

The Lasting Impacts of Offline Periods in Lime Dosed Streams: A Case Study in Raccoon Creek, Ohio

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Abstract Hewett Fork in Raccoon Creek, Ohio was a large source of acid mine drainage (AMD) to the main stem of Raccoon Creek, impacting the biological community for several kilometers. To reduce this impact, the AMD treatment was implemented in the Hewett Fork subwatershed to treat water from the largest mine drainage source in the watershed near the village of Carbondale. From prior to installation of wetland treatment in 2000 and installation of the lime doser in 2004, the pH of the mine discharge has been raised from about 4 to about 9, which greatly improved biological communities in Hewett Fork and Raccoon Creek. During the summer of 2010, the doser was off-line for approximately 2 weeks. While the chemistry of Hewett Fork showed little lasting change due to non-treatment, biological surveys show the effect of temporary non-treatment. In the year and a half since the doser was off-line, surveys have shown that the fish community was seriously impacted due to non-treatment and it has not yet recovered; the macroinvertebrate community, on the other

hand, showed little impact due to non-treatment, and has shown no lasting effect of non-treatment.

Keywords Calcium oxide · Active treatment · Doser · Biological recovery

Introduction

Raccoon Creek is a direct tributary of the Ohio River. The Raccoon Creek Watershed in Southern Ohio has a drainage area of 1,772 km² (684 square miles); it is 75 % forested and is very rural. 8,721 ha of surface mines and 10,364 ha of underground mines were abandoned before the Federal Surface Mine Control and Reclamation Act was passed in 1977. Most of the mining occurred in the head waters of Raccoon Creek and in the Little Raccoon Creek subwatershed marked on Fig. 1. Hewett Fork is a subwatershed in the headwaters of Raccoon Creek watershed (shaded dark gray in Fig. 1). Three major sources of acid mine drainage (AMD), shown in Fig. 2, affect Hewett Fork, Carbondale East and West drifts, Carbondale Creek and Trace Run (Fig. 2). Before treatment, mine drainage from Hewett Fork caused fish kills in the mainstem of Raccoon Creek (Rice et al. 2002).

After previous wetland treatment did not meet acidity load reduction targets (NPS 2009), an Aquifix lime-doser (Fig. 2) was installed in the Spring of 2004 using the discharge of Carbondale East drift to power the auger. Passive treatment systems estimated to be either insufficient or cost prohibitive at this site. While the initial use of kiln dust caused bridging in the doser, subsequent dosing with calcium oxide has been effective in not only buffering the acid from Carbondale East and West, but also from Carbondale Creek and Trace Run (NPS 2009) for all but a few recorded

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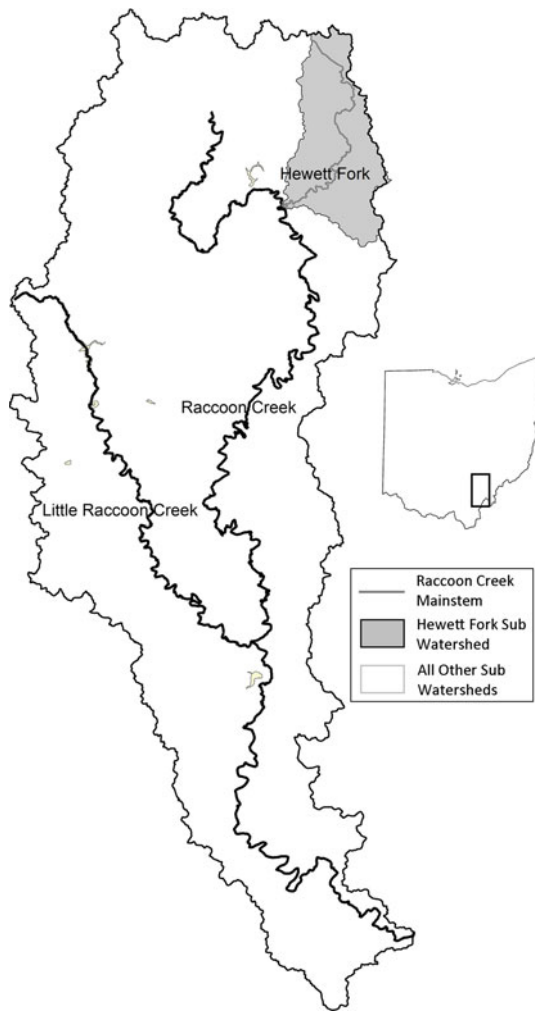


Fig. 1 Raccoon Creek Watershed with Hewett Fork subwatershed highlighted in grey

events. Due to space and financial restrictions, no sediment pond or polishing wetland was included in the treatment system, so a stretch of stream downstream from the doser discharge collects the majority of the precipitates formed during treatment. Initially, the goal of the Carbondale Doser was to reduce the impact that Hewett Fork had on the mainstem of Raccoon Creek, 17.7 km (11 miles) downstream. While achieving warm water habitat use designation in Hewett Fork was never an articulated goal, monitoring since construction has shown that it is achievable.

The Ohio EPA (OEPA) classifies streams based upon use designation recommendations that take into account a combination of biological, chemical, and physical attributes (OEPA 1997). Raccoon Creek is considered a warm water stream since water temperatures are too high to support salmonids or other cold water species. The use designation categories used in Raccoon Creek are Exceptional Warm Water Habitat (EWH), Warmwater Habitat

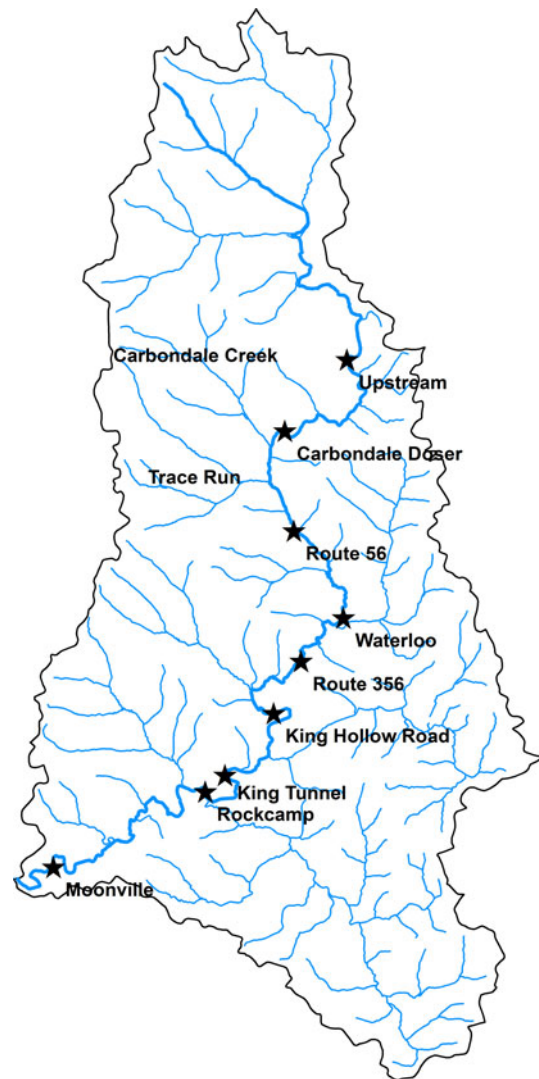


Fig. 2 Map of sampling points in the Hewett Fork subwatershed of Raccoon Creek

(WWH) and Limited Resource Water–Acid Mine Drainage (LRW-AMD). Attainment of each use designation is based upon biocriteria defining health of fish communities and macroinvertebrate communities, as shown in Table 1. While the macroinvertebrate biotic index used here (MAIS, Macroinvertebrate Aggregate Index for Streams) is not officially used for stream designation, it is used in this region as an approximation for the official measure (ICI, Invertebrate Community Index), which may only be assessed once per decade by Ohio EPA due to resource restrictions. Hewett Fork was originally designated as LRW-AMD, suggesting that it has no near-term prospect for recovery; however, after treatment, some sites in the lower reaches of Hewett Fork are in partial attainment (meeting some but not all of the biocriteria) of WWH.

This paper is a case study of the effects of the Carbondale doser running out of calcium oxide for an interval

Table 1 Ohio EPA biocriteria for stream use designations (OEPA 2007)

	EWH	WWH	LRW-AMD
QHEI	75	60	n/a
IBI	50	44	18
MAIS		12	

MAIS is not officially used by OEPA as a biocriteria. QHEI is a measure of habitat quality but not a measure of attainment

during the summer of 2010. The empty doser was discovered within a week; material ordering and shipping times led to a down-time of nearly 2 weeks. While this was the result of simple human error, it provided an ideal opportunity to study both the effects of non-treatment or the shock of untreated water and the biological recovery of the stream. Although it has been investigated, telemetry monitoring of doser contents is not feasible at this site due to its remote location and lack of cellular coverage; a hard line telemetry system is out of the financial scope of the Raccoon Creek Partnership. In addition to the empty doser, the concrete channel downstream of the doser that channels dosed mine water to Hewett Fork had recently been emptied of excess calcium oxide precipitates by vacuum truck (during Spring 2010), so much of its residual buffering capacity was removed and the residence time in the channel was reduced.

Methods

Water chemistry was measured multiple times per year at the monitoring sites shown in Fig. 2, including monthly samples from Waterloo to Moonville from July 2010 to June 2011. Biological quality was assessed at each site, although which assemblages were assessed varied by year based on the annual sampling plans of the Raccoon Creek Partnership, Ohio Environmental Protection Agency, Ohio Department of Natural Resources and Ohio University. Assessment of fish communities results in a multimetric index of biological health called the Index of Biotic Integrity (IBI) (Karr 1981) and the assessment of macroinvertebrate communities results in a multimetric index of biological health called the Macroinvertebrate Aggregate Index for Streams (MAIS) (Smith and Voshell 1997). This study presents biological data collected at the seven locations on Hewett Fork shown in Fig. 2. The Route 56 site represents the sacrifice zone in Hewett Fork downstream from the doser; Waterloo, Route 356, and King Hollow Road sites represent the transitional zone between poor and fair biological quality and King Tunnel, Rockcamp, and Moonville are sites that were expected to show strong biological recovery. Site information is shown in Table 2;

Table 2 Site names and locations for all sites evaluated on Hewett Fork

Site name	River (km)	Distance downstream of doser	Drainage area
Upstream	22	n/a	7.7 ac/3.1 ha
Carbondale doser	17.7	0	n/a
Route 56	15.8	1.2 mi/1.9 km	14.9 ac/6 ha
Waterloo	13.4	2.7 mi/4.3 km	16.5 ac/6.7 ha
Route 356	11.6	3.8 mi/6.1 km	19.9 ac/8.1 ha
King Hollow Rd	10.3	4.6 mi/7.4 km	22 ac/8.9 ha
King Tunnel	8	6 mi/9.7 km	27 ac/10.9 ha
Rockcamp	6.4	7 mi/11.3 km	35 ac/14.2 ha
Moonville	1.4	10.1/16.3 km	40.2 ac/16.3 ha

Fig. 2. In addition to these sites, water quality was measured at the discharge from the Carbondale East and West drifts before April 2004, and the discharge from the doser after April 2004. Water quality was measured at all sites quarterly from July 2010 to Oct. 2011 and monthly for the sites from Waterloo downstream to Moonville from July 2010 to June 2011.

Field data was measured with a sonde or handheld meter (equipment: Yellow Springs Inc. 600 XLM datasonde or Myron L Ultrameter 6P) and included temperature (degrees Celsius), pH, specific conductivity ($\mu\text{S}/\text{cm}$), and dissolved oxygen or ORP (mg/L and percentage saturation or mV). A three point pH calibration and calibration with 1,500 $\mu\text{S}/\text{cm}$ conductivity standard were conducted the morning of each field day. Calibration checks were performed to check the probe life; probes were changed if the calibration checks were not within ± 0.1 pH standard units and $\pm 10\%$ of the conductivity standard level. Water flow was measured at each site with a SonTek Flow Tracker handheld-ADV, a pygmy flow meter, or a Baski collapsible cutthroat flume. Filtered preserved (5 ml 20% v/v HNO_3), non-filtered preserved, and non-filtered non-preserved samples were gathered and sent to the Ohio Department of Natural Resources—Division of Mineral Resources Management Environmental Lab in Cambridge, Ohio for analysis of chemical water quality characteristics. All samples were stored at 4 °C until analysis. Analysis was performed for acidity, alkalinity, pH, temperature, specific conductance, hardness, total dissolved solids, total suspended solids, dissolved oxygen, sulfate, calcium, magnesium, aluminum, iron and manganese using a Perkin Elmer Optima 2000 ICP, a Dionex ICS-2000 Ion Chromatography system and a Brinkmann Automated Titration system. All field data is catalogued on Ohio University's Voinovich School's web-based watershed database (<http://www.watersheddata.com>).

All 2010 bioassessments were performed after the doser was offline and subsequently refilled. Macroinvertebrate

surveys were performed during July 2010, within two to 3 weeks after the doser was refilled. Fish surveys were conducted from Aug. 3–6, 2010, with a second survey on Sept. 20, 2010 at key sites to confirm the impact of non-treatment. The results presented here show the chemical and biological response to 2 weeks of non-treatment and the level of biological recovery during the year after the doser was refilled.

Index of Biotic Integrity (IBI)

The index of biotic integrity (IBI) is a multimetric index for fish populations (Karr 1981; OEPA 1988). It is used in Ohio to assess the attainment of water quality use designations for warm water streams (OEPA 2007). The IBI is calculated based upon 12 different factors; each factor is given a score of either 1, 3, or 5. The minimum score is 12 and the maximum is 60. A score of 44 is required to attain a WWH use designation for wadable sites in the Western Allegheny Plateau ecoregion of Ohio (includes Raccoon Creek watershed). The metrics that are included in this multimetric index for wading streams are total number of species, number of darter species, number of sunfish species, number of sucker species, number of intolerant species, percent tolerant species, percent omnivores, percent insectivore species, percent top carnivores, number of individuals, percent simple lithophils, and percent with DELT (deformities, eroded fins, lesions, and tumors) anomalies. The sites on Hewett Fork were assessed according to Ohio EPA protocols, including a 200 m reach of stream sampling from downstream to upstream during the index period of April 15 to Oct. 15.

Macroinvertebrate Aggregated Index for Streams (MAIS)

The Macroinvertebrate Aggregated Index for Streams (MAIS) is a family-level rapid bioassessment method for macroinvertebrates (Smith and Voshell 1997) accepted by the Ohio EPA as a level 2 (rapid) bioassessment method for assessment of mine impacted streams in the Western Allegheny Plateau ecoregion, including Raccoon Creek (Johnson 2009). MAIS scores are calculated based on nine metrics and can range from 0 to 18. These metrics include number of Ephemeroptera (caddisfly), Plecoptera (stonefly) and Trichoptera (mayfly) families, number of mayfly families, percent abundance of mayflies, percent of population made up by the five most dominant taxa combined, Simpson Diversity Index (integrates richness and evenness), Modified Hilsenhoff Biotic Index (taxa are weighted by pollution tolerance), number of intolerant taxa, percent of the sample that are scrapers (macroinvertebrates that feed on periphyton), and percent of that sample that are

haptobenthos (macroinvertebrates that require clean, coarse, firm substrates) (Johnson 2009). The sites on Hewett Fork were all sampled using standardized rapid bioassessment methods. Within a 150 m reach, three riffles were sampled using kick nets and all other available habitats were sampled with 20 jabs of a d-ring dip net. All individuals were picked from the nets in the field and preserved in ethanol for identification to family and quantification. For consistency, macroinvertebrate sampling was conducted during July of each year.

Results

While the Carbondale doser improved the chemical and biological quality of Hewett Fork when it was installed in Spring 2004, the doser was inadvertently left empty for approximately 2 weeks during late June 2010. The last IBI measurement prior to that time was in 2008 at Waterloo, 4.7 km (2.9 miles) downstream from the doser, with a score of 24 (up from the pre-treatment minimum value of 12); the last prior MAIS measurement was in 2009, with a score of 6 (no pre-treatment data exists). In the week prior to the doser being off-line (on June 23, 2010), an electro-fishing demonstration (not a full survey) was performed at Waterloo by the authors. During this demonstration, in addition to many pollution tolerant species, several longear sunfish in full mating color, least brook lamprey, and redbfin shiners were found, indicating water quality and habitat improvements. Redfin shiner and least brook lamprey were new species at this site and least brook lamprey are a declining species in Ohio (OEPA 1988).

Prior to construction of the doser, Carbondale East and West contributed over 317.5 kg/day (700 lbs/day) of acid into Hewett Fork. Between installation of the doser in Spring 2004 and June 2010, when the doser was temporarily off-line, the discharge from the doser (Fig. 3) and Moonville at the mouth of Hewett Fork (Fig. 4) were consistently net alkaline. It appears that the doser being off-line did not significantly affect the aquatic chemistry of Hewett Fork, as shown in Fig. 4. Since the doser was refilled, the dosing rate has been adjusted several times to minimize the maintenance necessary due to excess calcium oxide in the concrete channel downstream. This, along with low flow effects have contributed to the variability of net alkalinity at both Waterloo and Carbondale, as shown in Figs. 3, 4. As shown in Fig. 3, since the June 2010 period of non-treatment, the discharge from the doser has been less consistently and less strongly net alkaline. The TMDL (total maximum daily load) for Raccoon Creek for biological recovery is 20 mg/L net alkalinity (OEPA 2002). From Spring 2004 to June 2010, the average net alkalinity of the doser discharge (Site 131) was

230 mg/L as CaCO₃, from June 2010 to October 2011, the average net alkalinity of the doser discharge was -5.4 mg/L as CaCO₃. In contrast, the net alkalinity at Moonville has remained consistently positive (average 24.2 mg/L as CaCO₃) and the net alkalinity at Waterloo has remained consistently net neutral (average 1.1 mg/L as CaCO₃) since the doser was installed. While the net alkalinity in the doser discharge has been variable from June 2010 to Oct. 2011, the metal concentrations at both Waterloo (average 2.5 mg/L total iron and 1.0 mg/L total aluminum) and Moonville (average 0.65 mg/L total iron and 0.18 mg/L total aluminum) have remained at the post-treatment levels despite both the period of non-treatment and the varying dosing rates the following year.

However, the health of the biological communities is a better indicator of long term improvement. Since the construction of the doser, biological health has improved throughout the Hewett Fork subwatershed, as seen in Figs. 5,6,7. As shown in Fig. 5, the IBI at Waterloo pre-treatment was 12, the lowest possible score. During the next few years, the IBI improved to a maximum of 30, and consistently achieved a score of 24. In the 2010 sampling season, fish were surveyed twice at Waterloo; both surveys resulted in a score of 12. During the 2011 sampling season, all sites except Moonville were sampled for fish; the IBI score at Waterloo remained at the minimum score of 12 and the remaining scores, as shown in Fig. 5, were significantly lower than the scores measured between 2004 and 2008, with the exception of King Tunnel. The low score at Rockcamp in 2011 is most likely a result of the difficult sampling conditions caused by deep water rather than poor water quality. While the IBI scores have been remarkably low in 2010 and 2011, the fish species richness has not decreased significantly, as shown in Fig. 7. Apparent decreases in species richness below river km 6.4 are most likely due to gradual deepening of the sample sites, making sampling more difficult. While this is merely a measurement of the number of fish species collected, consistent species richness with decreasing IBI scores suggests that the system cannot support either large communities or communities of intolerant or moderately intolerant fish. The data implies that the short term pollution spike followed by minimal treatment impedes the ability for the fish population to rebound. While this paper does not attempt to diagnose the mechanism, many possibilities exist including temporary exceedence of a tolerance value for a particular contaminant and interruption of reproduction (e.g. Driscoll and Schecher 1990; Gotomski 1990).

The macroinvertebrate scores in 2010 returned to the pretreatment level of 3 at Route 56 and Waterloo, the lowest levels measured at these sites since the doser was installed, as shown in Fig. 6. The 2007 macroinvertebrate survey also showed low scores (MAIS score = 3) at Route

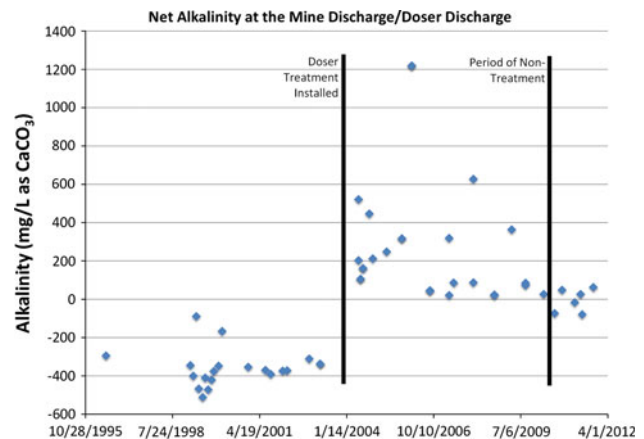


Fig. 3 Net alkalinity of mine discharge (pre-treatment) and doser discharge (post-treatment)

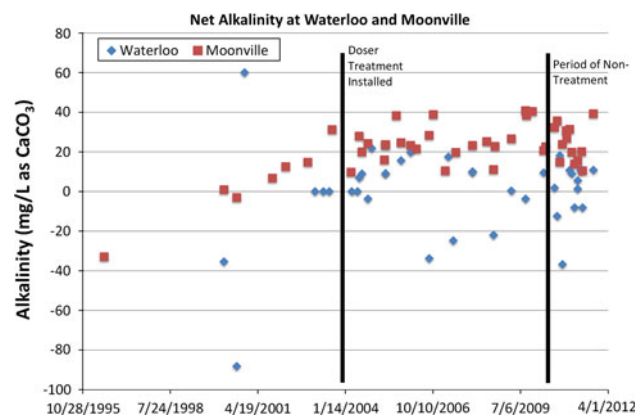


Fig. 4 Net alkalinity measurements at Moonville, Waterloo, and Carbondale focussing on the period of non-treatment

56 and Waterloo due to drought conditions. The remainder of the downstream sites surveyed in 2010 showed no significant drop in MAIS scores from any post-treatment year. Additionally, the temporal effect of non-treatment is short. As shown in Fig. 6, the 2011 MAIS scores had returned to 2004–2009 levels. The macroinvertebrate community showed greater resilience than the fish community, with the impacts limited both spatially and temporally. Although the impacts of long-term acidification on macroinvertebrate communities through loss of sensitive taxa and replacement with more tolerant forms has been well documented (Hall et al. 1980; Rosemond et al. 1992; Weatherly and Ormerod 1991), many taxa, including the more sensitive mayfly, caddisfly, and stonefly taxa, can in fact tolerate short exposures (5–10 days) to low pH (4.0–5.0) (Allard and Moreau 1987; Bernard et al. 1990; Courtney and Clements 1998; Kratz et al. 1994; Vuori 1995; Weatherly and Ormerod 1991). In fact, the disappearance of mayflies from acidified waters is more often attributed to higher mortality at emergence (Bell 1971; Hall et al. 1980; Zische

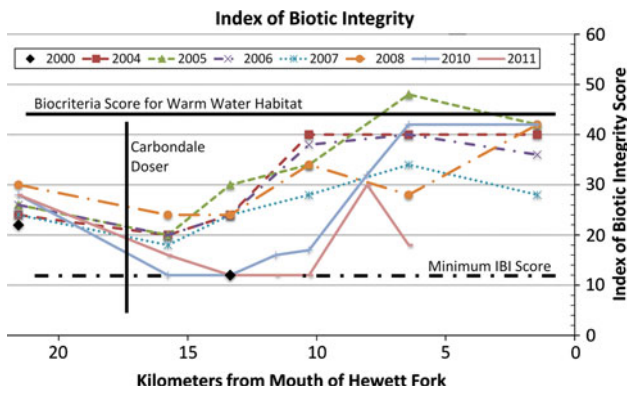


Fig. 5 Index of Biotic Integrity measured in Hewett Fork from 2000 to 2011. The scores for 2010 and 2011 show the impact of non-treatment on the fish communities in Hewett Fork. The 2011 score for Rockcamp (River km 6.4) is artificially low due to increased difficulty sampling due to the depth of the site

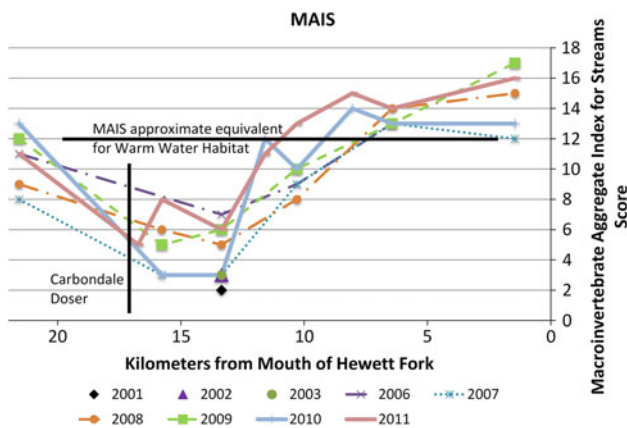


Fig. 6 Macroinvertebrate Aggregate Index for Streams scores measured in Hewett Fork from 2001 to 2011. The period of non-treatment had a small effect in the 4.8 km (3 miles) downstream from the doser, similar to the impact of a recorded drought year (2007)

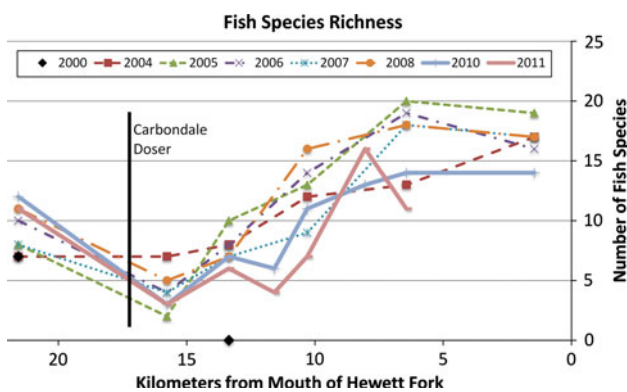


Fig. 7 Fish species richness from the Hewett Fork fish surveys between 2000 and 2011; while non-treatment did affect several fish metrics, the species richness was not significantly impacted

et al. 1983), inhibition of oviposition in acid waters (Sutcliffe and Carrick 1973), or drift from the affected area (Hall et al. 1980; Hopkins et al. 1989) than mortality.

Stream macroinvertebrate communities have the capacity to recover rapidly, within days or weeks, after physical disturbance or drought, especially if there are upstream populations from which individuals can disperse (drift) downstream into the affected area (Churchel et al. 2006; Fritz and Dodds 2004; Gjerlov et al. 2003; Wallace 1990). Recovery may take longer if macroinvertebrates have to disperse over greater distances, for example by adult flight. Nonetheless, there are examples of nearly full recovery from AMD impairment occurring within 1–2 years after remediation (Cairns et al. 1971; Nelson and Roline 1996). Recovery at more isolated sites can take more than 5 years if there are no nearby source populations (Fuchs 1990; Richards and Minshall 1992). Episodic acid pulses can retard recovery of stream macroinvertebrates (Kowalik et al. 2007). Macroinvertebrate assemblages in streams with a history of acidification may show less response to and faster recovery from shorter bouts of acidification if the sensitive taxa have already been eliminated and the majority of taxa present are those with more tolerance to acidification.

Conclusions

While alkaline addition can be extremely effective at minimizing the impacts of AMD and improving biological communities, equipment failures, human error, and lack of maintenance can lead to treatment shutdown. A single short-term mistake can take its toll on the health of a watershed for years to come. Hewett Fork did not have the resilience to quickly bounce back from a short period of non-treatment. Fish communities have been affected for two field seasons for over 11 km (7 miles) downstream from the doser, while the impact to the macroinvertebrate community was smaller at both spatial and temporal scale. While the lime doser has allowed biological communities to return to Hewett Fork and the headwaters of Raccoon Creek, without long-term maintenance and operation funds for both active and passive treatment systems to sustain improved water quality and biological recovery, streams like Hewett Fork will return to pre-treatment conditions.

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References

Allard M, Moreau G (1987) Effects of experimental acidification on a lotic macroinvertebrate community. *Hydrobiologia* 144:37–49
 Bell HL (1971) Effect of low pH on the survival and emergence of aquatic insects. *Water Res* 5:313–319

- Bernard DP, Neill WE, Rowe L (1990) Impact of mild experimental acidification on short term invertebrate drift in a sensitive British Columbia stream. *Hydrobiologia* 203:63–72
- Cairns JJ, Crossman JS, Dickson KL, Herricks EE (1971) The recovery of damaged streams. *ASB Bull* 18(3):79–106
- Churchel MA, Batzer DP (2006) Recovery of aquatic macroinvertebrate communities from drought in Georgia Piedmont headwater streams. *Am Midl Nat* 156:259–272
- Courtney LA, Clements WH (1998) Effects of acidic pH on benthic macroinvertebrate communities in stream microcosms. *Hydrobiologia* 379:135–145
- Driscoll CT, Schecher WD (1990) The chemistry of aluminium in the environment. *Environ Geochem Hlth* 12(1):28–49
- Fritz KM, Dodds WK (2004) Resistance and resilience of macroinvertebrate assemblages to drying and flood in a tallgrass prairie stream system. *Hydrobiologia* 527(1):99–112
- Fuchs U, Statzner B (1990) Time scales for the recovery potential of river communities after restoration: lessons to be learned from smaller streams. *River Res Appl* 5(1):77–87
- Gjerløv C, Hildrew AG, Jones JI (2003) Mobility of stream invertebrates in relation to disturbance and refugia: a test of habitat templet theory. *J N Am Benthol Soc* 22(2):207–223
- Gostomski F (1990) The toxicity of aluminium to aquatic species in the US. *Environ Geochem Hlth* 12(1):51–54
- Hall RJ, Likens GE, Fiance SB, Hendry GR (1980) Experimental acidification of a stream in the Hubbard Brook Experimental Forest, New Hampshire. *Ecology* 61:976–989
- Hopkins PS, Kratz KW, Cooper SD (1989) Effects of an experimental acid pulse on invertebrates in a high altitude Sierra Nevada stream. *Hydrobiologia* 171:45–58
- Johnson KS (2009) Performance of a family-level macroinvertebrate index (MAIS) for assessing acid mine impacts on streams in the Western Allegheny Plateau. Final report for ohio department of natural resources. Ohio University, Athens
- Karr JR (1981) Assessment of biotic integrity using fish communities. *Fisheries* 6(6):21–27
- Kowalik RA, Cooper DM, Evans CD, Ormerod SJ (2007) Acidic episodes retard the biological recovery of upland British streams from chronic acidification. *Glob Change Biol* 13(11):1365–2486
- Kratz KW, Cooper SD, Melack JM (1994) Effects of single and repeated experimental acid pulses on invertebrates in a high altitude Sierra Nevada stream. *Freshwater Biol* 32:161–183
- Nelson SM, Roline RA (1996) Recovery of a stream macroinvertebrate community from mine drainage disturbance. *Hydrobiologia* 339(1–3):73–84
- NPS (2009) 2009 NPS report—Raccoon Creek Watershed—Carbon-dale II Doser. Non-point source monitoring system. <http://www.watersheddata.com>. Accessed Nov 30 2011
- Ohio Environmental Protection Agency (1988) Biological criteria for the protection of aquatic life: users manual for biological field assessment of Ohio surface waters. Ecological Assessment Section, Division of Water Quality, vol II, Columbus
- Ohio Environmental Protection Agency (1997) Biological and water quality study of the Raccoon Creek basin (1995). OEPA technical report MAS/1996-12-7, Ecological Assessment Unit, Division of Surface Water, Columbus
- Ohio Environmental Protection Agency (2002) Total maximum daily loads for the upper raccoon creek final report. Division of Surface Water, Ohio Environmental Protection Agency, Columbus
- Ohio Environmental Protection Agency (2007) Water use designations and statewide criteria. OEPA Rule 3745-1-07, Columbus
- Rice C, Hoy JB, Hoy R, Last J, Farley M, Grow J, Knapp M, Simon K (2002) Acid mine drainage abatement and treatment (AMDAT) plan for the headwaters of the Raccoon Creek watershed. Raccoon Creek Partnership, Athens
- Richards C, Minshall GW (1992) Spatial and temporal trends in stream macroinvertebrate communities: the influence of catchment disturbance. *Hydrobiologia* 241(3):173–194
- Rosemond AD, Reice SR, Elwood JW, Mulholland PJ (1992) The effects of stream acidity on benthic invertebrate communities in the south-eastern United States. *Freshwater Biol* 27:193–209
- Smith EP, Voshell JR (1997) Studies of benthic macroinvertebrates and fish in streams within EPA Region 3 for development of biological indicators of ecological condition, part 1, benthic macroinvertebrates. Report to US EPA, Cooperative Agreement CF821462010. USEPA, Washington
- Sutcliffe DW, Carrick TR (1973) Studies on the mountain streams of the English Lake District. I. pH, calcium and the distribution of invertebrates in the River Duddon. *Freshwater Biol* 3:437–462
- Vuori KM (1995) Species- and population-specific responses of translocated hydropsychid larvae (Trichoptera, Hydropsychidae) to runoff from acid sulphate soils in the river Kyrönjoki, Western Finland. *Freshwater Biol* 33:305–318
- Wallace JB (1990) Recovery of lotic macroinvertebrate communities from disturbance. *Environ Manage* 14(5):605–620
- Weatherly NS, Ormerod SJ (1991) The importance of acid episodes in determining faunal distributions in Welsh streams. *Freshwater Biol* 25:71–84
- Zische JA, Arthur JW, Nordlie KJ et al (1983) Acidification effects on macro invertebrates and fathead minnows (*Pimephales promelas*) in outdoor experimental channels. *Water Res* 17:47–63