Implementing the Watershed-Scale Approach to Remediation of Acid Mine Drainage from Abandoned Mine Lands in West Virginia, USA

Nathan DePriest[1], Rachel Spirnak[2]

[1]West Virginia Water Research Institute, West Virginia University, Morgantown, WV, USA, nate.depriest@mail.wvu.edu, ORCID 0009-0008-2965-4733

[2]West Virginia Water Research Institute, West Virginia University, Morgantown, WV, USA, rachel.spirnak@mail.wvu.edu, ORCID 0000-0003-2999-198X

Abstract

The West Virginia Water Research Institute (WVWRI) characterized watersheds in West Virginia (WV), USA, with water quality impairment from acid mine drainage (AMD) from abandoned mine lands (AML), prioritized such watersheds for watershed-scale AMD remediation, and developed conceptual plans for remediation. The characterization and prioritization procedures developed in the project provided a valuable blueprint for evaluating AMD impairments at a watershed scale. Prioritization of watersheds promoted informed decisions on remediation implementation. Designs documented critical considerations for remediation planning. Successful demonstration of the approach through this project aims to promote widespread implementation.

Keywords: Mine drainage, remediation, restoration, watersheds, abandoned mine lands

Introduction

Acid mine drainage (AMD) affects approximately 4,000 stream km in West Virginia (WV), USA (Skousen *et al.* 2019). Remediation of AMD in WV has historically utilized a point-source approach focused on treatment of individual regulated discharges, including active mining operations and bond forfeiture (BF) sites. Limitations to the approach are evident in restoration efficacy and cost, as the majority of AMD impairment in WV watersheds is often from unregulated abandoned mine land (AML) discharges. AML discharges remediation typically utilizes at-source passive treatment due to limited funding. Recent funding of approximately $140 million allocated to WV through the Infrastructure Investment and Jobs Act (IIJA) in each fiscal year 2022 through 2025 provides an unprecedented opportunity to remediate AMD from AML in WV at a larger scale.

The watershed-scale approach to AMD remediation aims to comprehensively address AMD throughout a watershed to balance restoration outcomes with long-term treatment cost. Implementation of the approach has been limited in WV, but a project in the Muddy Creek watershed demonstrated favorable economic and restoration outcomes by using combined in-stream and centralized treatment (Spirnak *et al.* 2025). Beyond Muddy Creek, watershed-scale projects in WV have been limited to in-stream treatment (e.g., Three Forks Creek Watershed) (Petty *et al.* 2008). Case studies, particularly using the centralized approach, are limited even at a conceptual or preliminary design level. Design of new watershed-scale AMD remediation projects is necessary to better understand implementation of the approach and to determine the most efficacious AMD remediation strategy in WV.

Implementation, financial, and environmental factors contribute to a watershed's suitability for watershed-scale remediation. While the spatial distribution of AML and associated AMD impairments is somewhat well known (WVDEP 2024a), the severity of impairment is not understood well enough to inform allocation of remediation funding. Widespread characterization efforts are necessary to support remediation decisions. WV also has unique jurisdictional concerns that have not been adequately evaluated. BF sites in WV, which are forfeited to the State when companies can no longer meet their treatment liability, must be treated to regulatory compliance. Watershed projects that require remediation of AMD sources of different jurisdictions (active regulated, BF regulated, AML unregulated) are difficult to pursue under current policies. Watersheds with AMD primarily or exclusively from AML are desirable targets because they do not require a discharge permit for treatment.

Methods

Watershed Characterization

Characterization efforts were focused in northern WV, where coal mine drainage is particularly acidic, causes widespread stream impairment, and is commonly associated with AML. Desktop evaluations considered watershed hydrology, stream impairment, AMD source jurisdiction (active, BF, and AML), mining history, and pollutant load. From November 2023 to December 2025, over 1,700 water quality samples were collected in over 50 watersheds. Four (4) were identified as priority watersheds for routine sampling: Robinson Run (HUC 050200030309), Greens Run (050200040705), Heather-Lick Run (HUC 50200040702), and Headwaters Deckers Creek (050200030201). All four watersheds are located within the Monongahela River basin in Monongalia and Preston Counties. Samples were classified according to type (in-stream, at-source AML, at-source BF, at-source active). Typical field parameters were monitored: flow, pH, temperature, conductivity, total dissolved solids (TDS), dissolved oxygen (DO), and oxidation reduction potential (ORP). Samples were collected for laboratory analysis of a full suite of AMD parameters, including alkalinity, acidity, and total and dissolved individual major metals.

Project Prioritization

Preliminary project prioritization considered treatment feasibility, restoration potential, existing data, and West Virginia Department of Environmental Protection (WVDEP) priorities. Preliminary subjective prioritization through informal mechanisms was necessary to identify watersheds of interest for initial and routine sampling. In parallel, a Watershed-Scale AMD Remediation Decision Tool was developed to promote objective watershed project prioritization by AMD treatment operators and decision-makers moving forward (Marino 2025). The tool used Multi-Criteria Decision Analysis (MCDA) and specifically the Analytical Hierarchy Process (AHP) method. MCDA is a useful decision-making tool when alternatives have multiple, often conflicting, variables to consider (Al-Bayati and Al-Zubaid 2020; Kozlov and Norek 2021). AHP is appropriate for both quantitative and qualitative assessments and has been successfully applied in site suitability, prioritization of research areas, and funding allocation decisions (Elghazouly *et al.* 2022). The Decision Tool was constructed in three levels: categories, subcategories, and criteria. Decision Tool criteria were developed using the Delphi Method (Okoli and Pawlowski 2004). A long list of criteria was developed by a multi-disciplinary team of engineers, geologists, chemists, biologists, and environmental scientists at WVWRI, then refined to a short list based on feedback from stakeholders and decision makers (e.g., local watershed groups, WVDEP). A rubric was developed to provide objective measures for scoring individual criteria on a scale of 1 to 5. Individual criteria scores were summed to develop subcategory scores. Weights were assigned to categories and subcategories based on feedback from stakeholders and decision makers. Criteria scores were combined with subcategory and category weights to determine a score for a given watershed on a scale of 0 to 1, with 1 corresponding to the highest priority. The Decision Tool was applied to one existing and one proposed watershed-scale AMD remediation project for validation and refinement. Additional details on tool development, criteria development and weighting, rubric development, and scoring are provided by Marino (2025).

Remediation Design

Conceptual designs were developed for four priority watersheds. Designs focused on centralized treatment as the remediation mechanism whenever possible. Designs identified the primary AMD sources of concern and methods for at-source treatment, elimination, or capture and conveyance to a centralized treatment location. Hydrologic and hydraulic constraints were used to evaluate treatment feasibility and identify a centralized treatment location. Designs focused on gravity conveyance of consolidated sources whenever possible to avoid operational and maintenance concerns associated with pumping AMD. Consolidation of sources and conveyance via the underground mines themselves was promoted to limit hydraulic conveyance lines. Preliminary designs are in progress. In preliminary designs, detailed methods for source capture and conveyance, active treatment, and sludge disposal are being evaluated.

Results and Discussion

Watershed Characterization

The four priority watersheds account for approximately 117 km of stream impaired by AMD and are 69-81% impaired by length (WVDEP 2016). Total underground coal mining in these watersheds was 6,855 hectares (ha); 42% of mining was classified as AML, and most mining occurred in the Upper Freeport (46%) or Pittsburgh (44%) coal seams (R. Toth, WVGES, personal communication, 2025). Over 90% of AMD discharges were classified as unregulated AML in all watersheds, except for Robinson Run, in which 39% of AMD discharges were from active regulated mining. Total acidity, iron, and aluminum loads for all watersheds from desktop evaluations of Total Maximum Daily Load (TMDL) reports were 3,514, 1,029, and 465 metric tons per year (tpy), respectively (WVDEP 2014, WVDEP 2024b).

Of the over 1,700 water quality samples collected in the project, 1,138 were collected in the four priority watersheds. At-source and in-stream samples accounted for 855 and 162 samples, respectively. Sampled AMD sources confirmed low pH and high acidity, iron, and aluminum (Tab. 1). Pollutant loads based on source sampling were similar but higher than those obtained via desktop analysis of TMDL reports. Preference was given to the data gathered from extensive sampling rather than TMDL reports, as the TMDL reports utilized modeling of less refined and recent data.

Project Prioritization

The Decision Tool was constructed in three levels (Fig. 1). Level 1 categories consisted of Implementation, Financial, and Environmental considerations. Implementation subcategories were Technical Feasibility and Community Engagement, financial subcategories were Cost and Benefit, and environmental subcategories were Impairments and Restoration. Weights for categories 1, 2, and 3 were assigned as 35, 30, and 35%, respectively, and subcategory weights were evenly split within each category. Decision-makers preferred an even distribution of weights to a higher weight for one category over the other.

Muddy Creek is the most robust existing watershed-scale AMD remediation project in WV and provided the opportunity to validate the tool and inform criteria scoring using existing data. Application of the tool

Table 1 *Summary of hydrologic and water quality data for sampled AMD sources in priority watersheds.*

Watershed	Stream length impaired by AMD (km)	No. AMD sources	Percent AML sources (%)	Flow (m^3/s), total	Acidity load (tpy), total	Iron load (tpy), total	Aluminum load (tpy), total
Greens Run	24.5	19	95	0.150	2,563	429	156
Robinson Run	16.7	24	61	0.052	1,175	285	72
Heather-Lick Run	15.4	51	98	0.202	2,104	261	175
Headwaters Deckers Creek	60.5	36	92	0.111	1,107	314	55
Total	117.1	130	–	0.515	6,949	1,289	458

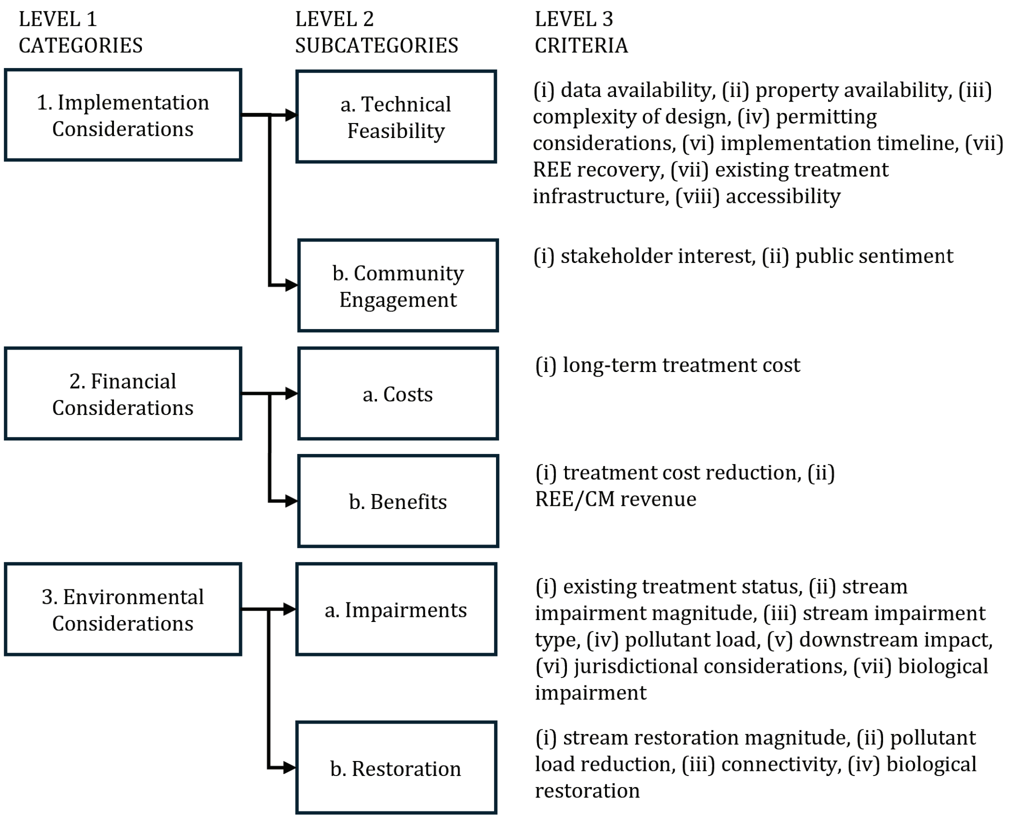

Figure 1 *Watershed-Scale AMD Remediation Decision Tool hierarchical structure and criteria.*

to Greens Run also evaluated the tool's effectiveness when evaluating a proposed project. The final scores for Muddy Creek and Greens Run were 0.622 and 0.654, respectively. Both watersheds have a similar level of impairment, restoration potential, and community engagement. Pollutant sources in Greens Run, however, are clustered more closely together, which improved technical feasibility and stream restoration magnitude. Proposed treatment in Greens Run would use centralized treatment, while treatment in Muddy Creek relied on a combination of centralized treatment for clustered sources and isolated in-stream treatment for sources in headwaters.

Preliminary application of the Decision Tool highlighted the following valuable considerations for scoring additional proposed projects moving forward: i) watershed size and pollutant spatial distribution were key factors in technical feasibility and stream restoration magnitude and should be considered closely; ii) quantitative criteria and scoring should be implemented whenever possible, as qualitative criteria (e.g., community engagement, public sentiment) are important but difficult to judge objectively; ii) databases should be built out as the tool is applied to more watersheds, as some quantitative criteria (e.g., treatment cost, biological impairment/restoration) lacked comprehensive data to easily score; iii) weighting of criteria is dependent on the number of criteria within that subcategory, so criteria should be limited to the minimum amount needed to adequately assess a watershed. Revisions to the Decision Tool based on the above considerations will be completed in future work. The Decision Tool will then be applied to a larger project dataset to produce a prioritized list based on Decision Tool output.

Remediation Design

Conceptual designs highlighted the importance of a watershed-specific approach to AMD remediation. Three of the four watersheds focused on centralized treatment, while one watershed (Headwaters Deckers Creek) required a network of at-source passive treatment systems due to the dispersed nature of the AMD. Most watersheds using the centralized approach can address all AMD discharges of interest with one centralized plant (Greens Run [Fig.2], Robinson Run), while one will need to complement centralized treatment with at-source passive or in-stream active treatment in the headwaters (Heather-Lick Run). Due to regulatory challenges, conceptual designs focused on AML sources only. When possible, however, design contingencies were recommended to account for regulated discharges (BF and active sites). These regulated discharges may be integrated into treatment if future policy allows.

In-progress preliminary plans for Greens Run and Robinson Run estimate total project costs at $9.5 and $11.2 million, respectively. Many design considerations were consistent across both watersheds and can inform remediation design in other watersheds. Priority considerations were as follows: i) pumping of AMD was limited by prioritizing gravity conveyance whenever possible through gravity lines or conveyance within the underground mines themselves; ii) a reliable location for long-term sludge disposal was identified at an early stage; iii) to minimize required maintenance for conveyance lines, pretreatment was installed where possible to convert any ferrous iron to ferric iron prior to collection; and, iv) extraneous surface water was separated from AMD wherever possible to limit treated flow to AMD only.

Treatment plant locations aimed to promote gravity flow and limit hydraulic conveyance lines. In Greens Run, this can be more easily accomplished due to proximity

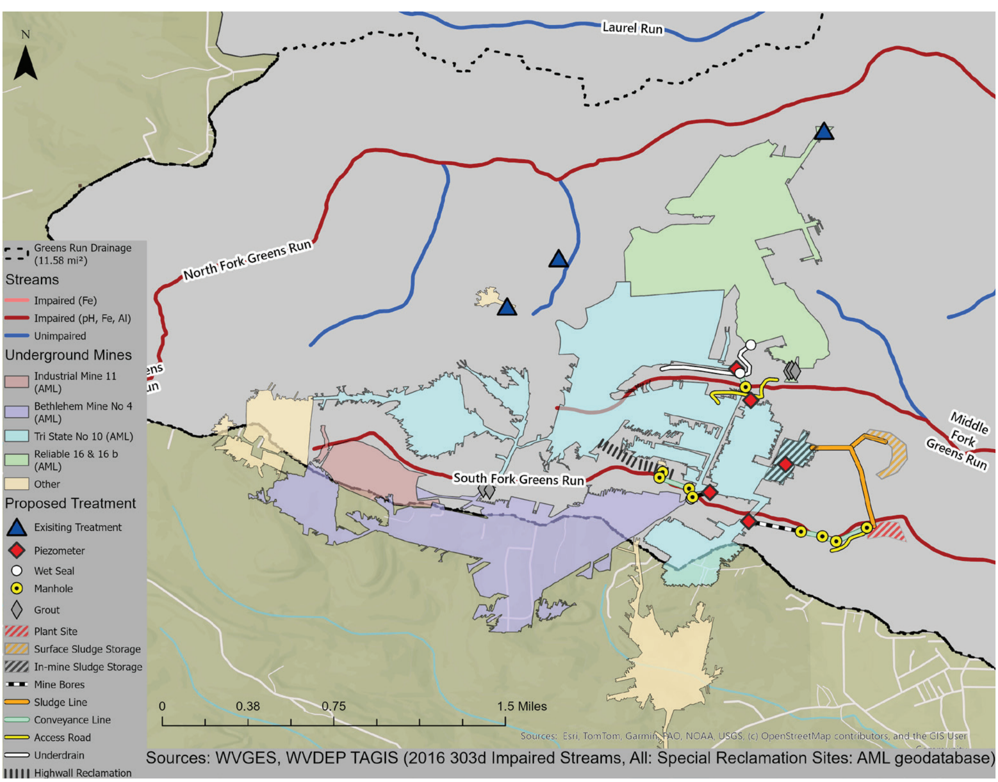

Figure 2 Conceptual design for watershed-scale AMD remediation in the Greens Run watershed.

of the sources to each other. In Robinson Run, pumping some sources to a centralized location is unavoidable due to limited locations for the plant site. Sludge disposal was a primary challenge, as almost all mines are up-dip and free-draining. Isolated sections of mines are limited but will be utilized for underground disposal, as surface storage is not feasible due to space constraints. Treatment plants will use rectangular clarifiers. This uncommon alternative to conventional circular clarifiers has been successfully implemented by WVDEP at multiple AMD treatment plants and has benefits in construction and maintenance; concrete clarifier structures can be pre-cast, smaller mechanical components can perform better in acidic conditions and be more easily replaced, and a rectangular footprint can be easily covered to mitigate weather concerns. Landowner considerations played a critical role in both projects. A network of individual private landowners who are supportive of the project was necessary to prove the feasibility of Greens Run, while the support of one to two private corporation landowners were instrumental in Robinson Run. Even with widespread landowner support, the scale of these projects (15 properties in Greens, 22 properties in Robinson) resulted in tailoring treatment plans to specifically avoid individual landowners not amenable to the project.

Conclusions

Watersheds across northern WV with impairments from AML AMD were identified as candidates for watershed-scale AMD remediation. Conceptual designs demonstrated the watershed-specific nature of evaluating remediation alternatives while also highlighting remediation mechanisms and design constraints that can be considered across all watershed projects. A Watershed-Scale AMD Remediation Decision Tool was developed to promote objective project prioritization and remediation funding allocations moving forward. Decision Tool development highlighted the importance of technical feasibility and restoration potential The multi-faceted, iterative approach utilized in this study can be employed in other regions to characterize, prioritize, and design watershed-scale AMD treatment with favorable economic and restoration outcomes.

Acknowledgements

The authors thank our colleagues at the West Virginia Water Research Institute (WVWRI) and West Virginia University (WVU) who contributed to this project and the West Virginia Department of Environmental Protection Office of Abandoned Mine Lands and Reclamation (WVDEP AML) for sponsoring this project.

References

Al-Bayati, II, Al-Zubaidy SS (2020) Applying the analytical hierarchy process and weighted sum model for small project selection in Iraq." IOP Conf. Ser.: Mater. Sci. Eng. 671 (1): 012158, doi:10.1088/1757-899X/671/1/012158

Elghazouly HG, Elnaggar AM, Ayaad SM, Nassar, ET (2022) Framework for integrating multi-criteria decision analysis and geographic information system (MCDA-GIS) for improving slums interventions policies in Cairo, Egypt. Alexandria Engr J 86, 277–288, doi:10.1016/j.aej.2023.11.059

Kozlov V, Norek T (2021) Towards objective multi-criteria drone evaluation based on VIKOR and COMET methods. Procedia Comput Sci. 192: 4522–4531, doi:10.1016/j.procs.2021.09.230

Okoli C, Pawlowski SD (2004) The Delphi method as a research tool: An example, design considerations and applications. Info & Mgmt 42(1), 15–29, doi:10.1016/j.im.2003.11.002

Marino JN (2025) Prioritizing AMD impaired watersheds for watershed-scale restoration using multi-criteria decision analysis. Graduate Theses, Dissertations, and Problem Reports. 12853. https://researchrepository.wvu.edu/etd/12853, doi:10.33915/etd.12853

Petty JT, Gutta B, Herd R, Fulton F, Stiles J, Strager M, Svetlick J, Ziemkiewicz P (2008) Identifying cost-effective restoration strategies in mining impacted West Virginia watersheds. In: Barnhisel RI (Ed), Proceedings of 2008 national meeting of the American Society of Mining and Reclamation: new opportunities to apply our science. Richard, VA p 837—355, doi:10.21000/JASMR08010837

Skousen JG, Ziemkiewicz PF, McDonald LM (2019) Acid mine drainage formation, control and treatment: approaches and strategies. Extr Ind Soc 6(1):241-249, doi:10.1007/s10230-025-01052-1

Spirnak R, Shafer M, Risch C, O'Neal M, Ziemkiewicz P (2025) Evaluation of watershed-scale acid mine drainage treatment in the Muddy Creek Watershed, West Virginia. Mine Water Environ 44:579-594, doi:10.1007/s10230-025-01052-1

WVDEP (2014) Total Maximum Daily Loads for Selected Streams in the Monongahela River Watershed, West Virginia. West Virginia Department of Environmental

Protection, Division of Water and Waste Management, Charleston, WV, US

WVDEP (2016) 2016 West Virginia Integrated Water Quality Monitoring and Assessment Report. West Virginia Department of Environmental Protection, Division of Water and Waste Management, Charleston, WV, US

WVDEP (2024a) SHP WVDEP GIS Data Abandoned Mine Lands Problem Inventory Point. https://tagis.dep.wv.gov/data/vector/SHP_WVDEP_GIS_data_abandoned_mine_lands_problem_inventory_point.zip Accessed 2026-03-06

WVDEP (2024b) Cheat TMDL 2010 Metals and pH Allocations Spreadsheet. Division of Water and Waste Management Water Quality Standards and Assessment Section, Charleston, WV, US