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Spatial Co-variation between Distance from Mining Activity and Water Chemistry on East Tennessee's Northern Cumberland Plateau

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ABSTRACT

Distance from the nearest upstream or upslope surface coal mining activity may impact certain water quality parameters, here studied in headwater streams near surface coal mining operations on East Tennessee's Northern Cumberland Plateau. Using United Mountain Defense's water quality database and Google Earth, I compared certain water quality parameters with distance from the nearest upstream or upslope mining activity. Conductivity, sulfate, and manganese were water quality parameters that exhibited significant spatial relationships with distance from mining activity. These three parameters all showed significant decreases as distance from mining activity increased. Aluminum, Iron, and pH were water quality parameters that showed no significant spatial relationship with distance from mining activity and had relatively low levels across all distances. The parameters with significant spatial relationships, specifically conductivity and manganese, were found in levels exceeding EPA-established guidelines, in some cases, a few thousand meters downstream. These far-reaching mining-induced impacts are likely causing severe distress to downstream fish populations and other aquatic organisms that are naturally found in these headwater streams.

NO ECOSYSTEM IS FREE OF HUMAN INFLUENCE (Vitousek *et al.* 1997). Humans depend on Earth's natural resources for survival (Wackernagel *et al.* 1999). Coal, a natural resource, is one of Earth's largest energy suppliers (Ahlbrandt 2002) and is often obtained through surface mining processes that negatively impact the environment, especially nearby water resources (Tiwary 2000).

Coal mining on the Cumberland Plateau in Northeastern Tennessee has meant devastation for many small headwater streams, the rivers they feed, and the communities they flow through. Early, historic mining practices in this region lacked runoff prevention, modern reclamation procedures, and other damage mitigation techniques that today's contemporary surface mining operations implement; however, present day reclamation attempts, even when engineered perfectly, still fail to completely eliminate the negative impacts of converting diverse forest ecosystems to sterile rubble slopes (Palmer *et al.* 2010).

Surface mining for coal on the Cumberland Plateau is a process whereby coal-rich ore is obtained by removing surface overburden to get to the coal and then filling the void

with the removed overburden, or mine spoil, as part of the reclamation process. Although this helps to rebuild the topography of the landscape, mine spoil is vastly different from the original soil. The mine spoil that is used to replace the topsoil is from deeper, un-weathered strata that have radically different pH levels, concentrations of minerals, and metals as compared to the weathered strata that formerly existed near the surface. This un-weathered spoil generates significant ionic loads that are leached into nearby ground and surface water resources as it weathers over time, contributing to acid mine drainage, high conductivity, and harm to downstream aquatic organisms (Orndorff *et al.* 2011).

Mined lands may take centuries to recover, or they may never fully recover. These lands have a long and persistent history of failed reclamation attempts, permit violations, water quality degradation, and deleterious effects on both human and wildlife populations (Moore 2005 & Palmer *et al.* 2010). Even though they are environmentally devastating, surface mining activities are often permitted under auspices of 'social and economic necessity'; however, coal mining on the Cumberland Plateau has been shown to be a revenue-negative activity within these communities (Nelder 2012) and poses a serious liability for the state and federal government under CERCLA in the long run (USEPA 2011).

This study focuses on the relationship between water chemistry and distance from the nearest mining activity. Does water chemistry change as distance from mining activity increases? In other words, how are mining activities impacting water chemistry and how far downstream do these impacts extend? Mining activities on the Cumberland Plateau are potentially severely impacting the water chemistry of fragile headwater streams that many aquatic organisms rely on and may also be negatively affecting larger bodies of water that they empty into some distance downstream.

METHODS

SINCE 2005, UNITED MOUNTAIN DEFENSE (UMD) has conducted field visits and water sampling activities throughout the Cumberland Plateau as part of its field activities program. The field activity program aims to track and monitor coal, oil, and gas permit activity, monitor and document activities, hazards, and violations affecting known native, threatened, or endangered species populations, quantify unknown or underreported stream and watershed quality criteria, and establish a database of water quality information that can be used to determine baselines, trends, and impacts in water resource conditions over time.

STUDY SITE—This study was conducted along the northern region of the Cumberland Plateau in Anderson, Claiborne, Campbell, Morgan, and Scott Counties; a region of Tennessee subjected to previous and planned coal mining activities located just south of the Tennessee—Kentucky border (Figure 1).

Specific areas and streams visited include:

Perimeter, Central, and South-Central portions of the New River watershed in Scott and Anderson Counties—Smoky Creek and tributaries and New River and tributaries including Ligias Fork, Sugarcamp Branch, Coon Pool Branch, Camp Creek, Laurel Fork, Skinned Ash Creek, Double Camp Creek, and unnamed tributaries.

Zeb Mountain, a site of major surface mining activity in Scott and Campbell Counties—Capuchin Creek, Lick Fork, and tributaries including Dan Branch, Drew Branch, and Granny Barnes Branch.

Campbell County's Hickory Creek and tributaries including Houston Ayers Branch, Hatmaker Branch, and Business Branch as well as Davis Creek and tributaries including Hogcamp Branch, Sandlick Branch, and unnamed tributaries.

Claiborne County's Tackett Creek and tributaries including Spruce Lick Branch and unnamed tributaries as well as Clear Fork and tributaries including Valley Creek, Hurricane Creek, Pigeon Roost Branch, and unknown tributaries.

All water samples were collected from flowing water resources in temperate, deciduous forest ecosystems, or in exotic, low to mid-succession grasslands and open forests created by mining 'reclamation' activities (Brenner *et al.* 1984) on or near current or former mining sites.

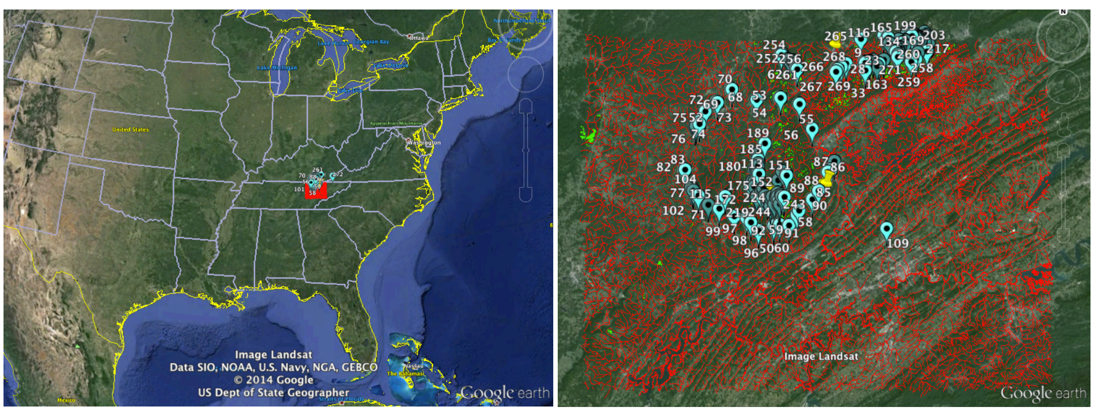

FIGURE 1. Study sites from far and near perspectives. Left: Study site relative to the Continental United States. Right: Study site from a zoomed-in, local perspective. 36°21'23 N Latitude, 84°21'01 W Longitude. Source: Google Earth.

TARGET PARAMETERS—Water discharged from surface mines, especially during significant rain events when sediment control structures are designed to overflow, commonly contains elevated concentrations of acidity, iron, manganese, aluminum, and sulfate (Sams & Beer 2000) as well as sediment with high concentrations of these materials. United Mountain Defense testing focuses on conductivity, arsenic, selenium, aluminum, manganese, iron, dissolved oxygen, pH, and sulfate. This study

focuses on how conductivity, aluminum, sulfate, manganese, iron, and pH change as distance from nearest mining activity increases.

DATA AND SAMPLE COLLECTION—Location information for testing points and violations was obtained using a handheld GPS unit, the Garmin Etrex Venture HC, which was used in conjunction with a Panasonic DMC-TS4 georeferencing camera. A GlobalSat model DG-200 GPS datalogger was used to track paths, mileage, and as a backup for the camera and handheld GPS. GPS data was saved as KML, GPX, and EXIF formats. Once collected in the field, GPS data was exported to spreadsheet format and proofed for missing duplicate or inaccurate values.

WATER QUALITY PARAMETERS—Water quality data was obtained using a YSI Professional Plus Handheld Multiparameter Instrument fitted with a YSI Quatro Cable. Probes for polargraphic dissolved oxygen (DO), conductivity/temperature and pH were affixed to the cable, with one probe position left empty. The unit was factory calibrated in November 2011, November 2012, and again in July 2013. Calibrations were conducted with YSI-supplied NIST-traceable pH and conductivity solutions prior to field-testing activities.

SAMPLES—Sampling followed established EPS guidelines (USEPA 2004 & U.S. Geological Survey 2006). Grab samples were collected with sealed handheld polypropylene (Nalgene or similar) open-mouth bottles provided, sealed, by Caliber Analytical Services, LLC. Bottles and caps were rinsed with sample water three times prior to being immersed and capped, with sampling taking place at mid-channel or as close to the stream center as possible. Samplers took care to stand downstream of the bottle and avoid all sources of suspended sediment as it was being filled. Samples were immediately placed in coolers on ice and shipped to the laboratory.

DISTANCE ANALYSIS—The information from each specific data point tested (GPS data and water quality data) was entered into a spreadsheet. The KML format of this data was also loaded into Google Earth so that each point on the spreadsheet corresponded with the same point on Google Earth based on GPS coordinates. Area streams and creeks appear in red on Google Earth courtesy of data obtained from The U.S. Geological Survey's National Hydrology Dataset. Current and former surface mining activity locations appear on Google Earth as green territory courtesy of Tennessee county coal surface mine data from ilovemountains.org. By using the USGS NHD layer, the TN county mine location layer, and UMD's GPS data points, the ground distance in meters from each individual data point to the nearest mining activity could be determined using Google Earth's path tool (Figure 2). It is important to note that some assumptions had to be made when obtaining this data. If the data point was located on a stream or creek (according to the USGS NHD layer), the distance to the nearest upstream mining activity was recorded. If the data point was not located on a stream or creek, the ground distance to the nearest upslope mining activity was recorded. If there was no upstream or upslope mining activity for a data point, distance was recorded as "3000+" meters. Ground distance

values in meters were recorded with corresponding data points in the spreadsheet for statistical analysis.

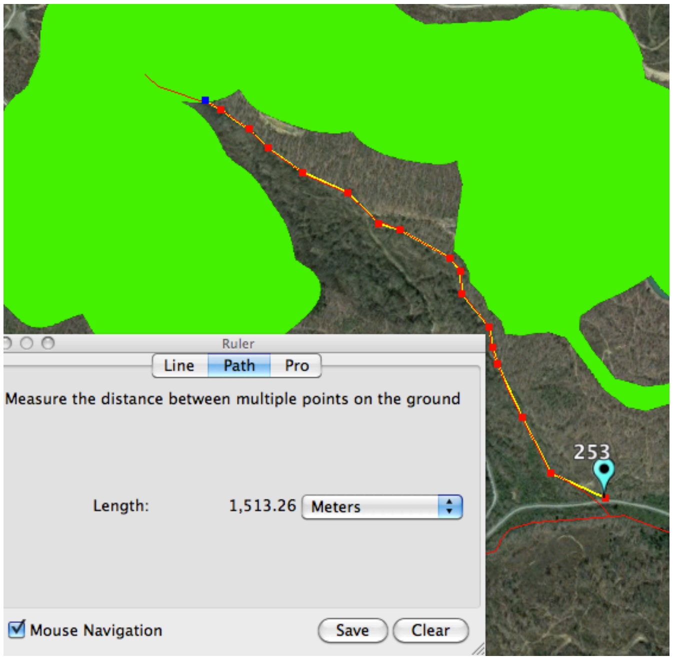

FIGURE 2. Sample showing how ground distance was calculated for each individual data point. The red layer (USGS NHD) signifies a stream or creek. The green layer (TN County mine location data) signifies a current or former surface mine. The blue point labeled '253' is a UMD testing point. The yellow line is the path created using Google Earth's path tool and ground distance is recorded in meters as seen in the window in the lower left corner. Source: Google Earth.

STATISTICAL ANALYSIS—Data were analyzed using XLSTAT (http://www.xlstat.com/en/) which allows a wide variety of univiariate through multivariate analyses. The initial step was to see which dependent variables (water quality parameters) were best explained by distance to mining activity. We examined this dependence as both linear and non-linear responses. Once we identified those variables, we graphed these relationships (in a bivariate manner) and utilized regression to describe them. Following that, the relationships were statistically analyzed to determine if they were significant at the 0.05 level of confidence.

RESULTS

WATER QUALITY PARAMETERS STUDIED—The water quality parameters analyzed as distance from mining activity increased were:

Conductivity
Aluminum

Sulfate
Manganese
Iron
pH

There is a statistically significant difference in conductivity as distance from mining activity increases (Figure 3; $y = -104.4\ln(x) + 1060.9$, $R^2 = 0.25715$). Conductivity values of water samples decreased as distance from the nearest upstream or upslope mining activity increased. The highest conductivity values were found in samples near mining activity. Once the 1,500-meter distance was reached, sample conductivity began to level off at approximately 300 µS/cm.

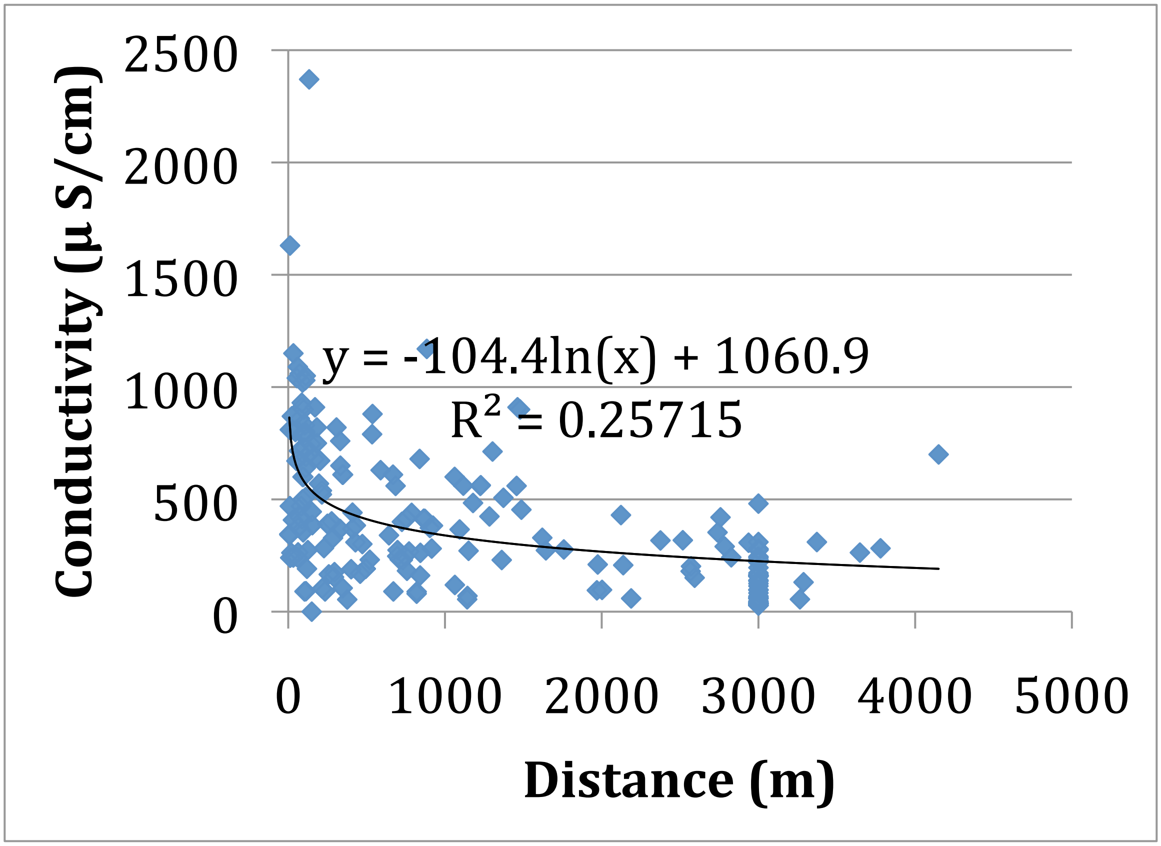

FIGURE 3. Measurements of water sample conductivity as distance from mining activity increases. There is a statistically significant difference between conductivity values (microsiemens/centimeter) and distance (meters) from mining activity ($y = -104.4\ln(x) + 1060.9$, $R^2 = 0.25715$).

Water sample aluminum values were not significantly different with increasing distance from mine activity (Figure 4). Aluminum values vary between 10 and 45 µg/L across all distances.

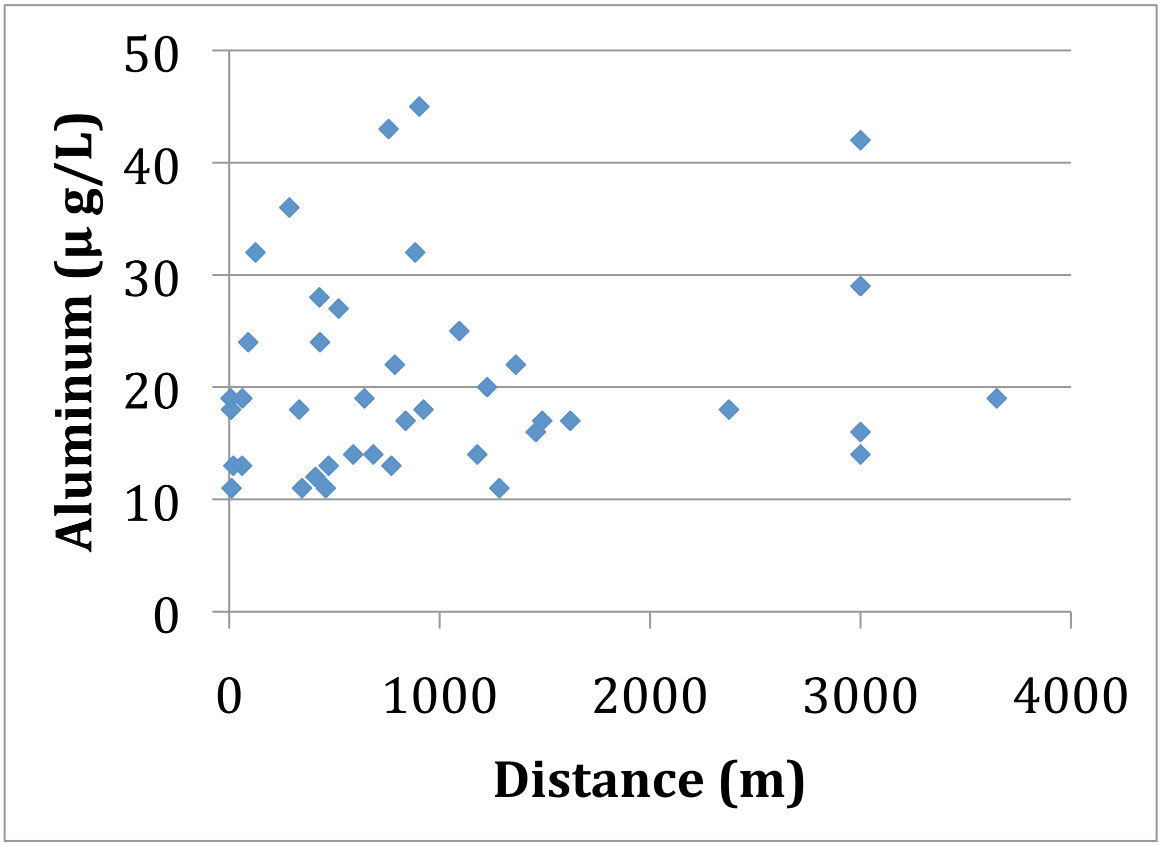

FIGURE 4. Measurements of water sample aluminum content as distance from mining activity increases. There is no statistically significant difference between aluminum values (micrograms/liter) and distance (meters) from mining activity.

There is a statistically significant difference in water sample sulfate values as distance from mining activity increases (Figure 5; $y = -35.94\ln(x) + 358.63$, $R^2 = 0.1431$). Sulfate values are much higher in water samples found nearer mining activity than those further away. Water samples near mining activity (< 100 m) had sulfate measurements as high as 900 mg/L. At about 1,500 meters, sulfate measurements began to level off at approximately 80 mg/L.

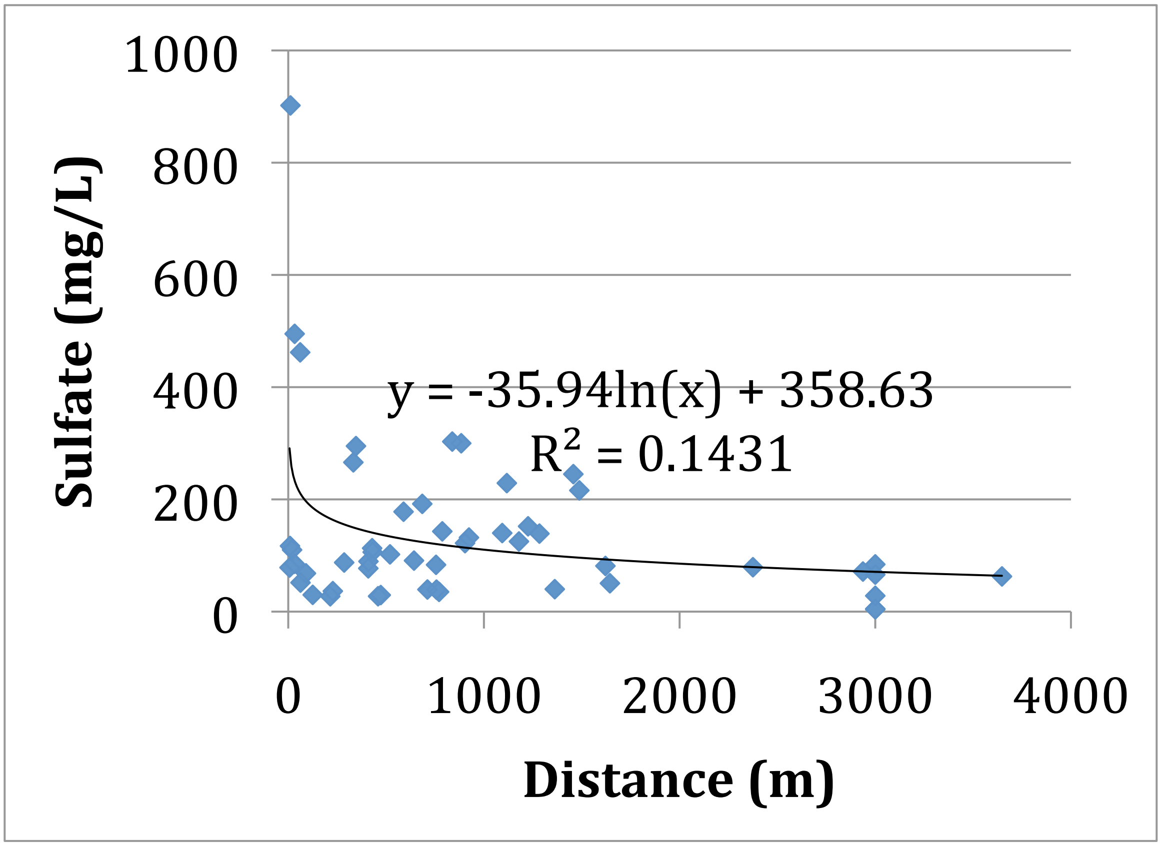

FIGURE 5. Measurements of water sample sulfate content as distance from mining activity increases. There is a statistically significant difference between sulfate values (milligrams/liter) and distance (meters) from mining activity ($y = -35.94\ln(x) + 358.63$, $R^2 = 0.1431$).

There is also a statistically significant difference in water sample manganese values as distance from mining activity increases (Figure 6; $y = -0.0097x + 120.5$, $R^2 = 0.00167$). Water samples nearer mining activity (< 500 m) had slightly higher manganese values (160 µg/L) than samples further from mining activity (80 µg/L at 4,250 m).

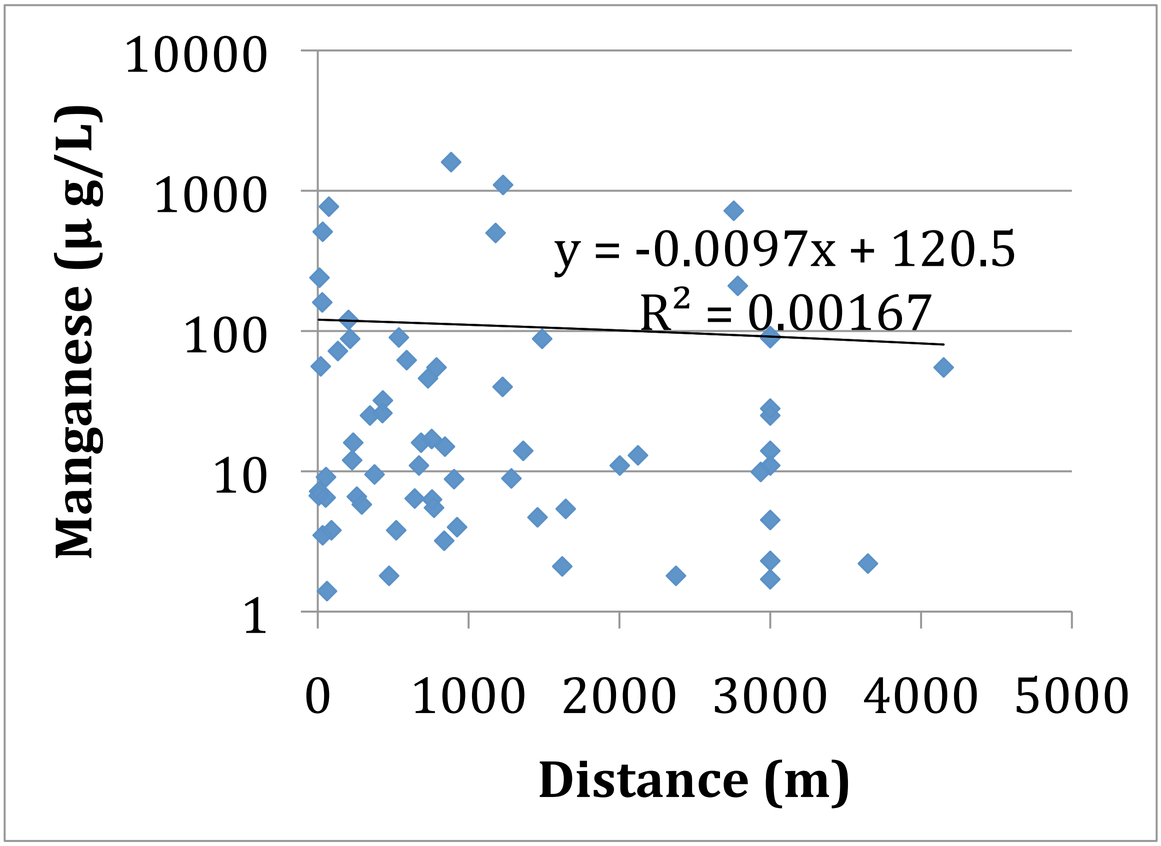

FIGURE 6. Measurements of water sample manganese content as distance from mining activity increases. There is a statistically significant difference between water sample manganese values (micrograms/liter) and distance (meters) from mining activity (y = -0.0097x + 120.5, R^2 = 0.00167).

There is no statistically significant difference between water sample iron content and distance from mining activity (Figure 7). As distance from mining activity increases, iron content slightly increases with one data anomaly of 1900 µg/L at approximately 1,500 meters from the nearest upstream/upslope mining activity.

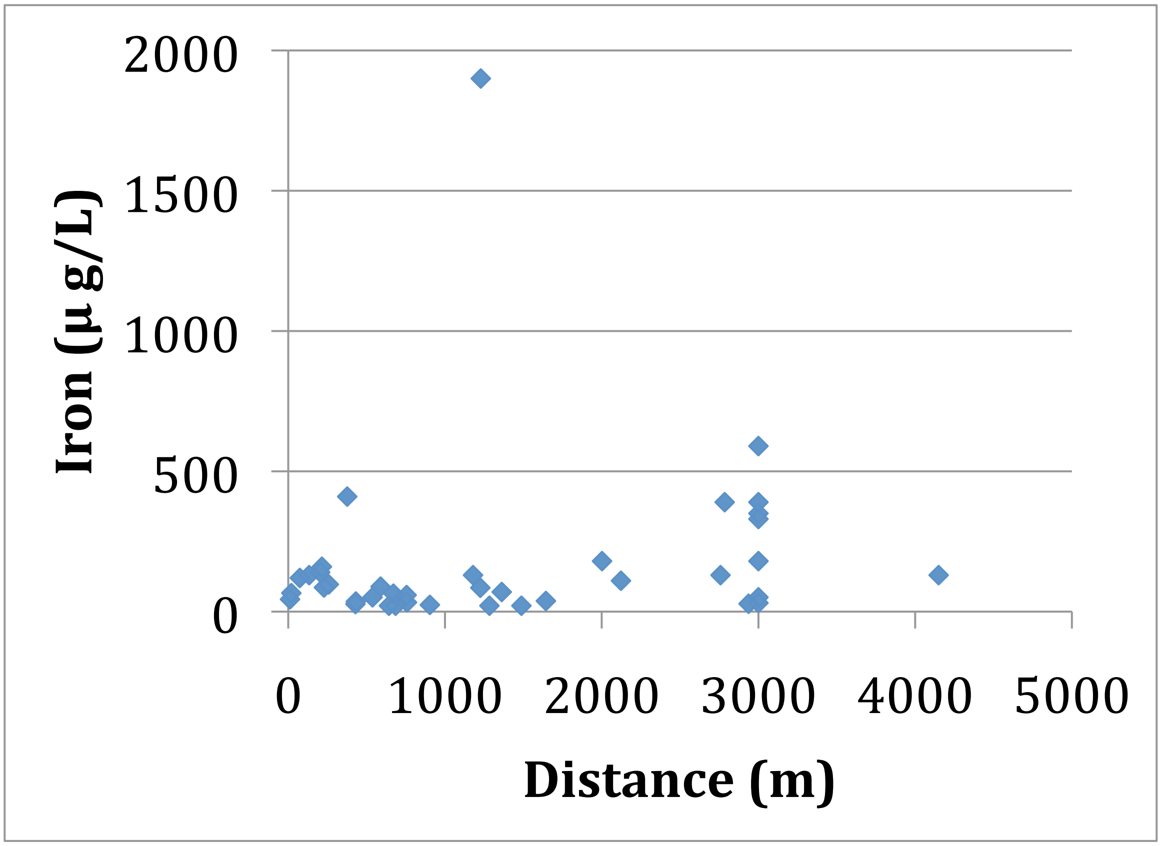

FIGURE 7. Measurements of water sample iron content as distance from mining activity increases. There is no statistically significant difference between water sample iron values (micrograms/liter) and distance (meters) from mining activity.

There is no statistically significant difference between water sample pH and distance from mining activity (Figure 8). For the most part, pH values hover between 7 and 9 regardless of distance from mining activity. With the exception of a few low and high data anomalies, pH values appear unaffected by distance from mining activity.

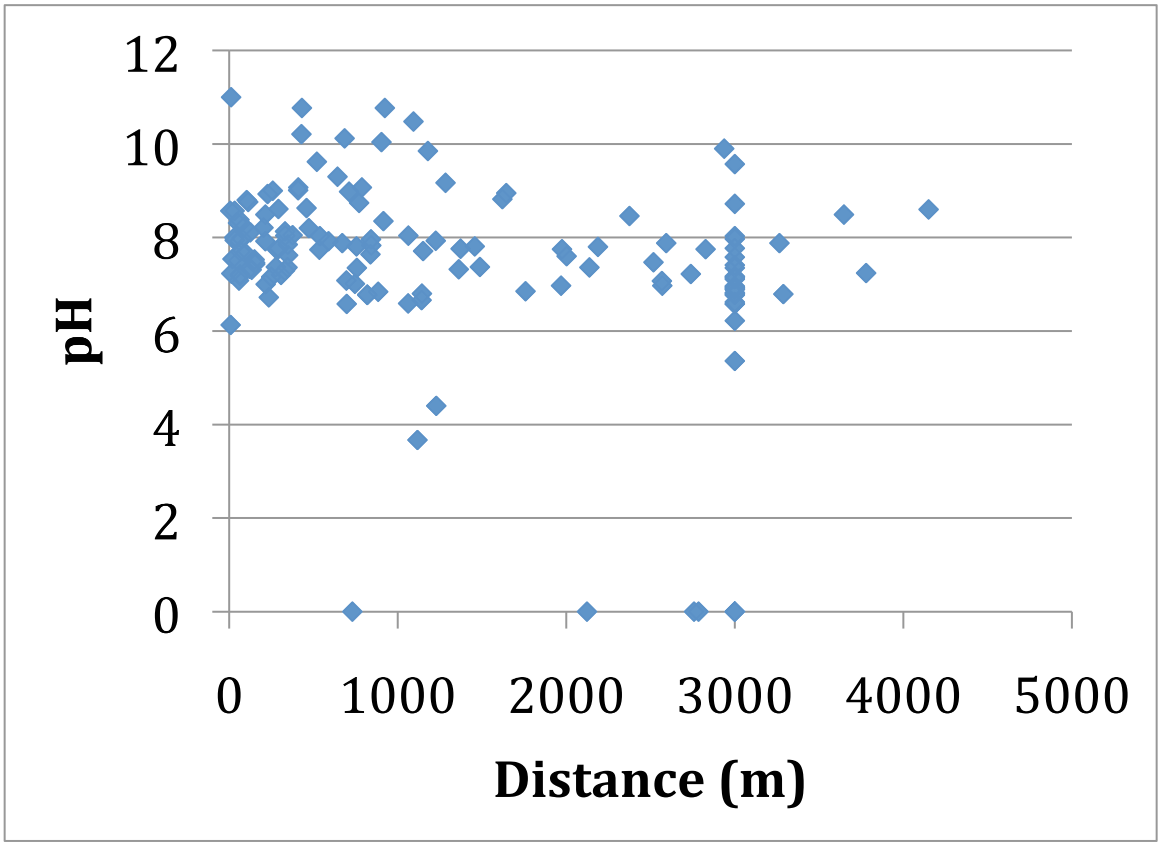

FIGURE 8. Measurements of water sample pH values as distance from mining activity increases. There is no statistically significant difference between water sample pH values and distance (meters) from mining activity.

There is a statistically significant relationship between water sample conductivity values and sulfate values (Figure 9; $y = 1.7784x + 182.85$, $R^2 = 0.86913$). Water samples with high conductivity values typically also had high sulfate values and vice versa (low conductivity samples had low sulfate content). Because conductivity and sulfate values both had statistically significant relationships with distance from mining activity, this means that water samples with high conductivity and sulfate values are found closer to mining activity and that, as distance from mining activity increases, water sample conductivity and sulfate values both decrease.

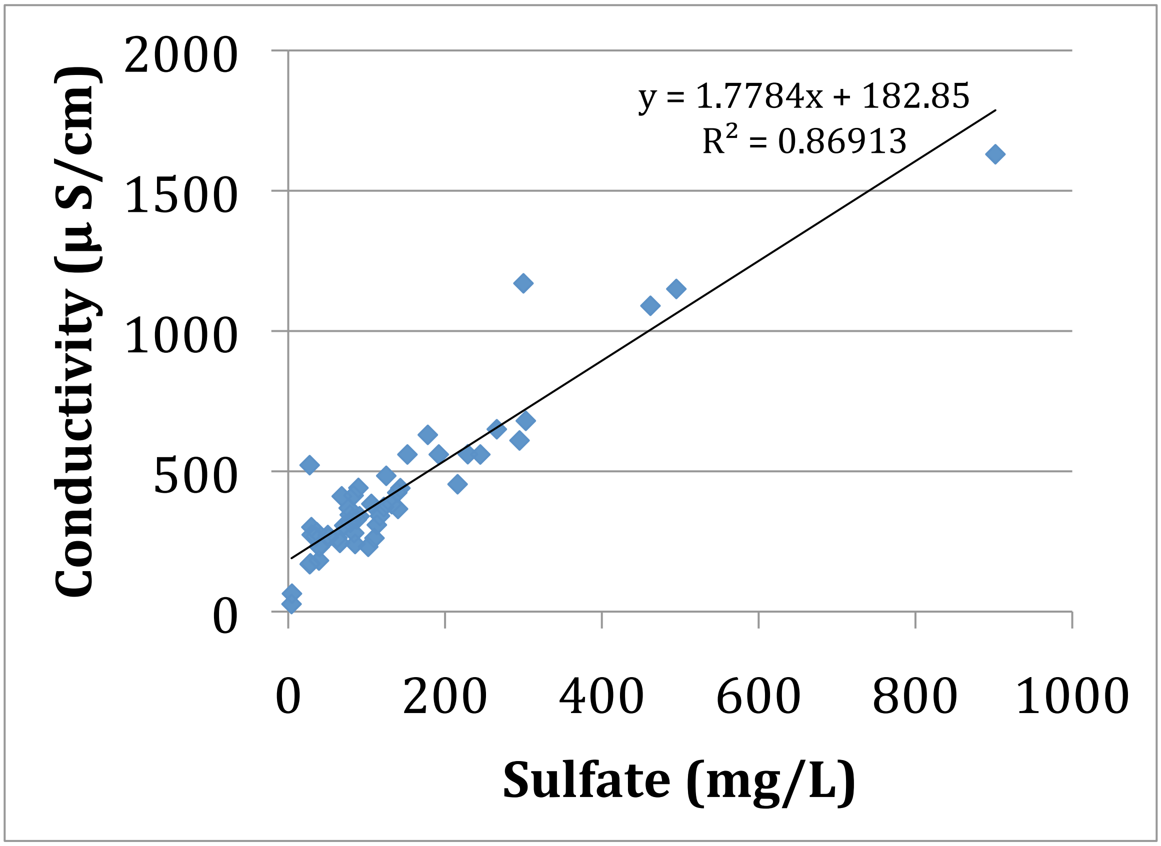

FIGURE 9. The relationship between water sample conductivity and sulfate values. There is a statistically significant relationship between conductivity (microsiemens/centimeter) and sulfate (milligrams/liter) content in water samples tested ($y = 1.7784x + 182.85$, $R^2 = 0.86913$).

DISCUSSION

The data from this study provide a key insight into how surface coal mining activities impact headwater streams spatially on East Tennessee's Northern Cumberland Plateau. Of the water quality parameters tested, conductivity, sulfate, and manganese had statistically significantly relationships with distance from the nearest upstream or upslope surface coal mining activity. Analyzed water samples had significantly decreasing measurements of these parameters as distance from mining activity increased. Aluminum, Iron, and pH water quality parameters showed no significant spatial relationship with nearby mining activity, which also provides key insight into how coal-mining activity impacts headwater streams spatially.

Electrical conductivity in water is controlled by the concentration of ions and can be used to directly estimate total dissolved solids (TDS). Many studies address the issue of TDS as a major stressor upon receiving streams in mined watersheds (Chapman *et al.* 2000; Goodfellow *et al.* 2000; Pond *et al.* 2008; Timpano 2011). Mine discharges with conductivity levels below 300 µS/cm typically do not cause

significant degradation of aquatic ecosystems; however, conductivity levels greater than 300 μS/cm and approaching 500 μS/cm cause significant adverse impacts on ecosystems (USEPA 2009). The data from this study show that, on average, conductivity levels in headwater streams fall below 300 μS/cm at approximately 1,000 meters from the nearest upstream or upslope mining activity. Conductivity levels greater than 300 μS/cm up to 1,000 meters downstream from mining activity are severely impairing already fragile headwater streams and the aquatic ecosystems they support.

Sulfate is a major component of acid mine drainage (AMD) contributed primarily by the weathering of iron sulfides that, when oxidized, form highly acidic, sulfate-rich solutions (Zipper *et al.* 2011). Secondary reactions of sulfuric acid with compounds in rocks and mine spoil can produce high concentrations of manganese and other constituents of mine drainage waters (Tolar 1982). Manganese, another spatially significant parameter, is typically found in elevated concentrations in waters downstream from mining activity (Robb & Robinson 1995). Like sulfate compounds, oxidized manganese emits compounds known to contribute to acid mine drainage and high TDS solutions that lead to highly acidic, highly conductive aquatic systems that are extremely detrimental to downstream organisms (Sams & Beer 2000). Water quality standards for sulfate are approximately 230-250 mg/L (Elphick *et al.* 2011; Pennsylvania Department of Environmental Protection 2012; Soucek & Kennedy 2005) and 50 μg/L for manganese (USEPA 2009). On average, analyzed water samples contained levels of sulfate greater than 230 mg/L at a distance of approximately 100 meters; however, average manganese values of approximately 95-150 μg/L (well above the 50 μg/L EPA established guideline) exist up to 4,500 meters downstream, the furthest distance measured. The combined impacts of conductivity and manganese levels exceeding established EPA guidelines extending, in some cases, a few thousand meters downstream severely impact the aquatic ecosystems in these headwater streams.

Aluminum and iron were water quality parameters analyzed that showed no significant spatial relationship to nearby surface coal mining activity. The lack of spatial relationship does not necessarily mean no negative stream impacts, just that levels of each parameter did not significantly increase or decrease with distance from nearest upstream or upslope mining activity. Aluminum and iron, like manganese, are often found in high concentrations that, when oxidized, contribute to high TDS and AMD solutions that are extremely detrimental to wildlife (Robb & Robinson 1995). The EPA-established standards for aluminum and iron are 87 μg/L and 1000 μg/L, respectively (USEPA 2009). The results of this study found zero data points exceeding aluminum standards and only one data point exceeding iron standards meaning that, most likely, neither of these water quality parameters play a role in downstream aquatic ecosystem degradation.

Measurements of water pH are important because they provide good overall indicators of AMD severity within streams. Streams that are impacted by AMD characteristically have low pH levels (< 6.0) that are highly detrimental to fish populations and other aquatic life (Telliard *et al.* 2009; Herlihy *et al.* 1990; Henry *et al.* 1999; DeNicola & Stapleton 2002). Only a handful of sub-6.0 pH values were recorded in this study, with many pH readings being slightly basic, possibly due to

calcium carbonate limestone content of underlying geologic materials in this region. It is unlikely that acidic pH values are contributing to any negative impacts to aquatic ecosystems caused by upstream mining activity.

The results of this study also showed an interesting relationship between conductivity and sulfate. The water quality parameters of conductivity and sulfate showed a positive correlation in that samples with high conductivity readings also contained high levels of sulfate. Because conductivity and sulfate parameters both exhibit statistically significant relationships with distance to mining activity, it can be deduced that water samples with high conductivity and sulfate content are from tests performed nearer mining activity and samples with lower conductivity and sulfate occur as distance from mining activity increases. This relationship provides further evidence that water samples nearer to mining activity are subject to more negative impacts from the mining activity than those further away.

It is no secret that surface coal mining activities bring environmental destruction and devastation to the areas in which they are practiced, specifically to watersheds. The results of this study provide evidence of significant spatial relationships between mining-impacted water quality parameters and distance from the nearest upstream or upslope surface coal mining activity. Of the parameters considered, conductivity, sulfate, and manganese all showed statistically significant decreases as distance from surface mining activity increased. Aluminum, iron, and pH exhibited no significant relationships and were all well under their EPA-established guidelines and likely not influential in aquatic ecosystem degradation at the tested locations. The three significant parameters, however, are very likely contributing to aquatic ecosystem degradation in streams, specifically those near mining activity. Many aquatic organisms find these water quality conditions undesirable, including the Blackside Dace, a threatened fish species endemic to small tributaries in the upper Cumberland River drainage in southeastern Kentucky and northeastern Tennessee (Black *et al.* 2013). This small, fragile fish species has a low conductivity tolerance (max. of 240 μS/cm) and has declined in abundance due to surface coal mining's contributions of conductivity in headwater streams throughout its natural habitat (Johnson *et al.* 2009). Upper reaches of headwater streams, often home to the most fragile ecosystems, are very close to many of these mining activities and thus at greatest risk for severely impaired water quality conditions.

Although this study provides key insight into how surface mining activity influences water quality on a spatial scale, much more work needs to be done in order to fully comprehend the environmental degradation wrought by mining activities every year. United Mountain Defense hopes to continue to analyze water quality data from surface coal mining activities while also expanding their testing efforts to include potential water quality impacts due to hydrofracking operations, an increasingly common natural gas extraction method on the Northern Cumberland Plateau. With help from student interns at the University of Tennessee, Knoxville, local volunteers, and members of United Mountain Defense, mining-impacted watersheds on East Tennessee's Northern Cumberland Plateau will continue to be analyzed and publicized in hopes of preventing future mining

activity, mitigate current damages, and preserve these fragile watersheds and the aquatic ecosystems they support for generations to come.

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