THE EXTENT OF MINE DRAINAGE INTO STREAMS OF THE CENTRAL APPALACHIAN AND ROCKY MOUNTAIN REGIONS

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Abstract. Runoff and drainage from active and inactive mines are contaminating streams throughout the United States with acidic and metal contaminated waters and sediments. The extent of mining impacts on streams of the coal bearing region of the Central Appalachians and the metal bearing regions of the Rocky Mountains were assessed by three approaches. First, chemistry data from streams sampled by the USEPA's Environmental Monitoring and Assessment Program (EMAP) and Regional EMAP (REMAP) were used to classify streams based on acid neutralizing capacity (ANC), sulfate (SO_4^{-2}), metals, and chloride (Cl^-) concentrations of the water. High sulfate and metal concentrations served as excellent indicators of mine drainage impacts in the watersheds. In the second approach, we determined the extent of mining activity within each U.S. Geological Survey 8-digit hydrologic catalog unit within the study regions and its proximity to streams based on classified thematic mapper (TM) satellite imagery and the USEPA's River Reach File Version 3 (RF3) data. Our third approach, using biological data collected from the EMAP and REMAP streams, looked at the correlation of these data with the stream chemical classification, and estimated the extent of mining impact based on biotic indices and microbial respiration. The stream chemistry approach estimated that 25-28% of the stream length in the regions were impacted by mine drainage. The TM approach estimated that 9-16% of the stream length in the regions were vulnerable to mining impacts. The stream biota indicated that the extent of mining impacts to streams might be as high as 9-67% of the stream length in the regions.

Key words: Appalachian streams, biotic indices, EMAP, mining impacts, REMAP, Rocky Mountains streams, thematic mapper imagery.

1. Introduction

Some of the most environmentally damaging land uses in the United States are associated with mining. While the total land area of the U.S. in mining is small (0.12%) (Starnes and Gasper, 1995), the impacts are much more extensive. Runoff and drainage from active and inactive mine sites are contaminating mid-Appalachian streams with acidic and metal contaminated waters and sediments. There are 66,500 documented sources of coal mine drainage in Appalachia, 3000-

5000 active or abandoned coal piles and impoundments containing $3 X 10^9$ metric tons of waste, resulting in the pollution of an estimated 17,000 km of streams (Cohen and Gorman, 1991).

In the western U.S., hardrock mining has been a part of the landscape for more than a century (Lyon *et al.*, 1993). Mines, ranging in size from small excavation pits to huge underground caverns honeycombed with mine shafts, were opened wherever precious metal ores were plentiful and accessible. As ore recovery became less economical, these mines were abandoned, and most were never reclaimed. These abandoned mines are characterized by toxic waste rock and tailings piles, and contaminated surface and ground waters (Western Governors Association, 1996). It has been estimated that there are more than 557,000 abandoned hardrock mine sites in the western United States (Lyon *et al.,* 1993). These abandoned mines have contributed to the contamination of more than 20,000 km rivers and streams and 70,000 ha of lakes and reservoirs. Colorado has a significant proportion (21,000) of these abandoned hardrock mines impacting more than 2000 km rivers and streams (Colorado Office of Active and Inactive Mines, 1996).

Chemical perturbations, either acidic and metal impacted, or simply metal impacted, will result in increased toxicity of sediments and overlying waters, and bioaccumulation of metals by surviving species. Loss of assimilative capacity, impairment of trophic interactions, and an overall reduction of energy and nutrient flows are expected (Burton *et al.*, 1987; Clements *et al.*, 1992; Hill *et al.*, 1997; Moore *et al.*, 1991).

This project was undertaken to compare chemical and biological monitoring, GIS modeling of stream proximity to mines, and remote sensing of stream proximity to mines to assess the extent of mining impacts to streams in Central Appalachian and Southern Rocky Mountains.

2. Methods

2.1. STUDY AREAS AND SAMPLE COLLECTION.

2.1.1. *Study Areas*

This study included streams from the coal-bearing portion of the Central Appalachian and the ore-bearing portion of the Southern Rocky Mountains (Fig. 1). In this paper, we present data collected by the US Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP, Central Appalachians) and Regional EMAP (REMAP, Southern Rockies) surveys conducted between 1993 and 1995. The surveys were restricted to first, second, and third-order streams (2nd-4th order in the Southern Rockies) on the 1:100,000 scale

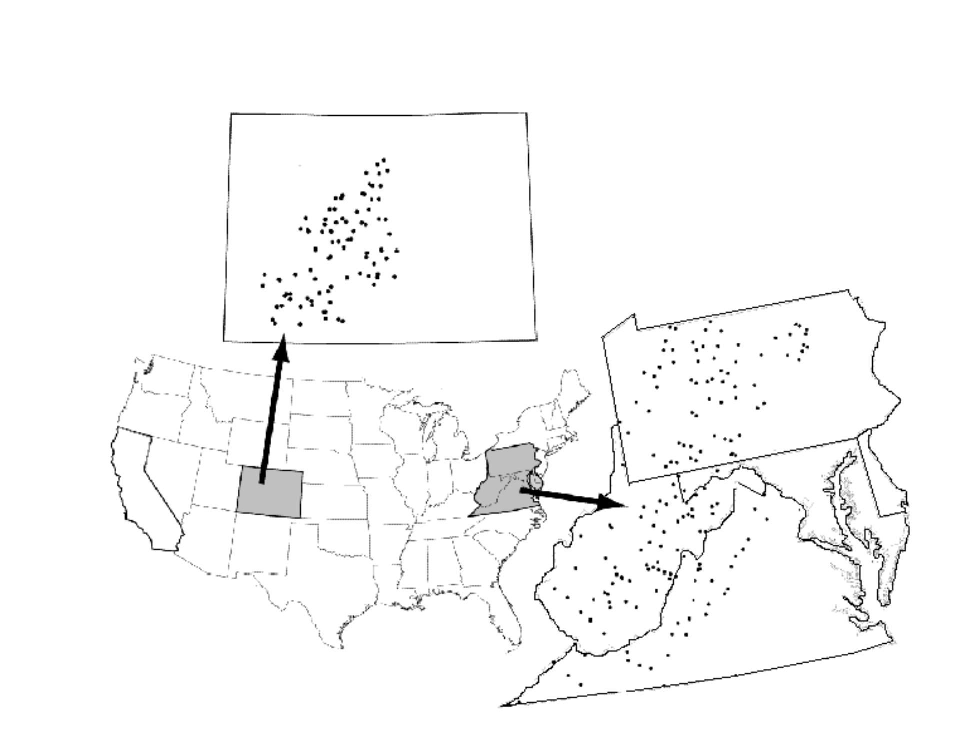

Figure 1. Locations of sampling sites in the Central Appalachian and Southern Rocky Mountain regions.

map (Reach File 3 (RF3) (USEPA, 1994) . Each site had a sample weight (expansion factor) calculated as the inverse of the probability of selecting that stream reach. Summing the sample weight of each site in the data set yields the total stream length in the study population. Samples were collected from 252 different streams representative of 58,100 km of streams in the Central Appalachian and 28,800 km of streams in the Southern Rocky Mountains.

2.1.2. *Stream Sampling*

Stream chemistry samples were collected using the EMAP protocols (Lazorchak *et al.*,1998). In addition to the base protocols, sampling included collection of water for metal analyses of the Southern Rockies streams (Hill *et al.*, 1997).

Fish, macroinvertebrates, periphyton, sedimient microbial respiration, and toxicity sample were collected using the EMAP stream protocols (Hill *et al*., 1997; Lazorchak *et al*.,1998).

2.1.3. *Mine Censuses of the Central Appalachian and Southern Rocky Mountains*

Total mining area in the Central Appalachian Mountains was estimated using remotely sensed data collected from Landsat satellites. Multispectral sensor (MSS) and thematic mapper (TM) imaging from the satellites were used to detect barren areas on the Earth's surface. Barren areas in the Central Appalachians were analyzed using spectral signatures of coal mining developed for this region by USEPA Region III. The absolute area of mining within any U.S. Geological Survey hydrologic catalog unit (8-digit HUC) was used to score the potential severity of mining impacts. Since drainage density (cumulative stream length within a HUC per surface area of the HUC) in this region is high (Leopold *et al*., 1964), all streams within a HUC were assumed to be impacted in proportion to the extent of mining within the HUC.

Remote sensing data were not available for the Southern Rockies and we relied on mine location information available from the US EPA Region 8 (USEPA ,1993). Mine locations in the Southern Rockies were overlain with Reach File 3 stream listing to determine the extent of mine drainage impacts on Southern Rockies streams. Mine impacts in the more arid Southern Rockies were conservatively estimated to extend to all streams within 1 km of a mine site.

2.1.4. *Statistical Analyses*

The extent of chemical and biological impairment of mining impacted streams was determined by analyzing the cumulative distribution of the weighted variables of interest (SAS, 1998) . The weighted variable scores (e.g., IBI, % EPT, PIBI) were plotted as histograms and the percentage of total stream length below threshold value for each variable was the percentage of stream length considered to be in poor condition.

3. Results and Discussion

3.1. ASSESSMENT OF MINING IMPACTS TO STREAMS

3.1.1. *Chemical Assessment*

Streams were divided into acidic and non-acidic groups using an ANC criteria of 25 μeq/L. Acidic streams were further classed as impacted by atmospheric deposition or by mine drainage using a sulfate criteria of 400 μeq/L. Acidic streams with SO_4 below 400 μeq/L were dominated by atmospheric sources of SO_4, whereas those with SO_4 above 400 μeq/L were dominated by watershed (mining) sources. Non-acidic streams with SO_4 concentrations above 1000 μeq/L were classified as mine drainage impacted (Herlihy *et al.*,1990). Using this model, 14,000 km of Central Appalachian streams (about 25% of the stream length in the coal-bearing region) were impacted by mine drainage., and 6,600 km of Southern Rockies streams (28% of the stream length) showed chemical evidence of mine drainage (Table I).

Southern Rockies streams were also classified on the basis of dissolved zinc (Zn) concentrations, with 14% of the total stream length exceeding Colorado's hardness-based Zn criteria (Colorado Department of Public Health, 1999) (Table I).

3.1.2. *Fish*

Fish collected from the Central Appalachian streams were used to calculate an Index of Biotic Integrity (IBI, McCormick *et al.*, in review). An IBI score of less than 50 is indicative of poor condition, and we estimated that 26,700 km of streams (46% of the total stream length) in the coal-bearing area of the Central Appalachians were degraded (Table I). The proportion of impaired stream length in the Kanawha and Upper Ohio basins, which have experienced high mining activity, was 59% and 62%, respectively.

In the Southern Rockies, where the depauperate fish assemblage precludes the use of an IBI, we selected the absence of fish and the proportion of species richness attributable to native taxa as indicators of mining impacts. McCormick *et al.* (1994) reported that native species, such as sculpins (*Cottus beldingi*) and cutthroat trout (*Oncorhynchus clarki*), were absent from Eagle River sites exposed to elevated metal concentrations from mine drainage. The proportion of species richness as native taxa is low throughout the Southern Rockies ecoregion of Colorado, with a mean of 26% of the richness comprised of native species, perhaps reflecting the state's aggressive fisheries stocking program (Nico and Fuller, 1999). Throughout the Southern Rockies study area, 22% of the stream lengths were fishless (representing 5,800 km of streams), 38% (10,900 km of streams) had no native taxa, and 67% had fewer than 50% of their richness attributable to native species. In the Upper South Platte and Upper Arkansas basins, which have high mining activity, the proportion of streams in which native species make up less than one-half of the assemblage rises to 93% and 92% of the total stream length in those basins, respectively (Table I). By comparison, 14% of the Central Appalachian streams were fishless and 6% were dominated by non-native taxa (Table I).

3.1.3. *Macroinvertebrates*

The proportion of the macroinvertebrate assemblage in Ephemeroptera, Plecoptera, and Tricoptera (EPT) collected from the study streams was used as an indicator of stream condition, with greater EPT expected in less impacted streams. Central Appalachian streams were considered in poor condition if the assemblage was composed of less than 29% (the 25th percentile) EPT taxa. Overall, 22% of the streams (representing 12,800 km of streams) in the coal-bearing portion of the Central Appalachians were in poor condition. In Kanawha and Upper Ohio basins, 31% and 50% of the stream lengths, respectively, were in poor condition (Table I).

Table I

Extent (km of stream and % of total km of streams) of mining impacted streams in the Central Appalachian and Southern Rocky Mountains

Method of Estimation	Extent of Impacted Streams in the Central Appalachians	Extent of Impacted Streams in the Southern Rockies
Chemical		
Sulfate	14,000 km (25%)	6,600 km (28%)
Zinc > CO criteria	ns	4,000 km (14%)
Biological		
Fish IBI	26,700 km (46%)	ns
Fishless	11,600 km (20%)	5,800 km (22%)
< 50% Natives	3,500 km (6%)	19,300 km (67%)
Macroinvertebrates		
% EPT	12,800 km (22%)	8,600 km (30%)
Periphyton		
PIBI	21,000 km (36%)	ns
Richness	26,000 km (44%)	7,500 km (26%)
Chl/AFDM	16,800 km (29%)	7,200 km (25%)
Respiration	16,800 km (29%)	6,300 km (22%)
Toxicity	ns	2,600 km (9%)
Census		
TM Analysis	5,200 km (9%)	ns
Mine Census	ns	4,600 km (16%)

ns=not sampled

For Southern Rockies streams, we set the EPT threshold at 27% of the assemblage (the 25th percentile), resulting in an estimated 8,600 km of streams (30% of the total stream length) in poor condition. The proportion of stream length in the Upper South Platte and Arkansas basins in poor condition are 32% and 38%, respectively (Table I).

3.1.4. *Periphyton*

Algae collected from streams in the Central Appalachians were used to calculate a periphyton index of biotic integrity (PIBI), similar to that calculated for fish (Hill *et al.*, in review). A PIBI score below 50 (the 25th percentile) is indicative of poor condition. Overall, 21,000 km of streams in the coal-bearing portion of the Central Appalachians are in poor condition, representing 36% of the total stream length (Table I).

A PIBI has not been developed for the Southern Rockies, and we used diatom richness and specific chlorophyll content (μg Chl/ mg AFDM) as indicators of stream condition. Streams with fewer than 18 diatom species (the 25th percentile) were classified as in poor condition. By comparison, diatom richness in the Central Appalachian streams is expected to be above 27 species (25th percentile). Overall, 7,500 km of streams (26% of the total stream length) in the Southern Rockies were in poor condition, compared to 44% of the stream length in the Central Appalachians. Similar results were found for streams of the Upper South Platte and Upper Arkansas basins, which had 26% and 21% of their stream length in poor condition (Table I).

Specific chlorophyll content was used as a non-taxonomic indicator of stream condition. This measure of the periphyton assemblage both decreases and increases under stress, and streams with specific chlorophyll values below 10 μg Chl/ mg AFDM (the lower 12.5th percentile) or above 240 μg Chl/ mg AFDM (the upper 12.5th percentile) considered in poor condition. Overall, 7,200 km of streams in the Southern Rockies were in poor condition, representing 25% of the total stream length, compared to 29% in the Central Appalachians (Table I).

3.1.5. *Sediment Microbial Respiration*

Sediment microbial respiration, which is inhibited by mine drainage (Hill *et al.*, 1997) was used as a measure of impairment of stream ecosystem function. Streams were deemed in poor condition if respiration was lower than 0.02 mg O_2 g^{-1} AFDM

h^{-1} (the lower 12.5th percentile) or above 0.14 mg O_2 g^{-1} AFDM h^{-1} (the upper 12.5th percentile) . In the Central Appalachians, 29% of the total stream length (16,800 km) was in poor condition, rising to 44% and 45% for the Upper Ohio and Kanawha basins, respectively (Table I).

Respiration in Southern Rockies streams indicated that 6,300 km were in poor condition, representing 22% of the total stream length in the ecoregion. The proportion of impacted streams rises to 33% and 39%, respectively, in the South Platte and Arkansas basins (Table I).

3.1.6. *Toxicity of Southern Rockies Streamwater*

Survival of *C. dubia* less than 80% in ambient streamwater was used as the threshold below which streams were classified in poor condition. Using this criterion, 9% (2,600 km) of the total Southern Rockies stream length were in poor condition (Table I).

3.1.7. *Mine Censuses of the Central Appalachian and Southern Rocky Mountains*

We set 1% of the watershed in mining as the threshold above which streams within 1 km of a mine would be classified as in poor condition, resulting in an estimated mining impact on 5,200 km of Central Appalachian streams (9% of the total stream length in the region (Table I). The potential impact rises to 18% of the total stream length in the Kanawha drainage basin, and 33% in the Upper Ohio drainage basin.

We relied on mine location information available from the U.S. Bureau of Mines for the assessment of potential mining impacts to Southern Rockies streams. We used more than 10 mines per 100 square miles of watershed as the threshold above which streams in that watershed were classified as being in poor condition, resulting in an estimate of 4,600 km of streams (16% of total stream length) in poor condition (Table I).

3.2. INTERPRETATION OF RESULTS

Estimates of mining impacts to streams, based on chemical signatures or mine censuses, were lower than those based on biological assessment. This may be due to several factors. First, remote sensing requires distinctive surface features that can be observed using some wavelength of electromagnetic radiation. Surface features such as mine spoils, characteristic of mining impacted areas, are detected with satellite imagery. However, deep mines, particularly those which were abandoned decades prior to monitoring and with little control on discharge of acid mine drainage, may contribute significantly to mining impacts on streams, but may not be detected by remote sensing. Such historically abandoned mines may be also undercounted by the mining census. In addition, both methods require assumptions about the extent of impacts associated with individual mine sites.

Second, water chemistry measurements are point observations that may vary both temporally and longitudinally along streams. Instream geochemical reactions and dilution increase ANC and decrease SO_4 and heavy metals, such as Zn, downstream from source areas of mine drainage.

Third, mine drainage can also have longer term and more extensive impacts on physical habitats in streams. This results in changes within the biotic community that are measured by assessments of fish, macroinvertebrates, periphyton, and sediment microbial respiration. The geochemical reactions that ameliorate the alterations in water chemistry associated with mine drainage generally produce fine particles, often composed of iron hydroxides, that embed coarser stream bed sediments and may armor the stream bed. This may occur for a distance much farther downstream from the mine source than indicated by measurements of ANC, SO_4, or metals.

Finally, stream biota may be responding to other stressors in addition to mining. Forestry, agricultural practices, and urbanization are also known to impact the biota of streams. However, it should be noted that the extent of these other stressors within the study watersheds (HUCs) are relatively small compared to mining.

In summary, chemistry and mine censuses indicate extensive mining impacts to streams of the Central Appalachian coal-bearing and the Southern Rockies ore-bearing regions. However, biological measures, which respond to both chemical inhibition and habitat impairment, suggest much more extensive impacts than those predicted by chemistry or census.

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