Comparing Acid and Metal Loading Before and After Stream Capturing Subsidence Closure

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Abstract

Closing stream-capturing subsidences over abandoned coal mines prevents surface water from entering mine voids and reacting with sulfide materials (pyrite) and oxygen. The common assumption that closures will improve water quality in discharges and receiving streams was tested at multiple sites by comparing acid and metal loadings, pre- and post-closure, using the Stoertz Water Quality Evaluation Method. Proven an effective tool for comparing loading estimations at mean annual flow, even with small sample size, this method still required complete, accurate, and precise data that spanned all flow regimes for statistically significant results. Four test sites in the Wayne National Forest in Ohio were selected for analysis based on data availability in the receiving water bodies.

Where adequate data existed, acid and metal loadings showed reductions after closure, in spite of measured increases in constituent concentrations, due to reduced flows attributable to subsidence closure. The Stoertz Water Quality Evaluation Method was applied to four subsidence closures to analyze the water quality changes due to the project. Two key conclusions can be made from this study. First, monitoring should be planned to collect sufficient time series data to represent chemical conditions across a typical range of flow regimes to facilitate evaluation of water quality changes. Second, this study suggests that subsidence closures do reduce acidity and metal loadings by reducing flow rate, while post-closure acidity and metal concentrations may be higher than pre-closure.

Key words: mine water, subsidence closure, coal mining

Introduction

The vast majority of underground coal mines in Appalachia were opened, “worked out” (meaning as much coal as possible was removed), then simply abandoned at closing (Abramson & Haskel 2006). Mining technique coupled with area geology often left insufficient support for portions of mine roofs, which collapsed, providing pathways for air and surface water to enter the voids left by extracted coal (Hill & Bates, 1979). Water and oxygen react chemically with minerals left exposed in the coal, producing acidic metalliferous drainage (Singer & Stumm 1970). The resulting discharge from mines, known as acid mine drainage (AMD), has degraded thousands of miles of streams in Appalachia (US EPA n.d.), as well as innumerous watersheds worldwide (Bell *et al.* 2000).

Coal mine subsidence occurs when materials overlying a mine void collapse into the empty space left by extraction of coal, causing a depression, hole, or fissure in the land surface over the mine. “Bulk,” or larger, broken up pieces of what comprised the room roof, piles up below the collapse, followed by layers of each subsequent strata material until all layers unable to bear the stress have subsided. In room and pillar mining, it has been shown that overburden up to about 30 times the height of the mined room can subside (Bell *et al.* 2000). Subsidence effects are lessened as the depth of overburden increases. A 4 foot high room at a depth of 130 feet may not show any surface effect at all, for example, compared to a 2 foot high room only 10 feet below the surface. Never, however, does bulk completely fill the mine void (Bell *et al.* 2000; Hill & Bates 1979). Ample space remains for flow of water and/or air, and allows for the possibility of further subsidence. Indeed, even in mine backfilling theory and technology, employed when developing mined areas, further subsidence is expected, and building plans over backfilled areas are designed to withstand a calculated amount of shift (Zhang *et al.* 2015).

Any number of stressors may trigger and influence land subsidence. In fact, mine subsidence is difficult to prevent and anticipate because so many factors may be involved (Marino & Abdel-Maksoud 2006, Lee *et al.* 2013; Bell *et al.* 2000). Lee *et al*. note that "data on subsidences are mostly qualitative and are difficult to convert into quantitative measures" (2013). Influencing factors include the type and depth of mine, type and depth of overburden, groundwater levels, possibility of inundation during high flow events such as torrential rain or flooding, mining method employed in extraction of material, proximity to ground faults, geologic stability, surface activity, airflow, and subsurface erosion (Bell et al. 2001; Bell *et al.* 2000; Hawkins & Smoyer 2011; Hill & Bates 1979; Marino & Abdel-Maksoud 2006; Wei *et al.* 2011; Winters & Capo 2004). Even using the recommended standard room and pillar removal ratio of 1:1, which is generally accepted to be the highest safe ratio (Bell *et al.* 2000; Hill & Bates 1979), subsidence may still occur. In "pillar robbing," subsidence is expected when pillars are mined further on the way out of the spent mine.

Methods for correction of mine subsidences typically utilize one of two approaches, or both: 1) filling and waterproofing an open subsidence so that it no longer captures surface water and sends it into the mine void; or 2) re-contouring and rerouting stream water around the open subsidence. The standard method of closing a stream capturing subsidence used in the Wayne National Forest (WNF) is to clear the area around the subsidence of trees and brush, then back fill the subsidence hole with limestone rock to the level of the mine roof. Borrow material, generally taken from an area close to the site is then used to fill in the remainder of the hole, and compacted. The area is contoured, then lined with an impermeable geo-synthetic clay liner, covered with topsoil and re-vegetated or lined with limestone rock if the subsidence was in a stream channel (Wayne National Forest 1997).

Restricting surface water from entering mine voids is often referred to as a method of preventing AMD from forming, thereby improving water quality (WQ) downstream (e.g. Bell *et al.* 2000; Fields 2003; Kleinmann 1990; Monday Creek Restoration Project 2005; USACE 2005; Wolkersdorfer 2008). Monday Creek Management Plan describes the problem with subsidence, saying "…collapsed overburden captures surface water into the mine voids, allowing contact with sulfide minerals and oxygen, thus generating AMD within the watershed" (Steinmaus & Black 2005). The 2005 final report for the Inventory of Abandoned and Inactive Mines, performed on WNF property by the Army Corps of Engineers (USACE 2005), states "The goal of stream subsidence closures is to…reduce AMD generation by preventing contact between stream water and pyritic minerals located within the underground mines." This is a logical assumption given the known chemical reaction when water, oxygen and sulfide materials (e.g. pyrite) combine (Singer & Stumm 1970). Hill and Bates noted that "water control methods appear intuitively to be good ways to reduce AMD, but their effectiveness has not been well documented" (1979). To this day, few studies have tested this assumption. This study aimed to determine if closing stream capturing abandoned coal mine subsidences affects WQ at their associated discharges.

Methods

Geographic Information Systems (GIS) query of the Abandoned and Inactive Mines (AIM) Inventory database identified 55 closed stream capturing subsidence features in Monday Creek Watershed, southeastern Ohio. Selection by location on a per closure basis, looking for WQ sampling sites within a 10 meter distance of the 55 identified closures did not reveal adequate sites for analysis, so a per mine or drainage area approach was taken instead. The GIS database allowed for a search of existing WQ data at or near discharges and flow paths where captures would have likely discharged prior to closure. Estimating flow paths considered the average 30% southeast slope of the coal seams in the area, and, using georeferenced hand-drawn historical mine maps showing the room and pillar orientation of each mine, identified 5 closed subsidences (Figure 1) which had likely discharge seep or drainage areas where adequate data existed for analysis.

Of these five closures, four were located over one large mine, with two likely discharges with adequate data for analysis. These were separated into two separate sites, with two different drainage points. Long Hollow, the tributary receiving discharge from a seep likely fed by two of the identified stream captures, gave its name to one site. The site with the other two subsidences over the same mine complex was named Cawthorn, for the name of the FS closure project of one subsidence. The other identified closure site was in the drainage area of one large FS treatment project, called Coe Hollow.

In addition to the sites selected with the GIS process, a fourth site, named Majestic Mine was selected for re-analysis of data from two prior thesis projects (Pigati 1997, Graham 2006).

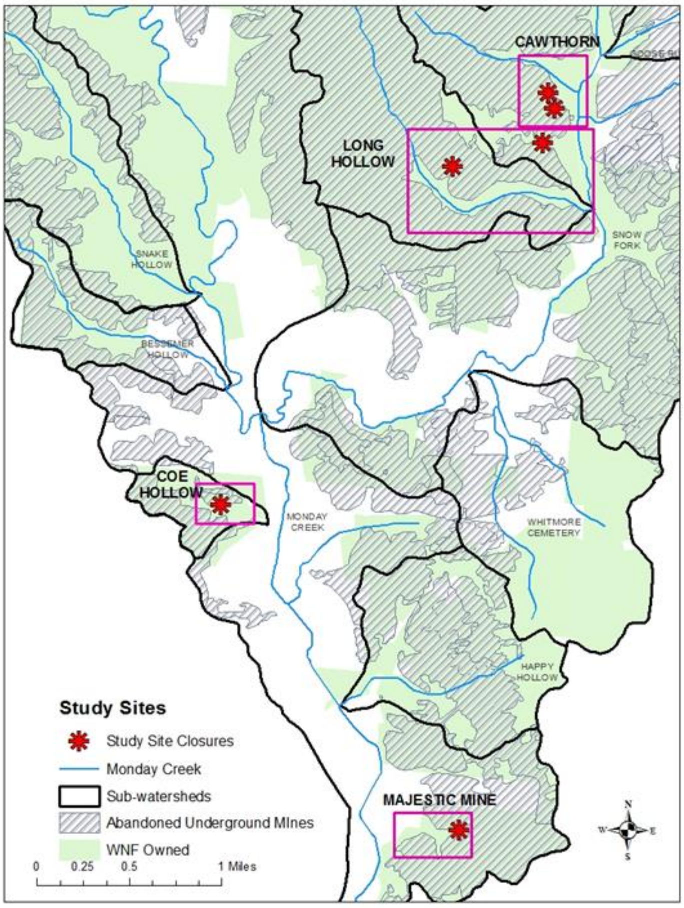

Figure 1 *Proximity of study areas, notated by pink boxes, to area streams, mapped underground mine workings, Wayne National Forest (WNF) ownership, and related subsidence closures, notated by red stars.*

Sample collection records, including field and laboratory data were downloaded from the web database, watersheddata.com. WQ data stored in the database is collected in a manner consistent with Ohio Environmental Protection Agency (OH EPA) WQ collection standards and evaluated at OH EPA certified laboratories, following standards detailed in “Quality Assurance Quality Control (QAQC) Plan for Surface Water Quality Data Collection and Analysis,” developed by Ohio Department of Natural Resources Division of Mineral Resources Management (ODNR-DMRM) (Bowman *et al.*, 2015). Most chemical data in the database is analyzed by the ODNR analytical laboratory, in Cambridge, OH.

Data for the Majestic Mine, which does not appear in the AIM Inventory because the site was remediated prior to the start of that study, and has not been routinely monitored for WQ, came from two Ohio University Masters theses which studied the mine (Pigati 1997, Graham 2006). Five WQ data samples taken between May and December of 1996 for the 1997 Pigati thesis contained the necessary parameters for analysis. Tennessee Valley Authority (TVA) chemical laboratory, utilized by the Forest Service (FS), analyzed the sample collected on 5/6/1996 and 12/9/1996, and ODNR laboratory in Coshocton, OH performed analysis on the other three samples. Pigati recorded flow measurements at the mine seep using a Parshall Flume (1997). In a 2006 thesis Graham completed fourteen sampling events from February to August of 2001. Flows for the study were measured with the same Parshall Flume used in the previous Pigati study. Graham collected all water samples in accordance with water sample collection methods dictated by the TVA laboratory (Graham 2006).

The Stoertz Water Quality Evaluation Method (Stoertz Method) was used to compare pre- and post-closure WQ data at each study site, to estimate loading relationships of acidity and metals before and after subsidence closure. This method is an easy way to assess loading behavior across flow regimes, and pre- and post-intervention, by comparing loadings at a consistent flow regime. The method has been used to assess treatment system performance in southeastern Ohio for more than a decade. The Pine Run Stream Capture project monitoring in Sunday Creek, Ohio, for example, utilized the Stoertz Method to report load reductions following the closing of a stream capturing subsidence (Bowman, 2011). The Stoertz Method is the method employed to determine statistically significant relationships in loading in AMD watersheds, even with small data sets (Kruse *et al.*, 2014). Prior to the development of this method, direct average loadings were compared over a specified period, (e.g. yearly), by multiplying flow times concentrations and then averaging. Direct comparison did not however, provide a means of comparison at a consistent flow regime, nor does it give indication of flushing behavior.

Using the Stoertz Method, loading, flow times concentration, adjusted for units, in this case pounds per day, was log transformed to provide a linear comparison of constituent loading (l) at annual flow (Q_n), pre- and post-remediation activity. Log normalized flow and log loadings with their flushing factors (F), were then plotted to compare in a linear relationship, pre and post-remediation, by means of the following equations:

$L = l\,(Q/\mathit{Q})^{F} = l\,Q_n^{F}$ Equation 1

$\log L = \log l + F \log Q_n,$ Equation 2

where F is flushing factor such that $F = 0$ in pure dilution, $F > 0$ for flushing behavior, and $F < 0$ for sparing behavior (Kruse *et al.* 2014). The difference between pre- and post-closure loadings, at the mean annual flow, indicated the estimated change in loading of parameters evaluated.

Mean annual discharge at seep sites (Cawthorn, Coe Hollow, and Majestic) were estimated by averaging measured flows. Mean Annual Discharge for Long Hollow, which considered the entire hollow drainage area for regressions, was estimated by utilizing the US Geological Survey (USGS) Streamstats program (http//streamstats.gov) to arrive at the Long Hollow drainage area, then multiplying draiage area by 1.01, the value of mean annual estimated discharge for basins in the Western Allegheny Plateau (Koltun & Whitehead, 2002).

To arrive at loading estimations Fe, Al, and Mn concentrations were added together to arrive at total metals. Flow measurements normalized by mean annual flow, acid and total metal loads were log transformed, and plotted on a scatter chart. Intercepts are at mean annual flow. Taking the inverse log of the intercepts returned loading estimations at mean annual flow in pounds per day. Post- closure loading estimations were subtracted from pre-closure loading to determine changes in loading from pre- to post-closure.

R^2 values were generated for all regressions to evaluate the fit of the lines, where results closer to 1 indicated best fit, with p values less than 0.05 judged to be statistically significant. All results were evaluated for agreement with the hypothesis that reducing flow into mine voids by closing stream capturing subsidences will improve water quality downstream, with particular weight given to statistically significant results.

Results

Regressions using the Stoertz Method for the Long Hollow site shown in Fig. 2 and 3 show an estimated daily acid load reduction of 3.14 lb/day (1.42 kg/day), and metal load reduction of 3.33 lb/day (1.51 lb/day). Compared to pre-closure loadings of 67.24 pounds per day of acid and 10.98 pounds per day of metals, this is a 4.68% acid load reduction and 20.32% reduction in metal loading. Analysis also revealed that the flushing factor changed from $F > 1$ pre-closure, to < 1 post-closure, indicating that pre-closure behavior purging had changed, post-closure, to sparing. This suggests some structural change influenced the flushing mechanism in the sub-watershed.

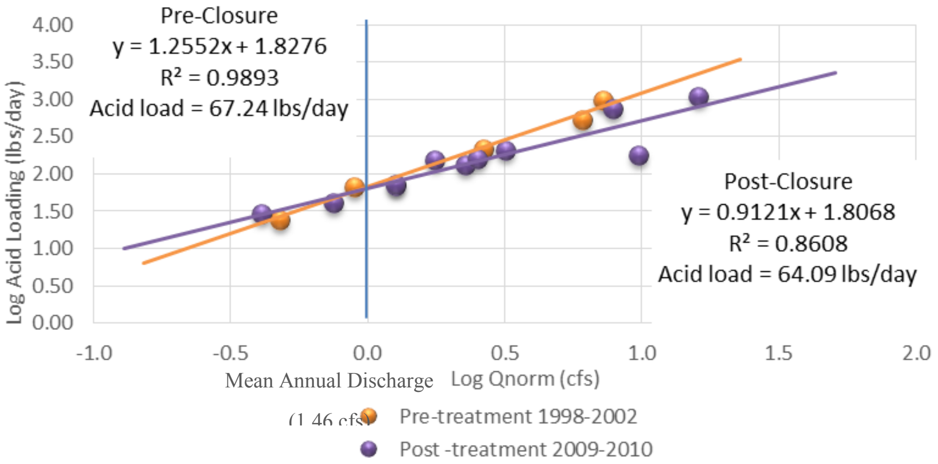

Figure 2 *Long Hollow regression graph showing acid loads at mean annual discharge (acid load = 67.42 lbs/day pre-closure and 64.09 lbs/day post-closure), change in flushing behavior (F = 1.26 pre-closure and F = 0.91 post-closure), and trend lines with good fit ($R^2 = 0.98$ for pre-closure and $R^2 = 0.86$ for post closure).*

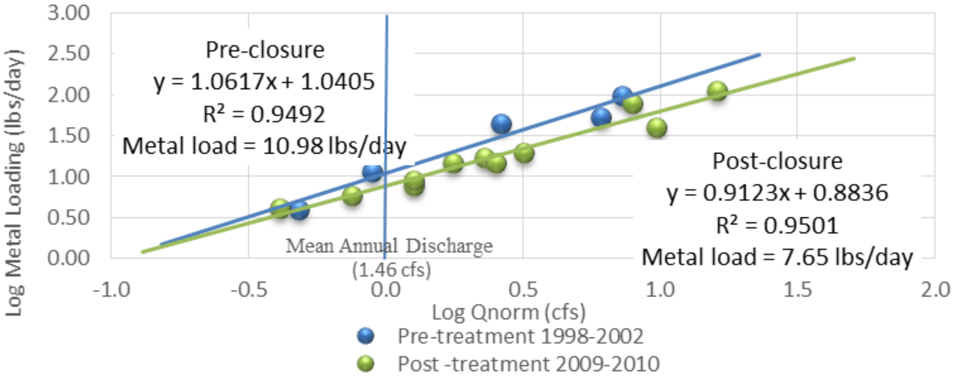

Figure 3 *Long Hollow regression graph showing metal loads at mean annual discharge (1.46 cfs/mi^2) (metal load = 10.98 lbs/day pre-closure and 7.65 lbs/day post-closure), change in flushing behavior (F = 1.06 pre-closure and F = 0.95 post-closure), and trend lines with good fit $R^2 = 0.95$ pre-closure and $R^2 = 0.95$ post-closure).*

Analysis at Cawthorn was stopped upon making the discovery that two historical data points were sampled at the wrong location, but it seemed worthy of note that the two sample events that were taken at the seep for this study, on preliminary analysis, returned lower acid and metal concentrations than pre-closure samples taken during comparable flow regimes. Accurate data could have helped to show if this is a seasonal anomaly or a trend in the mine discharge across flow regimes.

Average acidity concentration at Coe Hollow seep pre-closure was 264.7 mg/l, while post-closure acidity averaged 367.1 mg/l. This average was elevated by what appeared to be a flushing event in June of 2011 which had an acidity concentration of 862 mg/l, more than double other acidity measurements. Metal concentration results were mixed; average Fe decreasing by almost 75%, and Al and Mn both increasing by approximately 62% and 25% respectively.

Stoertz Method regressions of the Coe Hollow data shown in Fig. 4 and 5 showed a decrease in acid loading by 19.7 lb/day (8.9 kg/day), and a metal load reduction of 17.3 lb/day (7.8 kg/day). This is a 5.46% reduction in acid load and a 26.7% reduction in metals from pre- to post-closure data. Regressions on post-closure data were determined to be significant ($p < 0.05$); however, pre-closure p-values were > 0.05 due to the small data set.

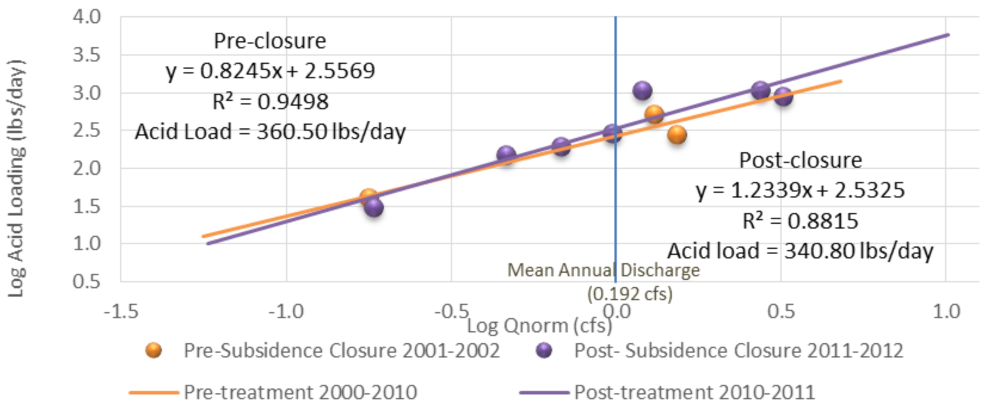

***Figure 4** Coe Hollow regression with treatment flows included, showing acid loads at mean annual discharge (acid load = 360.5 lbs/day pre-closure and 340.8 lbs/day post-closure) and trend lines with good fit (R2 = 0.95) pre-closure and weaker fit (R2 = 0.88) post-closure.*

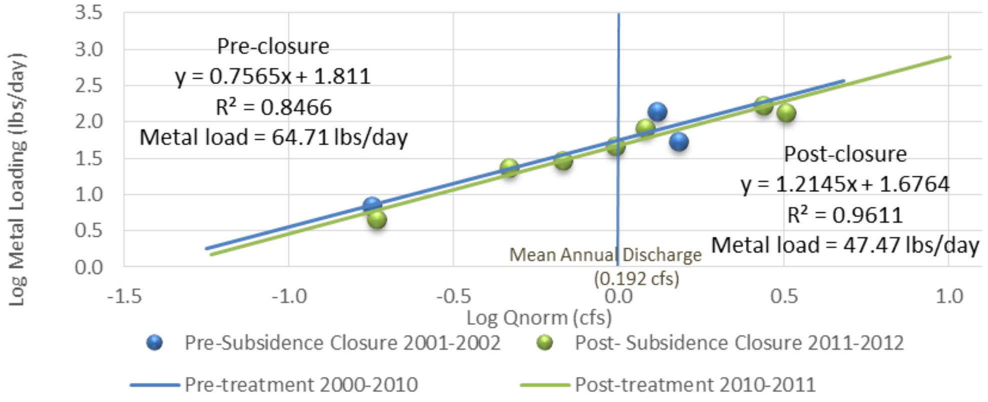

***Figure 5** Coe Hollow regressions, with treatment system flows included, showing metal loads at mean annual discharge (metal load = 64.71 lbs/day pre-closure and 47.47 lbs/day post-closure) and trend lines with good fit (R2 = 0.85 pre-closure and R2 = 0.96 post-closure).*

Using the pre-closure data from Pigati (1997), and post-closure data from Graham (2006), the Stoertz Method was used to compare pre- and post-closing loading conditions at the Majestic Mine. In this case, however, it was necessary to normalize flows using a separate mean annual discharge for each study period. With the drastic reduction in flow in the post-closure data, apparently resulting from the subsidence closure, using the 72% larger normalized pre-closure flow would result in inaccurately high loading estimations after the subsidence closure. Bowman *et al.* made this same adjustment in assessing the Pine Run and Rogers Hollow subsidence closures (2011).

Regressions showed an estimated 60.5% reduction in acid load, shown in Fig. 6 and 7, and a 67.19% total metal load reduction at the seep following closure, data not shown to save space. Iron, manganese, and aluminum are added together for total metals in this regression, however, because Graham compared iron alone, regressions were re-run using only iron loading. Results showed iron reduction of 67.05%, a difference of only 0.14% from total metal reduction.

While concentrations did increase at the seep after remediation, as Pigati (1997) theorized, regression results show that loading decreased. This concurred with Pigati's (1997) expectations and Graham's (2006) findings. Put in different terms, while the WQ of the mine drainage degraded, in terms of constituent concentration, after the closing of the subsidence, the amount of AMD transporting pollution materials out of the mine reduced the total amount of material that could affect Monday Creek.

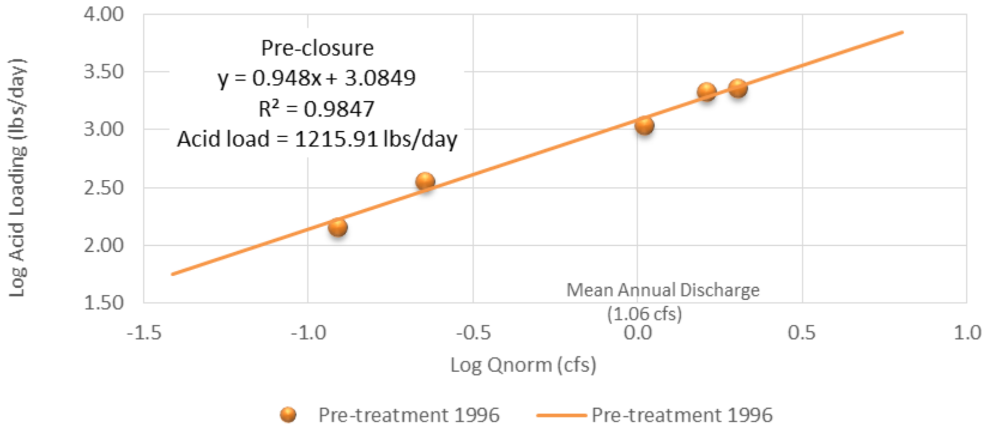

Figure 6 *Majestic regression showing acid loading at mean annual flow (acid = 1215.91 lbs/day pre-closure), pre-closure, with good trend line fit (R^2 = 0.98).*

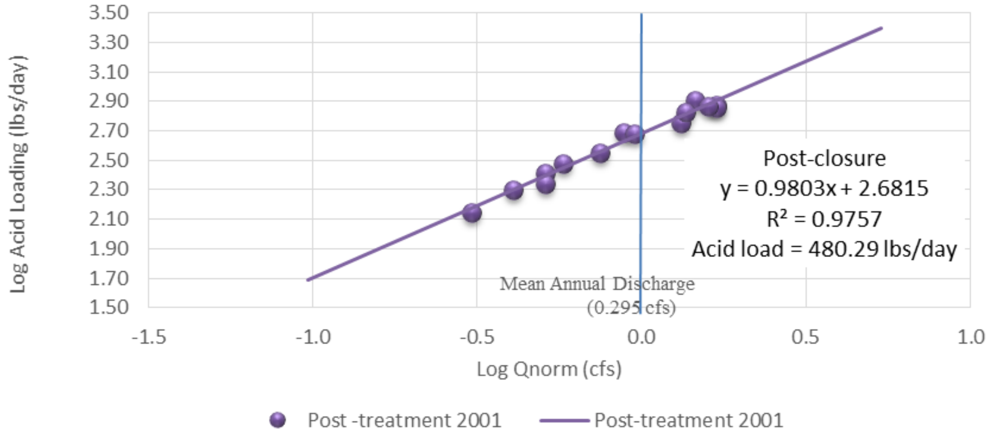

Figure 7 *Majestic regression showing acid loading at mean annual flow (acid = 480.29 lbs/day post-closure) with good trend line fit (R^2 = 0.98).*

Conclusions

Changes in water quality were reflected in comparisons of pre- and post-closure data. Aspects of the study suggest that closing stream capturing subsidences resulted in hydrological and chemical changes at discharges. In the case of the Majestic mine, statistically significant regressions indicate that closing the stream capturing subsidence reduced flows as well as acid and metal loads. Each of the other sites also suggest, albeit not as strongly, that there have been loading reductions after stream capturing subsidence closure.

Data did not conclusively indicate agreement with the common assumption that stream capturing subsidence closures result in WQ improvement at all sites. Technically, at the seeps and discharges where data was adequate for analysis, concentrations were generally shown to increase, a sign of degradation. Where flows were also significantly reduced, however, loadings to receiving streams were also reduced, resulting in an assumed reduction of pollution downstream, agreeing at least cursorily with the common assumption. However, none of these cases proved stream capturing subsidence closure to have prevented AMD from forming.

Acknowledgements

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