cross-referencing with PADEP's 2022 Integrated Water Report and various other reports, it was found that approximately 168 miles have been or are being restored. These include:

- Rausch Creek (1.69 miles)
- Babb Creek (14 miles)
- Hollywood (33 miles)
- Cresson (22 miles)
- Barnes and Tucker/Lancashire (30 miles)
- Tioga (20 miles)
- Catawissa (44 miles)

Case Study Opportunities

In many Pennsylvania watersheds, AMD impacts tend to exhibit a patchy distribution for which one subcatchment may be severely impacted due to AMD while an adjacent subcatchment may be recognized for special protection status as High Quality or Exceptional Value. Such patchwork creates opportunities for in-situ case study comparisons. The PADEP has published technical guidance documents that could serve as a framework to quantify nutrient load effects:

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[2] Not all counties in Pennsylvania have completed CAPs, as they are currently only required in the Chesapeake Bay watershed. For more information, visit: PA DEP Countywide Action Plans.

- Water Quality Monitoring Protocols for Surface Water PADEP 2023
- General Source and Cause Method PADEP 2023
- Eutrophication Cause Method Technical Report PADEP 2023

While numerous potential case study sites exist, these locations emerge as top priorities:

1. Moshannon Creek (Clearfield/Centre Counties and part of Bald Eagle Creek 8-digit Hydrologic Unit Code watershed)
   The north-flowing main stem is extensively damaged by a multitude of legacy deep and surface bituminous coal mine features, but generally tributaries that enter from the east (Centre County, PA) are unimpacted by AMD whereas tributaries that join from the west (Clearfield County, PA) are severely impacted.
2. Tioga River (Tioga County)
   The main stem's lowermost ~20 miles is severely degraded by a series of AMD discharges from tributaries near Blossburg. The remaining sources will be addressed through an active treatment plant currently in final design (2025-2027 construction). The impoundment structure at the river mouth provides unique opportunities to evaluate phosphorus release from colloid and iron mineral phases during the transition from polluted to unpolluted conditions.
3. Catawissa Creek (Schuylkill/Northumberland Counties)
   The main stem is extensively impaired for ~30+ miles due to high-volume AMD from the anthracite Audenreid Tunnel, while most tributaries remain unaffected. The agricultural land use in the valley adds complexity for nutrient load assessments.

These sites align with the Chesapeake Bay Program's need for:

- Pre/post-remediation comparisons of nutrient spiraling metrics;
- Documentation of legacy phosphorus mobilization risks; and
- Validation of pollutant-reduction credits for AMD projects.

Social Science Considerations for Engaging Landowners with Contaminated Water Sources and Impaired Streams

A number of studies regarding the impact of AMD on ecosystem services, social justice, and community resilience in the Chesapeake Bay region are underway and beginning to appear in the literature. Within the Susquehanna River basin section of the Chesapeake Bay region, AMD reclamation activities involving landowners and citizens of the coal towns and associated abandoned mine lands are organized under the Western Pennsylvania Coalition for Mine Reclamation (WPCAMR) and EPCAMR. Robert Hughes, Director of EPCAMR, has discovered the following eight social science considerations are imperative to achieving success:

1. **Rational Choice Perspective**
   Discuss with landowners the importance of cleaning up their potable water sources and streams impacted by AMD to improve water quality on or along their property. Emphasize the health and safety benefits, as well as the downstream benefits of such projects. Make certain they are fully aware of any liability concerns and the protections available under the Environmental Good Samaritan Act. Inform them of funding sources to reduce financial burdens and explore potential revenue opportunities, such as water use, metal recovery, electrical generation, geothermal potential, and recreational benefits.
2. **Classical Political Philosophy Perspective**
   Landowners should seek support letters for AMD projects from local government bodies, community leaders, and county, state, and federal legislators. Encourage them to value restoration from a land ethic perspective and to support sustainable, long-term projects that secure clean water for future generations. Highlight the legacy they can leave for their families or the downstream communities that benefit from their stewardship.
3. **Interpretivism Perspective**
   Recognize that each landowner will have their own perspective and opinion on the benefits of restoration, often based on their personal views rather than external explanations. Projects are unlikely to move forward unless the landowner’s concerns are addressed and assurances are provided. Partners should first ask about the landowner’s level of knowledge and historical or social connection to the land and water to understand their unique perspective.
4. **Structuralism Perspective**
   Provide landowners with educational materials that explain the benefits of watershed restoration and the various treatment system technologies available. Build positive working relationships to gain permission for site access, water quality sampling, and streambank measurements. Show how these elements are part of a larger, interconnected watershed plan to help landowners see the broader impact of restoration efforts.
5. **Behavioralist Perspective**
   Work with landowners to provide quantifiable, objective, and unbiased data gathered through sound science and strong quality assurance and control measures. Use this data to justify the need for AMD or watershed restoration projects and to clearly communicate the benefits and urgency of addressing AMD issues.
6. **Realism Perspective**
   Acknowledge that landowners will understand AMD as a pollution problem but will also be concerned about liabilities and financial risks. Address these concerns while being realistic about potential economic gains, such as revenue generation or economic development opportunities, to make restoration projects more appealing.
7. **Pluralism Perspective**
   Prioritize landowners’ thoughts, concerns, historical context, and connection to the land

and water when planning restoration projects. Encourage partnerships where landowners become members of community watershed organizations to reduce skepticism and mistrust. This collaborative approach can lead to more successful and less adversarial outcomes.

8. **Institutionalism Perspective**
   Inform landowners of public institutions and programs that offer funding and support for improving land and water quality impacted by AMD or abandoned mines. Highlight the role of governmental agencies and regional or local non-profit organizations in facilitating funding and building landowner, public, and private partnerships.

Evaluating Incidental Nutrient Additions from Acid Mine Drainage (AMD) Treatment Systems to Streams and Receiving Waters

Improvements in water quality from AMD and AML reclamation could inadvertently promote PO_4 mobilization from soils, sediments, and particulate matter within watersheds. Where AMD mixes with surface water, geochemical reactions lead to the hydrolysis and precipitation of Fe and Al from the water column. This process can result in the accumulation of hydrous metal oxides, such as hydrous ferric oxide (HFO; e.g., $Fe(OH)_3$) and hydrous aluminum oxide (HAO; e.g., $Al(OH)_3$), which coat stream sediments. These coatings can range from poorly adhesive gelatinous floc (e.g., Furrer et al., 2002) to strongly adhesive "ferricrete" (e.g., Furniss et al., 1999; Gammons et al., 2021).

Hydrous metal oxides have been shown to adsorb substantial amounts of P, often exceeding 90% (Ruihua et al., 2011; Simmons, 2010; Smyntek et al., 2022; Spellman et al., 2020; Strosnider et al., 2011). For example, in Bradley Run, a 1st-order stream in Cambria County, Pennsylvania, within the Chesapeake Bay watershed, AMD mixes with treated municipal wastewater (MWW) containing approximately 12 mg/L of PO_4 (Spellman et al., 2022). Approximately 1,400 meters downstream from the mixing zone, dissolved PO_4, Al, and Fe concentrations decreased by 94%, 91%, and 98%, respectively. Geochemical modeling (Cravotta, 2021; Spellman et al., 2022) identified the primary mechanisms for P attenuation as precipitation of variscite ($AlPO_4 \cdot 2H_2O$) or amorphous aluminum phosphate ($AlPO_4$), along with adsorption to HFO.

Prior to AMD remediation in 2020, it was estimated that metal precipitation in Bradley Run attenuated approximately 950 kg/year of total P, preventing dissolved P transport downstream to the Chesapeake Bay. This demonstrates that AMD-impacted streams can significantly reduce dissolved P through sorption to metal oxides and co-precipitation with metal phosphate minerals, as documented in multiple studies (Ruihua et al., 2011; Simmons, 2010; Smyntek et al., 2022; Spellman et al., 2020; Strosnider et al., 2011).Considering the abundance of AMD in Pennsylvania, P removal via instream interactions with AMD discharges could play an important role in decreasing overall nutrient transport to downstream water bodies.

The lower pH conditions often found in AMD-impacted landscapes can also reduce dissolved P concentrations. In surface waters affected by AMD with typical pH values ranging from 3 to 7, aqueous phosphate species (e.g., $H_2PO_4^-$, HPO_4^{2-}) are adsorbed by HFO and HAO solids, which commonly coat soil and sediment particles (Goldberg and Sposito, 1984; Dzombak and Morel, 1990; Geelhoed et al., 1997; Ulrich and Pöthig, 2000; Karamalidis and Dzombak, 2010; Kopácek et al., 2000; Adler and Sibrell, 2003; Kopácek et al., 2015). This is supported by experimental data (Simmons, 2010) and geochemical models (Parkhurst and Appelo, 2013) developed by Cravotta (2021).

For example, modeling simulations for a solution containing 3.1 mg/L of PO_4 and 0.09 g/L of HFO indicate that over 85% of PO_4 is adsorbed at pH 6.5 (Figure 4). However, as pH increases, PO_4 desorption increases; at pH 9, less than 30% of PO_4 remains adsorbed. This impact of pH of PO_4 transport is critical to consider when evaluating long-term water quality trends in the Susquehanna River Watershed and projecting the potential impacts of mine reclamation on dissolved PO_4 concentrations in Pennsylvania streams.

Historical trends in the Susquehanna River, the largest contributor of water and nutrients to the Chesapeake Bay, illustrate this relationship. Since the 1950s, pH levels in the Susquehanna River have steadily increased, while sulfate and metal concentrations have declined due to decreased acid and metal (iron and aluminum) inputs from legacy coal mining and, to a lesser extent, atmospheric deposition (Raymond, 2009; Kaushal et al., 2013; Burrows et al., 2015). As a result, PO_4 sorption to particulate matter and streambed sediments was likely more favorable in the 1950s, when pH values were more acidic ($pH < 7$), compared to current pH levels (~8) in the Susquehanna River Watershed.

As more AMD is remediated in Pennsylvania, the subsequent increases in stream pH and decrease in metal oxides on stream bottoms could result in higher dissolved PO_4 concentrations. This highlights the importance of considering pH and metal oxide dynamics when assessing the long-term impacts of AMD remediation on nutrient transport and water quality.

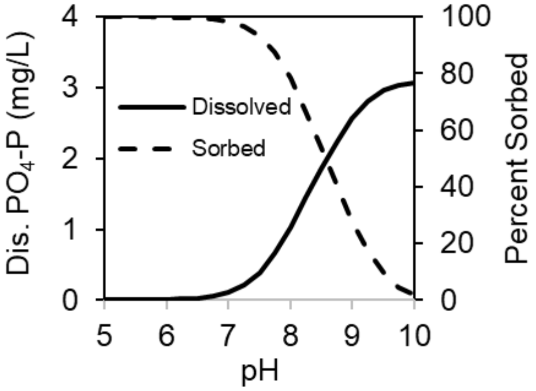

Figure 4. Dissolved PO_4-P concentration and percent of PO4 sorbed to hydrous ferric oxide (HFO) when a solution containing 3.1 mg/L PO4-P and 0.09 g/L HFO (with a specific surface area of 600 m2/g consisting of 5 x 10-6 moles of strong binding sites and 2 x 10-4 moles of weak binding sites) was titrated to different pH's. Simulations were conducted using a PHREEQC model (Parkhurst and Appelo, 2013) developed by Cravotta (2021) with surface complexation data from Dzombak and Morel (1990).

The interaction between treated mine water and dissolved PO_4 in streams has not been extensively studied. However, treating AMD with calcium (Ca)-containing compounds, such as limestone or lime, to increase pH could potentially reduce instream PO_4 through co-precipitation reactions with Ca and PO_4. At sufficiently high concentrations, dissolved Ca from AMD treatment could react with PO_4, precipitating apatite ($Ca_5(PO_4)_3OH$). The formation of Ca-PO_4 minerals could mitigate concerns that AMD reclamation might increase downstream PO_4 concentrations.

Additional Considerations

Certain treatment system best management practices (BMPs), such as Vertical Flow Ponds, use compost in a top layer, which could cause nutrient addition. Depending on the source, the compost itself could leach N and P. Additionally, some mitigation techniques, such as reclaiming land above a mine pool with biosolids or overfertilizing wildlife food plots, can increase nutrient concentrations that seep into the mine pool and discharge downstream. Evidence of this has been reported by EPCAMR in the Loyalsock Creek Watershed within the Susquehanna River Basin.

Underground mines act as conduits for surface and subsurface pollutants. A large French drain system, for example, collects above-ground pollutants dissolved in surface water, which then leach into underground mine pools and outlets at a single location. Atmospheric deposition of nitrogen and other pollutants above these mine pools can also be concentrated to one discharge. The SPARROW model in the Countywide Action Plan Toolkit suggested a geologic layer in the Northern Anthracite Coal Field may be leaching phosphorus. This could originate from shale or carbonate rocks above or below the coal, or potentially from wildcat sewers or illicit sewage leaks that infiltrate underground mine pools.

Overall, AMD treatment has the potential to create a positive nutrient reduction downstream, particularly if planned and considered during initial design. Reviewing and collecting additional data from existing AMD treatment systems, such as those in Datashed or state-funded active treatment plants where TN and TP are sampled, could strengthen the case for their removal alongside typical AMD parameters (e.g., iron, aluminum, manganese, sulfur, TDS, oxidation-reduction potential (ORP), etc.). If AMD treatment systems demonstrate effective removal of TN and TP, the assimilative capacity of downstream waterways could increase, allowing for higher pollution or waste allocation loads due to reduced concentrations of metals, TN, and TP.

Identifying Data Collection Needs and Timing for Planned AMD Restoration Projects

Data needs should be driven by scientific questions or objectives. Once objectives and questions are clearly defined, an experimental design can be developed, and data needs can be outlined. Without explicit questions or objectives, it is difficult to comment on specific data requirements. For example, if the goal is to model P and N dynamics to predict nutrient cycling or assess the impact of legacy phosphorus, recent studies emphasize the importance of short-duration, high-frequency data collection (e.g., Dupas et al., 2016, Duncan et al., 2017; Baker and Showers 2019). Ideally, high-frequency multi-constituent data that can examine/capture diel variation, storm events, and seasonal/annual variation, would be ideal to conceptualize and predict the fate and concentration of nutrients in a given watershed (Burns et al., 2019).

Experimental designs should also incorporate pre/post data collection or reference (healthy) sites for statistical analysis. Pre/post data collection involves sampling before and after a management action, while reference sites provide a comparison to a healthy or unaffected system. These approaches enable quantitative assessment of the impact of AMD treatment on nutrient loading.

Recommendation: Grab samples should be collected on a quarterly or monthly basis, as continuous sampling is often too challenging and expensive. Additionally, composite sampling procedures can vary among individuals, making quality assurance and quality control (QA/QC) difficult to manage. When collecting grab samples for water chemistry analysis, it is essential to also measure flow rates, as load calculations require both concentration and flow rate data.

Prior to developing an AMD treatment design, AMD discharges are typically monitored for Fe, Al, Mn, SO_4, Acidity, Alkalinity, DO, and flowrate on a monthly or quarterly basis for 1 year. Once the monitoring phase is complete, mass balance analyses are performed, and a restoration plan is developed for the watershed. This process guarantees that engineers and project managers address the primary pollution sources and design a treatment system capable of handling seasonal variations in flow and water chemistry.

Given that many AMD treatment projects are grant funded, there is value in requiring grant recipients to include nutrient parameters (such as PO_4, TP, TN, NO_3) in their monthly sampling analysis. This approach provides critical baseline data before AMD treatment systems are constructed. After construction, water quality parameters (e.g., dissolved metals, PO_4, TP, TN, NO_3) and flowrates should be re-sampled at locations identified in the restoration plan. This allows for the quantification of nutrient load reductions and/or increases following treatment, providing a clear assessment of the system’s effectiveness.

Additional Considerations

Many programs now routinely collect grab samples for nutrients and sediments alongside standard AMD parameters, such as pH, DO, and conductivity. Discharge measurements should also be taken at all AMD discharges under consideration. EPCAMR uses a YSI Photometer 9500 to measure nitrates and phosphates in the field, providing a cost-effective method for nutrient monitoring. While the YSI Pro Quatro multi-parameter probe was tested for nitrate monitoring, results were inconsistent compared to those obtained with the photometer. For additional accuracy, lab samples can be sent to a certified laboratory, such as the PADEP Lab, for analysis and verification of field results, provided funding is available.

Real-time continuous monitoring stations could be implemented on waterways and discharges to track flow continuously, enabling load calculations. Quantifying key parameters over at least one year that capturing both high-flow and low-flow conditions, would provide valuable data for engineers to design AMD treatment design-specific systems tailored to specific flow, water chemistry, land availability, and landowner cooperation.

Exploring Resource Recovery Benefits: Potential Uses and Handling of Materials Beyond Treatment Facilities

The high capital costs associated with AMD treatment can be partially offset by recovering valuable REES and the potential for REE recovery from AMD treatment facilities should be explored. REEs possess unique physical and chemical properties that make them critical for a wide range of military and manufacturing applications (Massari and Ruberti, 2013; Goodenough et al., 2018). However, demand for these elements has far outpaced supply due to their rarity in concentrated forms (Alonso et al., 2012). Identifying alternative sources of REEs, such as AMD, is essential to meet this demand. For example, coal mine drainage outflows in the Appalachian Basin are estimated to generate approximately 538 metric tons of REEs annually (Stewart et al., 2017).

While AMD represents a potential source of REEs, recovery efforts remain largely unexplored. Current research focuses on adapting technologies used for REE extraction from dilute wastewater to AMD systems. These technologies include precipitation, solvent extraction, ion exchange, adsorption, molecular recognition technology, magnetic separation, membrane filtration, flotation, electrodialysis, reverse osmosis, and nanofiltration (Table 3). However, many of these methods have limitations when applied to AMD, with adsorption and ion exchange emerging as the most viable options. Several emerging technologies (i.e., molecular recognition technology, magnetic separation, ionic liquids, and cloud point extraction) show promise for REE recovery from AMD (see Table 3 for pros and cons; Mwewa et al., 2022).

Given the complexity of emerging technologies and methodologies, technical reviewers recommend partnering with universities or private companies experienced in REE extraction from AMD. For instance, Pennsylvania State University, West Virginia University, and Virginia Tech have expertise in this area. A notable example is the West Virginia Department of Environmental Protection, which has begun constructing a full-scale AMD treatment plant to demonstrate the recovery of high-grade mixed REE oxide concentrate.

Several potential benefits of resource recovery from AMD have been documented in the literature:

Benefit 1: AMD can contain trace concentrations of REEs, with reported dissolved REE levels ranging from less than 1 to approximately 2,000 µg/L, roughly 1,000 times higher than concentrations found in freshwater (Hedin et al., 2019; Cravotta, 2008). REEs include the 15 lanthanide elements (atomic numbers 57 to 71) and yttrium (collectively referred to as REYs). Due to their unique chemical and physical properties, REEs are essential components in many advanced technologies, including fuel cells, magnets, superconductors, electric vehicles, wind turbines, and batteries (Du & Graedel, 2011; Kunhikrishnan et al., 2022). However, REE extraction is currently dominated by China, which supplies over 60% of the global market. The extraction process can have significant environmental and human health impacts and is not always economically viable (Du & Graedel, 2011; Chakhmouradian & Wall, 2012; Kunhikrishnan et al., 2022). Based on AMD flow rates and REE concentrations in Appalachia, estimates suggest that approximately 550 tons of REEs could be produced annually (Stewart et al., 2017). These REEs can concentrate in AMD treatment solids, with concentrations ranging from 88 to 2,194 ppm (Hedin et al., 2019). However, the elevated concentrations of iron, aluminum, manganese, and other metals in AMD make the economic recovery of REEs challenging.

Benefit 2: Acid mine drainage treatment produces iron and aluminum oxides, often referred to as mine drainage residuals (MDRs), that are commonly disposed in mine pools or landfills. However, others have proposed that phosphorus runoff from agricultural fields could be reduced if manures spread on farm fields were mixed with MDRs (Sibrell et al., 2010; Adler and Sibrell, 2003; Hedin et al., 2020). Manures amended with MDRs have less water extractable phosphate due to the high concentrations of iron and aluminum hydrous oxides in MDRs that are effective in sorbing P and sequestering P in fertilizers (Rakotonimaro et al.; 2017; Sibrell et al., 2010; Adler and Sibrell, 2003; Sekhon and Bhumbla, 2013). However, common concerns pertaining to MDR land application include potentially high levels of toxic trace elements and potential influence on crop yields.

Benefit 3: Another potential beneficial use of MDRs or even untreated AMD is their application in municipal wastewater treatment plants for phosphorus recovery (Sibrell et al., 2010; Spellman et al., 2020). PO_4 is typically difficult to remove from municipal wastewater unless it is accumulated in microbial cells or sorbed onto iron oxyhydroxide precipitates (Johnson & Younger, 2006).

Johnson and Younger (2006) demonstrated that co-treating AMD and municipal wastewater in a pilot wetland system achieved phosphorus removal rates of up to 50%. In this system, phosphorus removal was strongly correlated with influent iron concentrations, indicating that iron oxide flocs played a key role in adsorbing phosphorus. Similarly, batch reactor tests showed that mixing AMD from a pit mine (total iron = 9,700 mg/L) with municipal wastewater resulted in up to 97% phosphorus removal (Ruihua et al., 2011). At a Fe/P molar ratio of 1.6, phosphorus removal was 88%, with higher removal rates observed at increased AMD dosages. Hughes and Gray (2013) also reported over 90% phosphorus removal in activated sludge reactors co-treating municipal wastewater and acid mine drainage.

Removal method	Advantages	Disadvantages
Chemical precipitation	Low capital cost, Simple operation, Able to remove most metals	High cost of precipitating agents, Might lead to production of excess sludge which poses disposal concerns
Solvent extraction	Can handle huge volumes, High selectivity depending on extractant used	Expensive process due to cost of extractants, Not economical in the treatment of dilute waste solutions
Cloud point extraction	High selectivity, High metal upgrade	Not tested for matric of solutions
Ion flotation	Simple and inexpensive, Low sludge generated, Low cost	Low flotation efficiency for complex, high ionic strength aqueous systems
Ion exchange	High metal selectivity, Metals can be removed and reused	Slow kinetics, Resin poisoning, Fouling
Adsorption	Cheap and simple process, Easy desorption of metals, Environmentally friendly	Performance is largely dependent on type of adsorbent
Molecular recognition technology	High selectivity, Green chemistry procedure	Expensive process
Magnetic separation	Low cost	Nonmagnetic materials cannot be extracted using this method
Membrane filtration	Efficient separation process, Low solid generation	Membrane fouling, Process complexity

Table 3. Summary of the advantages and disadvantages of the various process methods for enrichment of rare earth elements (REEs). Recreated from Mwewa et al. (2022).

Recommendations

To address knowledge gaps and maximize co-benefits of AMD remediation for Chesapeake Bay water quality, the recommendations below are suggested.

Enhanced Monitoring and Data Collection

- Pre/Post-Treatment Sampling: Implement quarterly grab sampling (TN, TP, metals, acidity) with concurrent flow measurements at strategic upstream/downstream locations, prioritizing mixing zones where AMD interacts with nutrient sources (e.g., WWTP discharges, agricultural runoff).
- Focus on high-priority watersheds with patchy AMD impacts (e.g., Moshannon Creek, Tioga River, Catawissa Creek) to compare impaired, healthy, and remediated reaches.
- Legacy Phosphorus Tracking: Include filtered vs. unfiltered phosphate analyses to distinguish dissolved vs. particulate P mobilization post-remediation.

Modeling and Decision Support Tools Geochemical Modeling

- Apply tools like PHREEQC and SPARROW to predict phosphorus release risks during AMD treatment and validate nutrient credit metrics for the Chesapeake Bay Program.
- Integrated Data Platforms: Leverage existing databases (e.g., PADEP's eMapPA, SRBC's Mine Drainage Portal) to standardize AMD-nutrient flux assessments across jurisdictions.

Strategic Funding and Innovation

- BIL-Funded Pilots:
    - Partner with universities (e.g., Penn State, WVU) to pilot Rare Earth Element (REE) extraction and recovery from AMD treatment residuals, aligning with national critical mineral priorities.
    - Co-treatment systems can combine AMD and municipal wastewater to sequester phosphorus (Johnson & Younger 2006). Additionally, mine drainage residuals (MDRs) rich in iron/aluminum hydrous oxides effectively reduce water-extractable phosphate when amended to manures, providing dual benefits for agricultural phosphorus management.
- Social Science Integration: Use Bipartisan Infrastructure Law (BIL) resources to engage landowners through incentives (e.g., liability protections, revenue-sharing) and highlight local benefits (e.g., restored fisheries, increased property values). Structure BIL-funded outreach using the eight social science frameworks, emphasizing economic incentives, institutional partnerships, and cultural alignment.

Policy and Collaboration

- Chesapeake Bay Program Alignment: Develop AMD-specific nutrient credit protocols to account for P sequestration trade-offs and aquatic life restoration benefits.
- Coordinate cross-agency (i.e., USGS, EPA) and state agency partnerships to standardize monitoring and share data on AMD-nutrient interactions.

Conclusion

Acid mine drainage presents both challenges and unexpected benefits for Chesapeake Bay nutrient management. While AMD severely disrupts aquatic ecosystems by impairing the natural nutrient cycling processes that typically slow downstream nitrogen and phosphorus transport, it simultaneously creates conditions that chemically sequester phosphorus through iron and aluminum hydroxide interactions. This paradox means that AMD remediation efforts must carefully account for both the restoration of biological functions and the potential release of historically bound phosphorus as water chemistry changes (Ensign and Doyle 2006; Baken et al., 2016).

The complex dynamics of AMD impacts are particularly evident in Pennsylvania's coal regions, where over 5,500 stream miles remain impaired. The patchwork distribution of affected waterways where severely degraded segments often flow alongside unaffected tributaries, as seen in Moshannon Creek and Catawissa Creek watersheds, creates natural laboratories for studying these processes. Recent research in locations like Bradley Run demonstrates how AMD interaction with nutrient sources can remove over 90% of phosphorus through metal-phosphate precipitation, suggesting these systems have been providing uncredited water quality benefits (Spellman et al., 2022). However, the same geochemical mechanisms that currently trap phosphorus may release it during treatment, requiring careful monitoring and modeling.

The Bipartisan Infrastructure Law's (BIL) historic funding increase for AMD remediation has become available at a crucial moment, offering opportunities to address outstanding scientific questions while allowing for the advancement of restoration. BIL funding could support innovative approaches ranging from rare earth element recovery from the treatment of byproducts to integrated systems that combine AMD treatment with municipal wastewater management. The law's 15-year timeline could be leveraged to enable comprehensive, multi-year studies that are much needed to properly evaluate treatment outcomes, particularly for legacy phosphorus mobilization risks.

Moving forward, successful AMD management will require coordinated efforts across scientific, policy, state, and local communities. By combining monitoring at priority sites, advanced geochemical modeling, and the strategic application of this new funding, it is possible to develop solutions which simultaneously restore aquatic ecosystems and protect downstream water quality, while also potentially recovering valuable resources. The Chesapeake Bay Program's framework provides an ideal structure to incorporate these insights by effectively integrating AMD remediation to broader watershed management goals.

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APPENDIX A: STAC Technical Review Request

STAC Acid Mine Drainage Technical Review Questions

1. What is the rate of nutrient (Total Nitrogen and Total Phosphorus) and sediment assimilation in a healthy watershed?

2. How can nutrient load reductions as a co-benefit of Acid Mine Drainage (AMD) treatment and watershed restoration be quantified?
    a. How many stream miles are impacted by AMD?
    b. How many have been/are being restored?

3. Which social science considerations for working with landowners who have contaminated potable water sources and impaired local streams should be considered?

4. Can AMD treatment cause a nutrient-situation (incidental)?

5. What data needs to be collected (grab sample or continuous) and at what stages of these projects that are currently being planned?

6. Literature review of the benefits of resource recovery:
   Can a material be used outside of the plant for other means? If possible, should we be handling it differently?
    a. Evaluate the benefit of chemical reactions like absorbance (USGS work in fisheries; Hedin Environmental funded by DEP to look at mixing AMD sludge with manure to stabilize phosphorus) and certain treatment designs that could be considered for resource recovery to meet nutrient management objectives.

APPENDIX B: Acronym List and Glossary of Terms

BAMR	Bureau of Abandoned Mine Reclamation
BIL	Bipartisan Infrastructure Law
BMP	Best Management Practice
CAPs	Countywide Action Plans (PA)
CBM	Chesapeake Bay Model
CBP	Chesapeake Bay Program
EPCAMR	Eastern Pennsylvania Coalition for Abandoned Mine Reclamation
HAO	Hydrous aluminum oxide
HFO	Hydrous ferric-oxide
MWW	Municipal Wastewater
ORP	Oxidation-Reduction Potential
OSMRE	Office of Surface Mining Reclamation and Enforcement
PADEP	Pennsylvania Department of Environmental Protection
SMCRA	Surface Mining Control and Reclamation Act
SRBC	Susquehanna River Basin Commission
USGS	United States Geological Survey
WPCAMR	Western Pennsylvania Coalition for Abandoned Mine Reclamation
WWTP	Wastewater Treatment Plant

Abandoned Mine Land (AML) - Lands, waters, and surrounding watersheds contaminated or scarred by extraction, beneficiation or processing of ores and minerals, including phosphate but not coal. Abandoned mine lands include areas where mining or processing activity is temporarily inactive.

Acid Mine Drainage (AMD) - A commonly used acronym for "Acid Mine Discharge" or "Abandoned Mine Discharge," both of which refer to the polluted water emanating from underground or surface ("strip") mines in the Chesapeake Bay watershed. Most of these discharges are acidic ($pH < 7$), although the pH does vary considerably, and the term AMD usually refers to the low alkalinity and high concentrations of dissolved metals (principally iron (Fe), magnesium (Mg), and aluminum (Al)).

Active Treatment Systems - Mechanized systems used to treat AMD, often involving chemical addition or mechanical filtration.

Desorption - The process of releasing heavy metal ions, like iron, copper, zinc, and manganese, that have been previously adsorbed onto a solid surface (like an adsorbent material) from acidic mine wastewater.

Diel Oxygen Method - A technique for measuring stream metabolism by tracking dissolved oxygen fluctuations over a 24-hour period.

Diel Trends - Daily fluctuations in environmental parameters such as dissolved oxygen, often used to measure stream metabolism.

Geochemical Modeling - The use of mathematical models to predict the behavior of nutrients and metals in aquatic systems.

Integrated Reports (IR) - The Integrated Report is a biennial report that provides the information required under sections 303(d), 305(b), and 314 of the federal Clean Water Act.

Legacy Sediments - Sediments that accumulate in streams over time, often containing adsorbed nutrients or metals from historical pollution.

Mine Drainage Residuals (MDRs) - Amorphous iron oxyhydroxides recovered from passive treatment systems, may serve as phosphorus sinks.

Net Ecosystem Production (NEP) - Difference between gross primary production and total ecosystem respiration, represents the total amount of organic carbon in an ecosystem available for storage, export as organic carbon, or nonbiological oxidation to carbon dioxide through fire or ultraviolet oxidation.

Nutrient spiraling - The cycling of nutrients as they are assimilated from the water column into benthic biomass, temporarily retained, and mineralized back into the water column. Described by four terms: uptake rate coefficient (k); uptake length (S_W), areal uptake (U), and uptake velocity (V_f).

Passive Treatment Systems - Low-maintenance systems used to treat AMD, often relying on natural processes like limestone dissolution or wetland filtration.

pH - The negative logarithm of the hydrogen ion concentration, in which $pH = -\log [H+]$.

Neutral solutions have pH values of 7, acidic solutions have pH values less than 7, and alkaline solutions have pH values greater than 7.

PHREEQC - a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Developed by USGS.

Rare earth elements (REEs) - Rare earth elements (REEs) are a group of 15 chemical elements in the periodic table, specifically the lanthanides.

Resource Recovery - The process of extracting valuable materials (e.g., rare earth elements) from waste streams like AMD.

SPAtially Referenced Regression On Watershed attributes (SPARROW) - Models estimate the amount of a contaminant transported from inland watersheds to larger water bodies by linking monitoring data with information on watershed characteristics and contaminant sources.

Sorption - The process of sorbing as by adsorption or absorption.

Stream Metabolism - The total biotic activity in a stream, affecting nutrient uptake rates, carbon flux, and trophic status.

Total Maximum Daily Load (TMDL) - The calculation of the maximum amount of a pollutant allowed to enter a waterbody so that the waterbody will meet and continue to meet water quality standards for that particular pollutant. A TMDL determines a pollutant reduction target and allocates load reductions necessary to the source(s) of the pollutant.

APPENDIX C: List of Figures

Figure 1. Map showing Chesapeake Bay and Susquehanna River watersheds, areas underlain by coal (gray), and the distribution of streams impaired by acid mine drainage (AMD)* from legacy coal mines (orange-red). In the eastern area, anthracite coal mines discharge AMD to numerous tributaries of the Susquehanna River, whereas in the western area, bituminous coal mines discharge AMD to tributaries of the West Branch Susquehanna River. Selected U.S. Geological Survey (USGS) streamgage locations on the Susquehanna River (triangle symbol) considered in this paper are part of the Chesapeake Bay Program nontidal monitoring network (Mason et al., 2022). [From Cravotta and others (2024)] 5

Figure 2. A map of the various coal fields of the conterminous United States. Source: US Geological Survey, 2017. 8

Figure 3. Example of good (shown in green) and bad sampling locations when considering how AMD may impact nutrient loads. [Source: Travis et. al.] 15

Figure 4. Dissolved PO$_4$-P concentration and percent of PO4 sorbed to hydrous ferric oxide (HFO) when a solution containing 3.1 mg/L PO4-P and 0.09 g/L HFO (with a specific surface area of 600 m2/g consisting of 5 x 10-6 moles of strong binding sites and 2 x 10-4 moles of weak binding sites) was titrated to different pH's. Simulations were conducted using a PHREEQC model (Parkhurst and Appelo, 2013) developed by Cravotta (2021) with surface complexation data from Dzombak and Morel (1990). 25

APPENDIX D: List of Tables

Table 1. Nutrient spiraling metrics for nitrate (NO_3), ammonium (NH_4), and soluble reactive phosphorus (SRP) reported by Newcomer Johnson et al. (2016) for reference (healthy) streams. Metrics abbreviations are as follows: S_W = uptake length, U = areal uptake, and V_f = uptake velocity. 13

Table 2. Acid Mine Drainage causes by 8-Digit Hydrologic Unit Code (HUC) in water ways of the Susquehanna River basin, Pennsylvania. 17

Table 3. Summary of the advantages and disadvantages of the various process methods for enrichment of rare earth elements (REEs). Recreated from Mwewa et al. (2022). 31