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CASE STUDIES

Evaluation of Watershed-Scale Acid Mine Drainage Treatment in the Muddy Creek Watershed, West Virginia

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Abstract
Acid mine drainage (AMD) from historic, unregulated mining in the eastern U.S. Appalachian Coal Basin has impaired thousands of stream km. Federal and state regulations enacted in 1977 distinguished between these unregulated or abandoned mine lands (AML) and post-1977 or regulated discharges. The regulations also required high standards of treatment for regulated, point-source discharges. Untreated AML discharges often contribute over 80% of the AMD load to watersheds, resulting in ongoing impairment despite major investments in the treatment of regulated discharges. This project evaluated watershed-scale restoration (WSR) with the objective of restoring the designated uses to a given watershed by treating AMD from both AML and regulated discharges based on their load contribution and the cost per recovered stream length. Results were compared to pre-project impairment levels and costs. Despite higher capital costs for WSR, lower operating costs resulted in net savings over the point source treatment strategy. Treatment of only regulated discharges was found to be more expensive over the long term and resulted in the recovery of zero stream km. Managing AMD treatment at a watershed scale rather than at regulated discharges only may produce superior economics in similar watersheds. Furthermore, restoration is achieved more quickly, with more stream km recovered.

Keywords Mining · Watershed restoration · Appalachia · Water quality · Economics · Stream recovery

Introduction

Acid mine drainage (AMD) is a global pollution issue resulting from mineral extraction activities. Sulfide minerals, commonly associated with metal ores and coal seams, produce AMD when exposed to an oxidizing environment through mining processes. AMD impairs streams with acidity, sulfate, and metals such as iron and aluminum (Barnes and Romberger 1968). In the United States, ≈ 20,000 stream km are affected by AMD, with ≈ 4000 impaired stream km in West Virginia (Skousen et al. 2019). Traditional AMD treatment occurs at the source where it exits the ground via a mine portal opening or a seep. Treatment generally includes the addition of an alkaline agent for pH adjustment and oxidation to allow for the precipitation of metal hydroxides. Severe sources of AMD are typically treated with continuous additions of an alkaline chemical reagent in what is known as 'active' treatment, whereas 'passive' treatment, consisting of biological or geochemical processes, is often used at other sites. Common components of passive treatment systems include constructed wetlands, limestone channels or drains, limestone leach beds, and settling ponds (Hedin et al. 1994; Gazea et al. 1995; Skousen et al. 2016). Active treatment systems vary from in-stream dosers to more expansive treatment systems that may consist of a chemical doser as well as limestone channels, aerators, mixing tanks, clarifiers, and settling ponds. In-stream dosers are silos situated adjacent to the stream channel which regularly distribute hydrated (calcium hydroxide) or pelletized (calcium oxide) lime into

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the stream via water-powered mechanisms such as tipping buckets (Coberly and Rice n.d.).

The 1977 Surface Mining Control and Reclamation Act (SMCRA) created separate programs for reclaiming abandoned mine lands (AML) (pre-1977) and regulating active coal mines (post-1977). However, there is often a combination of several AML and regulated mine sites within each watershed. The West Virginia Department of Environmental Protection's (WVDEP) Office of Special Reclamation (OSR) is responsible for treating AMD discharges from post-1977 coal mines that have transferred their surety bonds and water treatment liabilities to the State. Known as bond forfeiture sites, the cost of treating these AMD discharges to Clean Water Act (CWA) standards is high, and unfortunately, the treated water is commonly discharged to streams that are severely impaired due to AMD from AMLs. Thus, the expense of treating bond forfeiture sites rarely results in stream restoration benefits. Dimensioning efficiency as stream length restored per unit cost, there has been a recent effort toward improving the environmental performance of watershed investments utilizing watershed-scale restoration (WSR) (Leitgeb 2002; Petty et al. 2008; Throud et al. 2000). In addition to in-stream dosers, WSR taps flooded underground mine pools to transport AMD to a conventional AMD treatment facility where large volumes of AMD can be treated efficiently. This shifts treatment away from often small discharges with high capital and operating costs relative to benefit. Compliance with watershed restoration objectives is then measured at a point downstream in the watershed rather than at the point where the discharge leaves the bond-forfeited property. WSR requires strategic planning and multi-organization cooperation to remediate impaired streams with strategically placed treatment.

The West Virginia Water Research Institute (WVWRI) and WVDEP partnered to study the watershed-scale approach to treatment as early as 2008. As a result of a cost and ecological benefit study in the Three Fork Creek watershed, four in-stream dosers were constructed by the WVDEP Office of Abandoned Mine Lands and Reclamation (WVDEP AML&R) in strategic locations following recommendations from the study (Petty et al. 2008). Three Fork Creek recovered successfully, and as a result, was removed from the state 303(d) list of impaired waters for dissolved aluminum impairment in 2014 (WVDEP 2014). The WSR approach was later applied in the Muddy Creek watershed, where OSR had been treating several forfeited mine sites to discharge standards without achieving measurable improvements in the receiving streams. The treated water represented $<5\%$ of the AMD load in Muddy Creek and flowed into streams that had a pH near 3.0 due to the extent of AML sources in the watershed. Therefore, full restoration would be impossible if only the regulated discharges were treated. In late 2015, the WVDEP commissioned WVWRI to compare the costs and benefits of in-stream and point-source AMD treatment in Muddy Creek. The performance of WSR via in-stream dosing was evaluated by dosing impaired tributaries over a one-year period, monitoring water quality in response to treatment, and comparing results to restoration targets. The study found that in-stream dosing, paired with planned restoration projects, would restore 5.5 km of Muddy Creek and cost less than the current at-source treatment projects, which had restored zero stream km.

In 2017, the U.S. Environmental Protection Agency (EPA) approved a variance pursuant to Clean Water Act § 303(c) and the implementing Code of Federal Regulations (CFR) of 40 CFR § 131, allowing for an innovative permitting strategy to implement watershed-scale treatment in the Muddy Creek watershed in order to provide optimal water quality improvements where the designated use and criterion were previously unattainable (Cooper 2017). The variance permitted the treatment of bond forfeiture and AML sites together and provides instream interim water quality criteria which the WVDEP follows for its in-stream National Pollutant Discharge Elimination System (NPDES) permit at the mouth of Martin Creek. A key basis for the variance was the WVWRI study (Ziemkiewicz and O'Neal 2017), from which the WVDEP determined that the most effective treatment with the least amount of inadvertent impact to the stream was the use of instream lime dosers in combination with the construction of a centralized treatment facility.

Following these recommendations, WVDEP OSR, with the help of capital and operating contributions from Southwestern Energy (SWE), constructed a large treatment facility along Muddy Creek ≈ 0.8 km downstream of the confluence of Martin Creek, the highest contributor of AMD in the watershed, contributing over 10,886 kg/yr of iron and 867,269 kg/yr of acidity (modeled) (WVDEP 2011). In March 2018, the Muddy Creek system (commonly referred to as T&T) went online. The T&T facility treats AMD from four bond forfeiture sources, including three partially flooded deep mines and one surface mine. These sources include T&T Fuels #2, Preston Energy, Viking Coal Company, and Mary Ruth Corporation. In addition, ≈ 950 L/min of pre-1977 AML water from a refuse coal area and one deep mine are conveyed from the headwaters of Fickey Run to the facility. The system, which has a capacity of $\approx 16{,}000$ L/min, is a replacement for point-source treatment at these locations. It features an advanced computer automation system and utilizes lime slurry, polymers, a mixing tank, and two clarifiers to raise pH and remove metals. Metals are retained within the clarifiers, while clean water is discharged to Muddy Creek in a continuous flow. Two in-stream lime slurry dosers located in the tributaries of Glade Run and Martin Creek provide additional treatment within the watershed. The trial study determined that lime dosing was effective treatment for these tributaries, while collecting and piping these sources to the T&T plant for treatment was determined to be unfeasible from a technical and cost perspective. The Glade Run doser has been in place since its installation in late 2015 for the doser trial study, while the Martin Creek doser was installed in 2022.

Study Area

Muddy Creek is a 25.6 km tributary of the Cheat River that drains 87 km^2 located in northern West Virginia (Fig. 1). Approximately 5.5 stream km in the Muddy Creek drainage are impaired by AMD. Most of the acid load comes from the Martin Creek sub-watershed, including Fickey Run and Glade Run. According to the Lower Cheat River Watershed Based Plan, Fickey Run is impaired by two AML and two bond forfeiture (BF) sites, while Glade Run is impaired by five AML and five BF sites (Friends of the Cheat 2020). Both Fickey Run and Glade Run flow into Martin Creek, which receives AMD from two AML sites before it joins Muddy Creek 5.1 km above its confluence with the Cheat River. Muddy Creek, Martin Creek, Glade Run, an unnamed tributary to Glade Run at river km 1.70 (UNT/Glade Run rkm 1.70), and Fickey Run had total maximum daily loads (TMDLs) developed for aluminum, iron, and pH in 2011 (WVDEP 2011). These streams were placed in Category 4a, for waters that already have an approved TMDL but are still not meeting standards, in the most recent USEPA-approved state Integrated Water Quality Monitoring and Assessment Report (WVDEP 2016a). Apart from the Martin Creek subwatershed, the Muddy Creek watershed is minimally affected by AMD. Muddy Creek is a designated partial trout stream from its headwaters to its confluence with Martin Creek (WVDEP 2016a).

Fundamental to our approach is data collected by the WVDEP Watershed Assessment Branch (WAB), now known as the Water Quality Standards and Assessment Section (WQSAS), in coordination with OSR and in compliance with directives within the EPA-approved variance. Water chemistry monitoring occurred throughout the watershed,

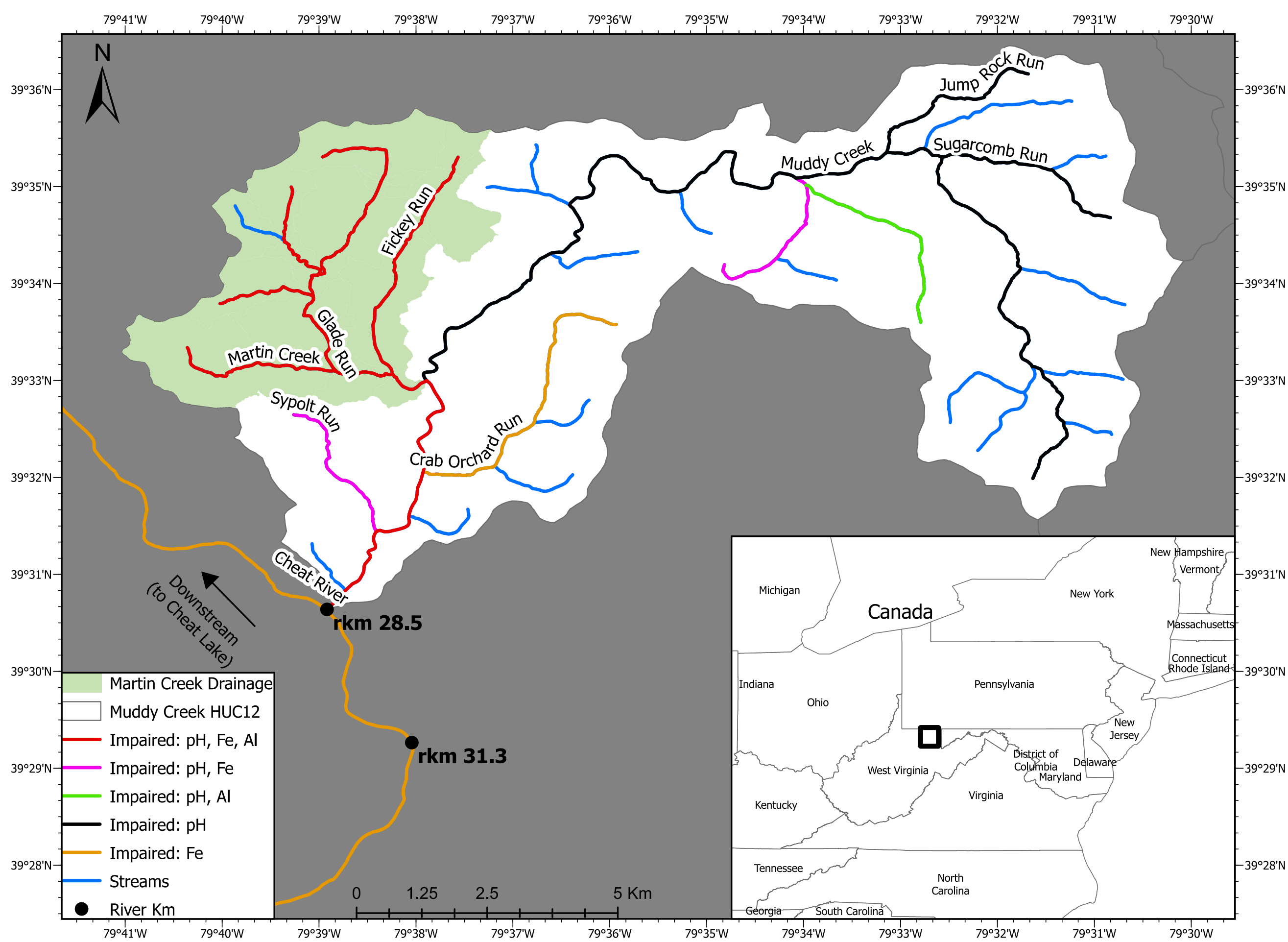

Fig. 1 Location of the Muddy Creek watershed and its stream impairments (WVDEP 2016a)

while macroinvertebrate surveys occurred at the mouths of treated streams, and fish surveys occurred in the mainstem of Muddy Creek. Where possible, only sites with pre- and post-treatment data were included in this study. Six water chemistry sites were selected. Among these six sites, four sites also included pre- and post-WSR macroinvertebrate surveys and two included pre- and post-WSR fish surveys. Two sites with limited fish monitoring data were included due to survey constraints. In total, seven sites were considered in this study (Fig. 2). The mouth of Muddy Creek was the only site with all three data types (chemical, macroinvertebrate, and fish surveys). This site combined the two locations 0.0 and 0.1 due to the proximity of the sites. Similarly, Muddy Creek 4.4 incorporated data collected at 4.6. Muddy Creek 4.6 only had pretreatment data, while Muddy Creek 4.4 only had post-treatment data. It was crucial to have data at this site as it is upstream of the main AMD disturbances within the watershed and was used as a control station for comparative purposes.

Methods

Ecological Analysis

Muddy Creek watershed data included pH, specific conductance (μS/cm), total aluminum (mg/L), total iron (mg/L), total manganese (mg/L), and sulfate (mg/L) from the WVDEP Water Quality Data Report (WVDEP 2023). One-half of the method detection limit for a particular analyte was substituted into the dataset whenever concentrations were reported as less than the detection limit (Fu and Wang 2012). Fish surveys and macroinvertebrate data were obtained from the WVDEP Water Quality Data Report—Benthic as well as personal communications (WVDEP 2023). Macroinvertebrate data were reported as West Virginia Stream Characterization Index (WVSCI) scores, total taxa, and % EPT. WVSCI is an index of biotic integrity based on six biological metrics that represent elements of the structure and composition of benthic macroinvertebrate communities, including total taxa, EPT taxa, % EPT, % *Chironomidae*,

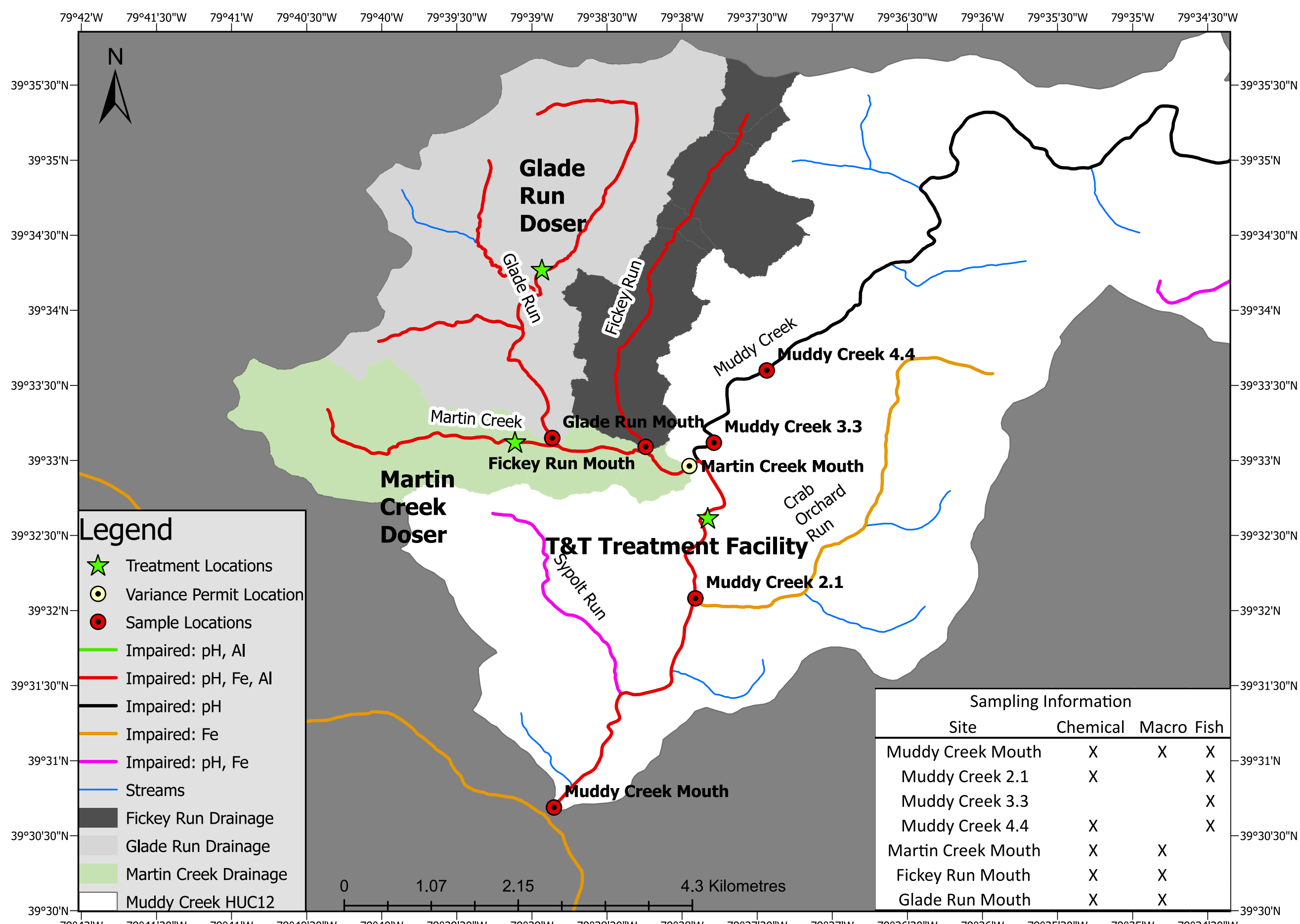

Fig. 2 Sampling and treatment facility locations within the Muddy Creek watershed

% 2 dominant, and the Hilsenhoff biotic index (family level). By standardizing the metric values to a common 100-point scale, each metric contributes to the combined index with equal weighting, and all of the metric scores represent increasingly "better" site conditions as scores increase toward 100. EPT is an index that can be expressed as a percentage of the sensitive orders (E = Ephemeroptera, P = Plecoptera, T = Tricoptera) to the total taxa found. A large EPT percentage indicates good water quality (Weber 1973). Additional WVSCI scores were gathered from two other studies in the watershed that followed the USEPA's rapid bioassessment protocols for wadable streams and rivers (Carlson 2013; Watson and Merovich 2014). These samples were collected at the same WVDEP locations: Muddy Creek Mouth, Martin Creek Mouth, Fickey Run Mouth, and Glade Run Mouth. These additional data were necessary to contribute additional pretreatment data.

Chemical and macroinvertebrate data were classified by sample location. Data were then categorized into two periods for each site, pretreatment (1996–2014) and post-treatment (2018–2022). Any data collected in the years 2015–2017 were excluded due to trial runs of the instream dosers, which resulted in variability of data from dosers starting up, malfunctioning, or being moved. If a sample site did not have both pre- and post-treatment data, it was also excluded from this study. Fish survey data were not categorized or statistically analyzed due to the limited number of surveys completed within the watershed.

Water quality and macroinvertebrate box plots were produced to provide visual summaries of data. Box plots show the mean (X), median (centerline), variation or spread (interquartile range – the box height), skewness (quartile skew – the relative size of box halves), and presence or absence of unusual values and their magnitudes (outliers). A simple Mann–Whitney U test was performed on water quality and macroinvertebrate data to determine if the means of each period for each parameter were significantly different. A hypothesized mean difference of zero and an alpha of 0.05 was set using the standard normal distribution. p values < 0.05 indicate a significant difference between pre- and post-treatment. Results are shown in table form.

Economic Analysis

The operations and maintenance (O&M) costs used in the economic calculations are based on costs incurred by OSR from 2017 to 2023 and estimates of what the point-source configuration would have cost over that same period. O&M costs include chemicals, waste disposal, and general maintenance and repairs. All construction and O&M costs, as well as projected costs for the installation of a sludge pump line, were obtained from personal communications with the WVDEP. Values from years prior to 2023 were adjusted using producer price indexes (PPIs) produced by the Bureau of Labor Statistics (BLS) and are denoted as $2023. The index data were adjusted to use 2023 as the base year. The series "PPI industry data for new industrial building construction, not seasonally adjusted" (base year 2007) was used to adjust capital expenditures for the watershed system and estimates of capital costs for the point-source system. The series "PPI industry group data for Waste collection, not seasonally adjusted" (base year 2003) was used to adjust O&M expenditures. The PPI Commodity for All Final Demand index values were used to adjust SWE's cash contributions to represent relative purchasing power in 2023. All PPIs used in this study are included in supplemental Tables S-1 through S-4.

For O&M costs with multiple years of data (the T&T plant, the Glade Run doser, and the Martin Creek doser) the average cost through FY 2023 was used. For O&M costs, OSR expenditure data were reported for fiscal year (FY) and indexes were an average of the two calendar years (CY) included in the FY. For comparison, capital costs were modeled as having occurred in year zero of the project when expenditures took place over several years (between 2017 and 2024). Similarly, all O&M costs were modeled as having begun in year one. Some estimates of point-source configuration were old, as early as 2011, and may have been less accurate than recent estimates as they have not been trued with contractual agreements. However, for capital costs these estimates were likely to be lower than actual costs, based on WVDEP's self-reported variances over the years, making them conservative. Abandonment costs to remove the original point-source treatment units (largely dosers) built in the early 2000s were not included in the analysis, as the purpose is to compare the differences between building and operating the two systems.

Results

The result of this comparison is specific to the watershed scale approach. We do not compare pre- to post-point source treatment or post-watershed to post-point source treatment. Results are presented for water quality, biological indicators, and economic analysis. A summary of results from the Mann–Whitney U test is displayed in Table 1. Parameters with a p-value less than 0.05 are considered significantly different.

Water Quality

The data showed improvements in water quality at all sites downstream of the treatment facilities for most parameters, which can be seen in the figures below for pH (Fig. 3), sulfate (Fig. 4), and metals (Fig. 5). The mouth of Muddy Creek

Table 1 Results from Mann–Whitney U test including sample count, pre- and post-treatment averages, z-test statistics, and p-value for each parameter completed at each river section within the study area

Stream section	Parameter	Sample count		Average		z test statistic	p-value
		Pre	Post	Pre	Post		
Muddy Creek Mouth	Al, total (mg/L)	16	8	8	1	−3.552	0.0004
	Fe, total (mg/L)	15	8	8.2	1.0	−3.873	0.0001
	Mn, total (mg/L)	16	5	1.8	0.73	−2.807	0.0050
	pH (su)	16	29	4	7.0	−5.406	0.0000
	Sulfate (mg/L)	15	8	305	263	−0.258	0.7963
	Specific conductance (µS)	16	30	812	484	−3.148	0.0016
	WVSCI	5	6	32.19	63.4	−2.611	0.0090
Muddy Creek 2.1	Al, total (mg/L)	12	6	8.3	2.0	−3.372	0.0007
	Fe, total (mg/L)	13	7	9.5	1	−3.606	0.0003
	Mn, total (mg/L)	13	5	1.6	0.97	−2.119	0.0341
	pH (su)	12	6	3.7	6.76	−3.372	0.0007
	Sulfate (mg/L)	13	7	244	272	−0.436	0.6630
	Specific conductance (µS)	12	6	692	559	−0.281	0.7787
Muddy Creek 4.4	Al, total (mg/L)	13	5	0.3	0.14	−1.922	0.0546
	Fe, total (mg/L)	13	5	0.2	0.14	−0.444	0.6573
	Mn, total (mg/L)	13	4	0.1	0.03	−2.208	0.0272
	pH (su)	13	5	7	7.18	−0.591	0.5542
	Sulfate (mg/L)	12	6	74	38	−2.154	0.0312
	Specific conductance (µS)	13	5	220	237	−0.148	0.8825
Martin Creek Mouth	Al, total (mg/L)	17	5	23	6.84	−3.016	0.0026
	Fe, total (mg/L)	17	5	21	2.1	−3.251	0.0011
	Mn, total (mg/L)	17	2	6.0	3	−1.461	0.1439
	pH (su)	16	5	3	4.88	−3.303	0.0010
	Sulfate (mg/L)	16	5	617	570	−0.578	0.5633
	Specific conductance (µS)	16	5	1331	1085	−1.156	0.2477
	WVSCI	7	4	22.8	41.65	−1.890	0.0588
Fickey Run Mouth	Al, total (mg/L)	13	5	40	15.5	−2.908	0.0036
	Fe, total (mg/L)	13	5	80	6	−3.105	0.0010
	Mn, total (mg/L)	13	2	7.7	2.8	−2.038	0.0415
	pH (su)	13	5	2.8	3.2	−3.056	0.0022
	Sulfate (mg/L)	11	5	1292	632	−0.736	0.4615
	Specific conductance (µS)	13	5	1910	1279	−1.971	0.0487
	WVSCI	4	4	12.9	19.5	−1.155	0.2482
Glade Run Mouth	Al, total (mg/L)	14	5	19	9.0	−2.037	0.0417
	Fe, total (mg/L)	14	5	2.5	2	−1.157	0.2472
	Mn, total (mg/L)	14	2	6.3	4.1	−1.111	0.2664
	pH (su)	13	5	3.38	6.30	−3.204	0.0014
	Sulfate (mg/L)	12	5	509	356	−0.527	0.5982
	Specific conductance (µS)	13	5	983	925	−0.641	0.5217
	WVSCI	4	4	17.25	43.48	−2.309	0.0209

displayed significant improvements in pH, aluminum, iron, and manganese. The pretreatment pH mean was 4 while the post-treatment mean was 7.0 ($p < 0.0001$). There was no major change in sulfate at Muddy Creek Mouth with a pretreatment mean of 305 mg/L to 263 mg/L post-treatment ($p = 0.7963$). Mean aluminum concentrations at the mouth of Muddy Creek were reduced by 88% from 8 mg/L pretreatment to 1 mg/L post-treatment ($p = 0.0004$). Mean iron concentrations were reduced by 88% from 8.2 to 1.0 mg/L ($p = 0.0001$). Manganese concentrations were reduced by an average of 59% from 1.8 to 0.73 mg/L ($p < 0.0001$).

Upstream of Muddy Creek Mouth, continued changes in water quality were documented. At Muddy Creek 2.1, there were significant improvements for every chemical parameter

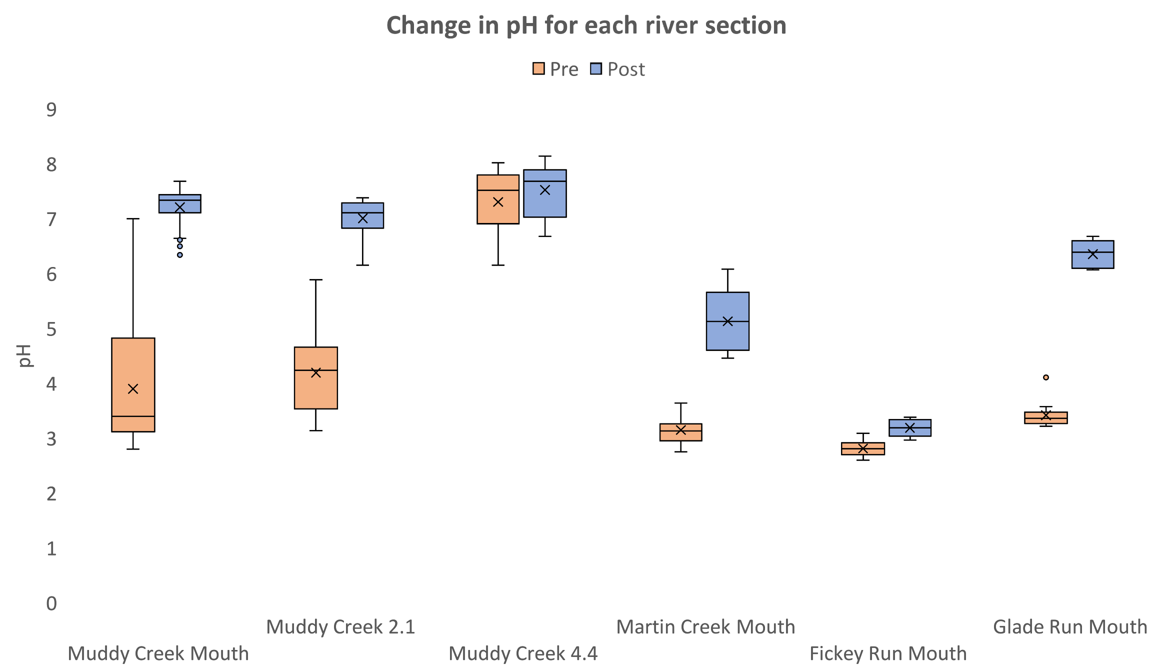

Fig. 3 Boxplots displaying the change in pH for each period and sample location, where X indicates the mean

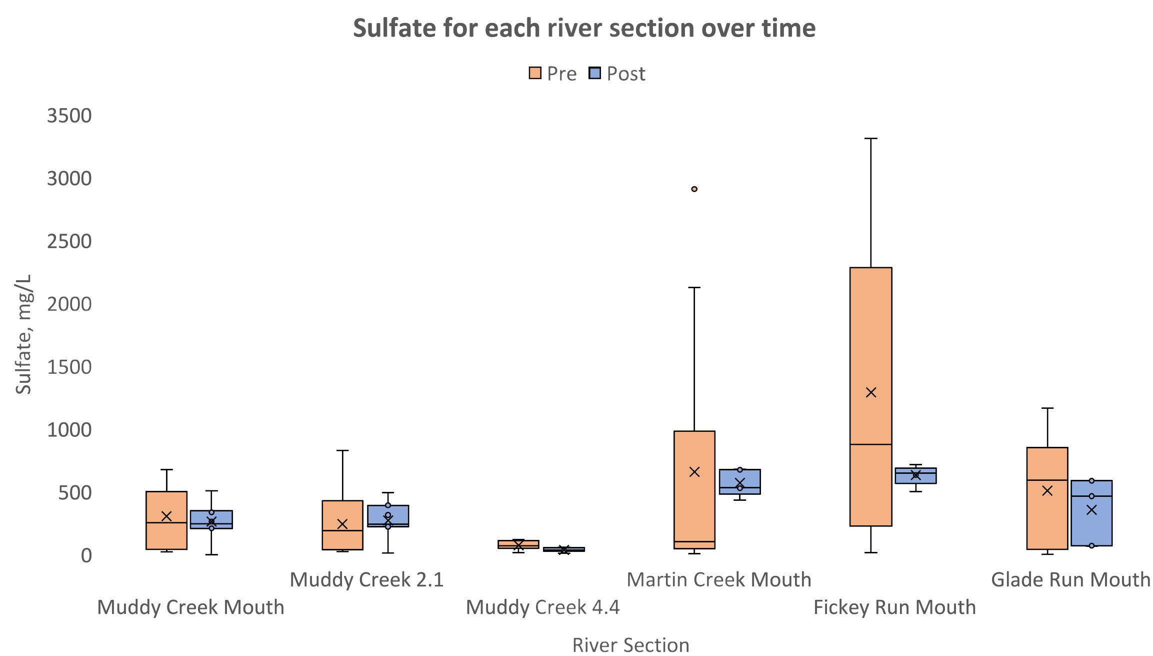

Fig. 4 Boxplots displaying the change in sulfate for each period and sample location, where X indicates the mean

except sulfate. The pH increased from a mean of 3.7–6.8 ($p=0.0007$). Sulfate concentrations were not significantly different with means of 244 mg/L for pretreatment to 272 mg/L post-treatment ($p=0.6630$). Aluminum concentration means decreased by 76% from 8.3 to 2.0 mg/L ($p=0.0007$). Iron decreased by 89% from a mean of 9.5 to 1 mg/L ($p=0.0003$). Mean manganese decreased 39% from 1.6 to 0.97 mg/L ($p=0.0341$).

The control site, Muddy Creek 4.4, had no marked change in pH, aluminum, and iron. The mean pH before treatment was 7, and 7.2 after the treatment period ($p=0.5542$). Mean sulfate concentrations were 74 mg/L pretreatment

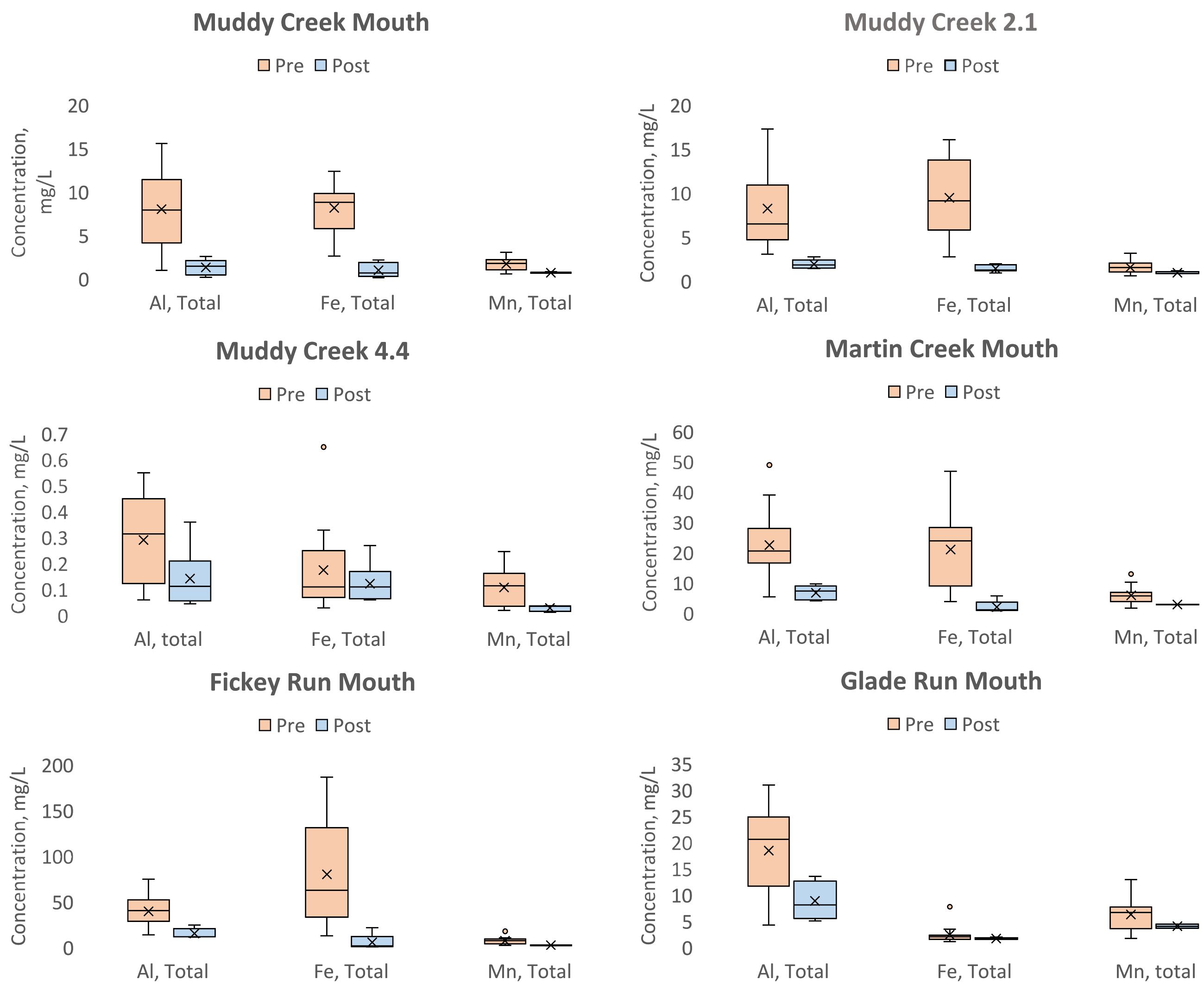

Fig. 5 Boxplots displaying the change in metal concentrations for each period and sample location, where X indicates the mean

and 41 mg/L post-treatment ($p = 0.0312$). Mean aluminum concentrations decreased by 53% from 0.3 mg/L before treatment to 0.14 mg/L post-treatment ($p = 0.0546$). The mean iron concentrations for pretreatment were 0.2 mg/L and 0.14 mg/L after treatment ($p = 0.6573$), a decrease of 30%. Mean concentrations of manganese decreased by 70%, from 0.1 to 0.03 mg/L after treatment ($p = 0.0272$).

Martin Creek Mouth saw significant changes in pH, aluminum, and iron. The pH increased from 3 to 4.9 when comparing pre- and post-treatment means ($p = 0.0010$). No major change in sulfate was observed, with a pretreatment mean of 617 to 570 mg/L ($p = 0.5633$). Mean aluminum decreased by 70% from 23 mg/L pretreatment to 6.84 mg/L post-treatment ($p = 0.0026$). Mean iron concentrations decreased by 90% from 21 to 2.1 mg/L ($p = 0.0011$). Finally, a decrease of 50% from 6.0 to 3 mg/L of manganese occurred from the pretreatment to the post-treatment period ($p = 0.1439$).

Fickey Run Mouth saw a significant increase in pH from an average of 2.8–3.2 ($p = 0.0036$). Additionally, mean metal concentrations were markedly less post-treatment. Iron means were reduced by 93% from 80 to 6 mg/L ($p = 0.0010$). Aluminum was reduced by 61% from 40 to 15.5 mg/L ($p = 0.0036$). Manganese decreased from 7.7 to 2.8 mg/L, a 64% decrease ($p = 0.0415$). Sulfate did not significantly change, from a mean of 1292 to 632 mg/L ($p = 0.4615$). The pretreatment sulfate concentrations ranged from 16 to 3312 mg/L, while post-treatment sulfate concentrations were within a much narrower range of 502–717 mg/L.

Finally, Glade Run Mouth did not see significant changes in sulfate, iron, or manganese when comparing means for pre- and post-treatment. However, the mean pH increased from 3.4 to 6.3 ($p = 0.0014$). Sulfate had a pretreatment mean of 509 mg/L and a post-treatment mean of 356 mg/L ($p = 0.5982$). Total aluminum decreased by 53% from 19 to 9.0 mg/L ($p = 0.0417$). The iron means decreased 20% from

2.5 to 2 mg/L (p = 0.2472). Finally, manganese decreased by 35% from 6.3 to 4.1 mg/L (p = 0.2664).

Biological Indicators

Macroinvertebrate surveys were completed at the mouths of Muddy Creek, Martin Creek, Glade Run, and Fickey Run pre- (1996–2014) and post-treatment (2018–2022) (Carlson 2013; Watson & Merovich 2014; WVDEP 2023). WVSCI scores at all sites increased post-treatment, with two sites exhibiting a significant increase (Fig. 6). An increase in the WVSCI score correlates to an improvement in stream health. The WVDEP generally requires a WVSCI score ≥ 72 for aquatic life uses (Warm Water Fisheries or Trout Waters) in wadable streams (WVDEP 2022). Muddy Creek Mouth saw a significant change (p = 0.0062) with an average WVSCI score nearly doubling from pre- to post-treatment. The site's average post-treatment score was 63.4 with one reading above the attainment threshold at 83.22. Glade Run Mouth also saw a significant change (p = 0.0143) with an average WVSCI score increase from 17.25 to 43.48 post-treatment. Fickey Run Mouth did not see a significant WVSCI score change (p = 0.1416), from an average of 12.9 pretreatment to 19.5 post-treatment. Similarly, Martin Creek Mouth did not experience a significant WVSCI score change (p = 0.0588); however, it had an average WVSCI score increase of 18.85 points from 22.8 pre- to 41.65 post-treatment. Correlating to the increase in WVSCI scores, all sites also displayed an increase in the total number of taxa present, and all but Martin Creek displayed increases in the% EPT (Table 2).

Eleven fish community surveys were completed by WVDEP among the Muddy Creek sample stations. Four surveys were completed at Station 0.0, three surveys at Station 2.1, one survey at Station 3.3, and three surveys at Station 4.4 (Table 3). A comparable pretreatment survey was not taken at Station 2.1, and a post-treatment survey was not taken at Station 3.3 due to low visibility within the water column. The mouth of Muddy Creek increased from zero fish pretreatment to over 130 fish during each post-treatment survey across a combined fifteen different species. While there was no pretreatment survey conducted at Station 2.1, post-treatment surveys show the presence of a combined seven species. Notably, sensitive species such as mottled sculpin and trout were found in the downstream stations of Muddy Creek during post-treatment surveys. Zero fish were found at Station 3.3, located just upstream of the confluence of Martin Creek, during the 2015 survey. Station 4.4

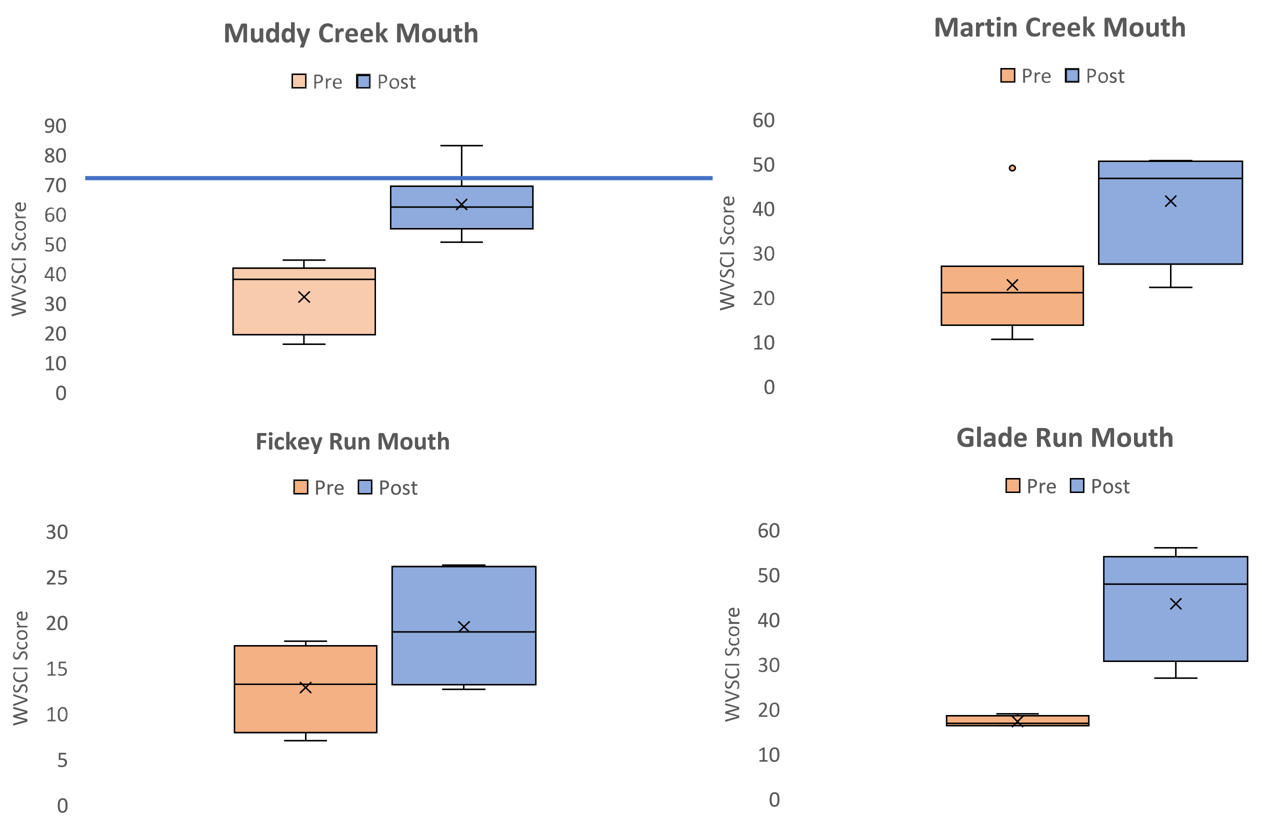

Fig. 6 Boxplots displaying the change in WVSCI scores for each period and sample location, where the blue line indicates the WVDEP threshold of 72 for meeting aquatic life uses and X indicates the mean

Table 2 WVSCI scores with% EPT and total taxa

Stream section	Parameter	Sample count		Mean	
		Pre	Post	Pre	Post
Muddy Creek Mouth	WVSCI	5	6	32.19	63.4
	% EPT	2	6	4.9	75.47
	# Total Taxa	2	6	5	11
Martin Creek Mouth	WVSCI	7	4	22.8	41.65
	% EPT	5	4	1	42
	# Total Taxa	5	4	2	7
Fickey Run Mouth	WVSCI	4	5	12.9	19.5
	% EPT	2	5	6	2
	# Total Taxa	2	5	2	4
Glade Run Mouth	WVSCI	4	5	17.25	43.48
	% EPT	3	5	0.3	41.46
	# Total Taxa	3	5	5	7

provides reference conditions of the cold-water fishery in Muddy Creek upstream of the junction with Martin Creek.

Economic Comparison of Approaches

The as-built Muddy Creek system had larger up-front capital costs than the point-source approach but will have superior economics in the long-run due to lower operating costs. The capital costs of the WSR system exceed the estimated avoided costs of building new units to treat all of the OSR sites at source by ≈ $5.7 million ($2023). Conversely, the annual treatment costs would average ≈ $830,000 less than a point-source approach. Many of the point-source locations are very remote and difficult to access, resulting in more expensive maintenance.

The watershed system capital costs were $25.4 million ($2023). These included:

- The primary water treatment plant (T&T) built in 2017 and the Glade Run doser used to treat a severely degraded feeder stream, with a combined cost of $14.9 million in $2017 ($23.3 million in $2023);
- A contribution of $2.5 million by SWE in 2017/2018 for capital expenses ($3.1 million in $2023);
- A sludge pump line to move sludge generated at the T&T plant—$2 million for a planned expenditure in 2024; and
- A new doser on Martin Creek built in 2022 to pretreat one of the more severely degraded feeder streams—$79,000 ($2023).

The Muddy Creek project has been able to leverage funds from Southwestern Energy (SWE), a natural gas producer in an adjacent county, adding to the benefits of the system. These contributions have been in the form of both capital and operating funds directed via the firm's ECH2O (Energy Conserving Water) program to support a commitment to water use neutrality hydrofracturing operations. This means that for each liter of freshwater SWE uses for well stimulation, the firm will replenish or offset an equivalent amount through conservation and innovation (WVDEP 2016b).

In the first two years of the project, SWE contributed $2.5 million to the pipeline system that transports AMD water from AML sites on Fickey Run. The firm continues to contribute $375,000 to $300,000 per year to offset operating expenses. If these contributions continue at $300,000 through the 10th year of operations, SWE will have contributed $5.6 million into the system ($6.5 million in $2023), and a total of $9.1 million could have been saved over an NPDES configuration. With the SWE funds, O&M costs to OSR are reduced to an average of $240,000/year (rounded) for the 10 years evaluated (Tables 4 and 5), saving ≈ $1.2 million per year over the NPDES approach. Going forward, OSR costs are assumed to be reduced to $280,000/year (rounded), saving ≈ $1.1 million per year over the NPDES approach.

Even with higher capital costs, it is estimated that the watershed approach will begin saving money in its seventh year of operations, which corresponds with 2024 (Fig. 7). When including funds contributed by SWE, the system likely began saving in 2020, its third year of operations.

Discussion

Muddy Creek has shown major improvements after watershed-scale treatment began. Before treatment, the mouth of Muddy Creek had an average pH of 4.3, an average iron concentration of 8.22 mg/L, and an average aluminum concentration of 8.10 mg/L. Since the implementation of WSR, Muddy Creek has maintained an average pH of 7.2 and concentrations of 1.02 mg/L of iron and 1.37 mg/L of aluminum, correlating to mean reductions of 83% for aluminum concentrations and 88% for iron concentrations. Elevated post-treatment metal values were likely associated with high total suspended solids (TSS) events. During higher stream flows, metals bound to sediments are transported in the water column. In this form, metals are not bioavailable to aquatic organisms. Benthic macroinvertebrate data suggest that the mouth of Muddy Creek has reached the attainment threshold, nearly doubling its WVSCI score since treatment began. This correlates with visual reductions in iron sedimentation, which had previously destroyed habitat available for benthics. Fish survey results show promising reestablishment of the lower portion of Muddy Creek as a cold-water fishery. Where zero fish were previously documented, fish counts are now routinely above 130 individuals across a combined

Table 3 Results from Muddy Creek fish surveys pre- and post-treatment, where 2015 represents pretreatment and 2019–2023 represent post-treatment

Common name	Scientific name	Site	0				2.1			3.3	4.4		
		Sample year	2015	2019	2021	2023	2019	2021	2023	2015	2015	2019	2023
Bluegill	*Lepomis macrochirus*		0	0	1	0	0	2	0	0	0	0	0
Brown Trout	*Salmo trutta*		0	0	0	0	0	0	0	0	6	1	3
Creek Chub	*Semotilus atromaculatus*		0	0	0	0	10	4	15	0	301	191	133
Green Sunfish	*Lepomis cyanellus*		0	3	12	4	12	11	7	0	0	0	0
Greenside Darter	*Etheostoma blennioides*		0	0	0	1	0	0	1	0	0	0	0
Longnose Dace	*Rhinichthys cataractae*		0	0	0	3	0	0	0	0	26	27	3
Mottled Sculpin	*Cottus bairdii*		0	1	1	0	3	0	0	0	225	653	340
Rainbow Trout	*Oncorhynchus mykiss*		0	0	0	0	1	1	1	0	0	2	12
River Chub	*Nocomis micropogon*		0	111	77	83	0	0	0	0	0	0	0
Rock Bass	*Ambloplites rupestris*		0	2	0	4	0	0	0	0	0	0	0
Rosyface Shiner	*Notropis rubellus*		0	10	38	19	0	0	0	0	0	0	0
Rosyside Dace	*Clinostomus funduloides*		0	1	1	0	0	0	0	0	0	0	0
Smallmouth Bass	*Micropterus dolomieu*		0	12	9	12	0	0	0	0	0	0	0
Spotfin Shiner	*Cyprinella spiloptera*		0	1	0	0	0	0	0	0	0	0	0
Stonecat	*Noturus flavus*		0	2	0	8	0	0	0	0	0	0	0
Tiger Trout Hybrid	*Salmo trutta* × *Salvelinus fontinalis*		0	0	6	0	0	0	0	0	0	0	0
Western Blacknose Dace	*Rhinichthys obtusus*		0	0	4	0	0	2	0	0	461	485	310
White Sucker	*Catostomus commersonii*		0	0	0	0	0	0	0	0	22	82	37
Yellow Bullhead	*Ameiurus natalis*		0	0	1	0	0	0	0	0	0	0	0
Total species			0	9	10	8	4	5	4	0	6	7	7
Total collected			0	143	150	134	26	20	24	0	1041	1441	838
Fish/meter			0	0.48	0.50	0.45	0.09	0.07	0.08	0	3.47	4.80	2.79

Table 4 Cost estimates and SWE contributions (values are in $2023 except for SWE nominal payments)

Year	FY	Estimated cost of NPDES configuration	Actual cost of watershed configuration	SWE nominal payments	SWE payments in $2023	Cost to OSR (watershed minus SWE payments)
0	2017	$19,731,471	$25,408,723	$2,500,000	$3,113,289	$22,295,434
1	2018	$1,406,706	$576,120	$214,000	$260,594	$315,527
2	2019	$1,406,706	$576,120	$375,000	$448,921	$127,199
3	2020	$1,406,706	$576,120	$375,000	$448,163	$127,957
4	2021	$1,406,706	$576,120	$375,000	$418,804	$157,316
5	2022	$1,406,706	$576,120	$300,000	$305,836	$270,285
6	2023	$1,406,706	$576,120	$300,000	$300,000	$276,120
7	2024	$1,406,706	$576,120	$300,000	$300,000	$276,120
8	2025	$1,406,706	$576,120	$300,000	$300,000	$276,120
9	2026	$1,406,706	$576,120	$300,000	$300,000	$276,120
10	2027	$1,406,706	$576,120	$300,000	$300,000	$276,120
10-Year totals		$33,798,527	$31,169,927		$6,495,607	$24,674,320
			Average 10-year operations and maintenance costs to OSR			$237,889
			Operations and maintenance costs to OSR beginning in 2023			$276,120

Table 5 Summary cost comparisons—point source/NPDES vs. watershed approach (in $2023, rounded)

Configuration/comparison	Cost type	Capital cost or savings	Operations and maintenance cost/year	10-year operations and maintenance cost	Total 10-year costs
Watershed configuration	Actual	$25,410,000	$580,000	$5,760,000	$31,170,000
SWE contribution	Actual and expected	$3,110,000	$340,000	$3,380,000	$6,500,000
Watershed w/ SWE contribution	Actual and expected	$22,300,000	$240,000	$2,380,000	$24,670,000
NPDES configuration	Estimated	$19,730,000	$1,410,000	$14,070,000	$33,800,000
Savings using watershed configuration	Calculated (NPDES minus watershed)	($5,680,000)	$830,000	$8,310,000	$2,630,000
Savings using watershed configuration w/SWE contribution	Calculated (NPDES minus watershed w/NPDES)	($2,570,000)	$1,170,000	$11,690,000	$9,130,000

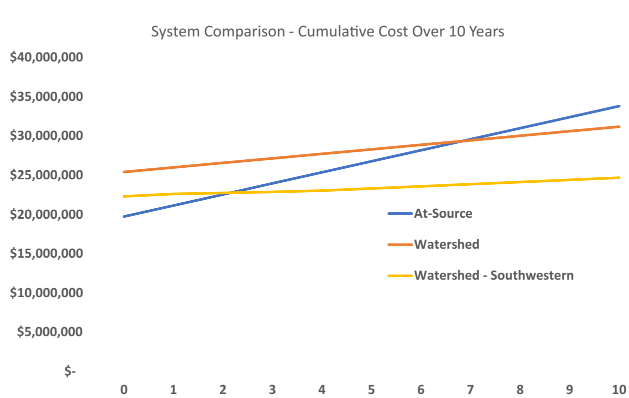

Fig. 7 Cumulative cost over 10 years—point source vs. watershed approach ($2023)

fifteen different species. Another notable improvement is the discovery of sensitive species such as mottled sculpin, smallmouth bass, and trout below the confluence of Martin Creek. These species are sensitive to toxic metals and pH produced from AMD (Allert et al. 2009). Sculpin have shown mortality, infertility, and avoidance in response to environmental contaminants associated with coal mining (Carline et al. 1994; Martin et al. 2020). Additionally, due to the lack of a swim bladder, mottled sculpin inhabit benthic habitats and are rather sedentary, with adults tending to maintain residency within small (< 0.5 m^2) patches for long periods (Petty 1998). Sculpin therefore are highly susceptible to local change and often serve as an indicator species.

It is difficult to assess the fish response between the mouth of Muddy Creek and the control station at 4.4 since there were no pretreatment surveys completed at Station 2.1. Results post-treatment show lower numbers than both the mouth site and the control site. This may be due to the presence of the short waterfalls located ≈ 0.8 km downstream of Station 2.1, which may slow fish migration upstream. The increase in connectivity resulting from the restoration of lower Muddy Creek will provide opportunities for fish recruitment from upper Muddy Creek as well as the Cheat River. Historically, the quality cold water fishery in upper Muddy Creek was cut off from the Cheat River below the confluence of Martin Creek. Fish communities in isolated headwaters have decreased diversity and abundance, and lower indices of biotic integrity (based on metrics related to species composition and ecological factors) than comparable non-isolated communities, despite suitable habitat (Stoertz et al. 2002). Thus, the downstream treatment of AMD will create aquatic corridors for fish migration to improve the fishery in upper Muddy Creek as well.

Upstream of major AMD inputs in the Middle Cheat, such as Pringle Run, the Cheat River is a productive fishery (supplemental Fig. S-1). In fact, the five forks of the Cheat (Blackwater River, Shavers Fork, Dry Fork, Glady Fork, and Laurel Fork) are well-known trout fishing destinations. Prior to 2010, the segment of the Cheat River from river km 82 to Cheat Lake was listed as impaired for pH and metals and was considered biologically dead. Due to the treatment of AMD within several key tributaries, the Cheat River is no longer listed as impaired by pH. Regular measurements from the 1970s to 2022 demonstrate decreasing iron and aluminum concentrations and increasing alkalinity (USEPA 2022). As a result of these improvements, there has been a resurgence in fish diversity. The entire length of the Cheat River now supports fish populations, including pollution-sensitive walleye and a healthy perch population. Fish survey reports from Cheat Lake during the 1950s documented a total of 14 species, predominately within the *Catostomidae* (suckers) and *Ictaluridae* (catfish) families (Core et al. 1959). Presently, Cheat Lake supports over 46 fish species, including large and smallmouth bass, walleye, northern pike, yellow perch, channel catfish, and sunfish. Channel catfish of quality length are abundant and fast-growing in Cheat Lake (Hilling et al. 2016). Each summer, the lake hosts several bass fishing tournaments. Despite anecdotal improvements, it is difficult to fully assess the effect of Muddy Creek's treatment on the Cheat River. Pringle Run and several other AMD-polluted tributaries enter the Cheat ≈ 14.2 km upstream of Muddy Creek. In addition, there are little to no published biological surveys within the segment of the Cheat River from Pringle Run to Cheat Lake. It is important that pre-project, Muddy Creek contributed ≈ 50% of the total acid load to the Cheat River. Muddy Creek is now net alkaline.

Improvements have also been documented in the Martin Creek subwatershed as a result of centralized treatment. Specifically, the subwatershed benefits from the direct capture and conveyance of AMD from flooded mine pools to the plant and in-stream dosers in Martin Creek and Glade Run. Before treatment, the mouth of Martin Creek had an average pH of 3.2 and mean iron and aluminum concentrations each above 20 mg/L. After treatment, it has improved to an average pH of 5.1 with 70% and 90% reductions in aluminum and iron, respectively. The Fickey Run and Glade Run tributaries also displayed marked pH improvements. Additionally, Fickey Run experienced a notable 93% reduction in iron and 61% reduction in aluminum. Given the improved chemical environment, benthic macroinvertebrate assemblages also improved in all three streams.

Despite improvements, the Martin Creek subwatershed has not yet fully recovered. The Martin Creek doser was installed in 2022, and therefore its effects are not captured in this study. Macroinvertebrate reestablishment after AMD treatment can take more than eight years due to multiple factors, including drought events, delayed or setback recovery, competitive exclusion, and lack of watershed vegetation (Gunn et al. 2009). Additionally, "sacrifice zones" occur downstream of dosers where iron and aluminum hydroxides precipitate. The length of the sacrifice zone in AMD-remediated streams depends on the stream velocity, gradient, and alkalinity, all of which influence its ability to carry away metal sediments (Kruse et al. 2013). Within the sacrifice zone, finer sediments may negatively affect the biological recovery of the stream. McClurg et al. (2007) found a 1.9–2.9 km zone of ecological impairment downstream from limestone sand treatment in acid deposition-affected watersheds of West Virginia. Sacrificial zones associated with AMD treatment can be much longer due to greater metal concentrations (Merovich & Petty 2007). In one Ohio stream affected by AMD, Johnson et al. (2014) found that precipitated metals were elevated for 2.9–5.0 km immediately downstream of the doser. The doser on Martin Creek is located ≈ 1.9 km from its mouth; thus, biological recovery may be limited in this tributary due to the sacrifice zone of metal precipitation.

The combination of lime dosers and the T&T treatment facility was expected to restore the lower 5.5 km of Muddy Creek below the confluence of Martin Creek to its designated use, thus effectively reestablishing biologic connectivity throughout the entire 26 km of Muddy Creek. This analysis shows evidence that Muddy Creek is reaching this goal just five years into treatment. Routine data collected at the mouth of Muddy Creek shows that it is no longer an important contributor of AMD-related impairments to the Cheat and is net alkaline with low metal concentrations. It has also shown WVSCI scores above the attainment threshold and a dramatic increase in fish abundance and diversity. The current variance is in effect until July 1, 2025, though the State may adopt a subsequent water quality standards variance consistent with § 131.14 of the Water Quality Standards Regulatory Revisions Final Rule. Martin Creek has met the interim criteria at the in-stream compliance point since its implementation. However, Muddy Creek mainstem is still occasionally outside of the parameters for healthy water quality standards related to iron and aluminum. While the T&T facility is a major component of watershed treatment, additional treatment measures are needed to address additional abandoned mine land sources. Approximately 1.1 km above Martin Creek, Muddy Creek receives AMD from several AML sources originating from the Dream Mountain Ranch. In 2024, Friends of the Cheat completed enhancements to a passive treatment system that treats these sources. The completion of enhancements to this system will contribute to the connectivity of the upper and lower portions of Muddy Creek. In addition, WVDEP is exploring the possibility of piping additional sources to the T&T plant, but several limitations exist. Some sources are not feasible to pipe to T&T due to hydraulics, cost, or jurisdictional challenges. Furthermore, treating additional sources at T&T may incur O&M challenges or exceed the plant's capacity. The current conveyance system from the headwaters of Fickey Run is difficult to maintain due to ferric hydroxide scaling and highlights the importance of pretreating ferrous iron. AML&R has constructed a low-pH iron oxidation bed at the Fickey headwaters to address this issue.

While AMD is the primary polluter of Muddy Creek, the mainstem and several tributaries (including Martin Creek and Fickey Run) are also impaired by fecal coliform (WVDEP 2014). Additional impacts to the watershed may include other nonpoint sources such as oil and gas development, harvested forest, roads, and barren land which may contribute to pollutant loads, streambank erosion, or sedimentation. These impacts have not been studied but could be incorporated into future phases of restoration planning (Friends of the Cheat 2020).

Prior to the variance, OSR had been treating sources of AMD at forfeited mine sites since as early as 1995 and was responsible for ten NPDES outlets within the Muddy Creek watershed. This included construction, operations, and maintenance at nine active sites with fifteen lime dosers, and one passive system at six bond forfeiture sites, not including three other sites planned for future construction. Costs to build and operate the existing sites totaled ≈ $3.4 million for construction and nearly $10 million for operations and maintenance (≈ $940,000 annually) prior to the approval of the variance in 2017 (Cooper 2017). Without an alternative permitting structure, OSR would have been required to retrofit seven existing treatment systems and construct two new sites within the Martin Creek subwatershed, all without restoration of Muddy Creek. The watershed approach allowed OSR to save money by avoiding both capital costs associated with building new point-source treatment systems to NPDES standards and operational costs by not having to treat water at point-source for all existing and new permits in the watershed. Many point-source locations are very remote and difficult to access, resulting in more expensive maintenance.

Approaching treatment from a watershed-scale rather than a point-source scale may produce superior economics in similar watersheds. Furthermore, the treatment is completed more quickly with more stream km recovered. Additionally, centralized treatment has the potential for recovering rare earth elements (REEs) and critical materials (CMs) from the AMD treatment byproducts (Larochelle et al. 2021). This would be less practical in small passive or doser systems. Projected revenues from REE/CMs will likely offset operations and maintenance costs at the facility, based on economic studies conducted at different AMD treatment locations (Larochelle et al. 2021; Ziemkiewicz 2023; Ziemkiewicz et al. 2023).

Muddy Creek serves as an early case study for WSR utilizing a combination of centralized and in-stream treatment. Each watershed is unique and may require a combination of different approaches to treat all AMD sources. Other watersheds may have the opportunity to treat all sources at one or several centralized plants by taking advantage of connected mine pools to collect the water at a few locations. This approach lessens conveyance maintenance challenges and avoids "sacrifice zones" associated with in-stream treatment. Plants should be designed with a factor of at least 20% applied to treatment sizing to accommodate uncertainty, including increased high flow events from climate change. One major challenge to WSR that must be considered is the existence of sources under different jurisdictions within one watershed. WSR is simplest in watersheds with only one type of mining (pre- or post-law). In watersheds with a mixture of pre- and post-law mining, the cooperation of different agencies is essential to the success of WSR. These agreements should be forward-thinking to allow for future expansions or upgrades that may not be apparent at the time of construction. Third-party contributions, without regard to the industrial sector, should also be encouraged. Ultimately, a regulatory solution that accommodates WSR as a viable alternative to permitted point source treatment is needed.

This study was limited by the availability of pretreatment data, especially biological data, flow data to calculate pollutant loadings, and data on the receiving Cheat River. Collecting data from the Cheat River downstream of

Muddy Creek is extremely difficult due to access limitations and whitewater, so available fish data was collected a considerable length (≈ 28 km) downstream in Cheat Lake. Future watershed-scale treatment projects should include biological considerations, such as stream connectivity and sacrifice zones, in the early planning stages. Additionally, a plan for fish and benthic surveys should be implemented before treatment in order to assess its effect on biological recovery.

Conclusions

Watershed-scale treatment reduces the number of treatment locations while restoring the maximum number of stream km. For less cost than the conventional point-source approach, the watershed approach treats most of the acidity in the stream rather than the small fraction that originates at regulated sites. Muddy Creek provides a case study for the effectiveness of this approach. After five years of treatment, evidence shows that it has greatly improved the water quality and biological richness of Muddy Creek, thus reconnecting upper Muddy Creek with the Cheat River system. Once the largest contributor of AMD pollution into the Cheat, Muddy Creek is now net alkaline.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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