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The environmental costs of mountaintop mining valley fill operations for aquatic ecosystems of the Central Appalachians

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Southern Appalachian forests are recognized as a biodiversity hot spot of global significance, particularly for endemic aquatic salamanders and mussels. The dominant driver of land-cover and land-use change in this region is surface mining, with an ever-increasing proportion occurring as mountaintop mining with valley fill operations (MTVF). In MTVF, seams of coal are exposed using explosives, and the resulting noncoal overburden is pushed into adjacent valleys to facilitate coal extraction. To date, MTVF throughout the Appalachians have converted 1.1 million hectares of forest to surface mines and buried more than 2,000 km of stream channel beneath mining overburden. The impacts of these lost forests and buried streams are propagated throughout the river networks of the region as the resulting sediment and chemical pollutants are transmitted downstream. There is, to date, no evidence to suggest that the extensive chemical and hydrologic alterations of streams by MTVF can be offset or reversed by currently required reclamation and mitigation practices.

Keywords: stream ecosystems; mountaintop mining; appalachians; water quality; macroinvertebrates

Introduction

"Streams are the gutters down which flow the ruins of continents."

Leopold, Wolman, and Miller (1964)

Most of the world's great rivers are born in vast networks of tiny headwater mountain streams. Each contributing stream carries eroded sediments and weathered solutes from its watershed toward the sea. When human activities alter the vegetation, the soil, and the contours of watersheds for resource extraction, agriculture, or settlement, we change the relationship between the stream and its valley. Most types of land-use change result in the increased movement of water, sediments, and dissolved chemicals from the uplands to downstream ecosystems.¹ Of all the many varieties of land-use change, none is as marked and as irreversible as surface mining, which strips away vegetation and surface soils and mechanically alters the underlying geology, leaving behind a landscape that is fundamentally recontoured, requires centuries for the development of new soil horizons, and where water is routed along new flowpaths, either overland or through unconsolidated rock spoil toward the draining stream. Unconsolidated rock has vastly increased surface areas exposed to the elements that are susceptible to increased rates of physical and chemical weathering; this leads to substantial losses of rock-derived chemicals from the watershed to downstream ecosystems. Mountaintop mining with valley fill operations (MTVF) is a relatively recent approach to surface mining techniques in which surface mining actually lowers watershed ridges to extract coal and fills watershed streams with the quantities of leftover rock. Throughout the southern Appalachians of the United States, small and steep forested watersheds are being converted to flattened grasslands in order to acquire coal. Streams within these watersheds are lost, buried beneath overburden. The impacts of these landscape alterations are not contained within mine boundaries—mined watersheds export larger volumes of water, masses of sediment, and higher

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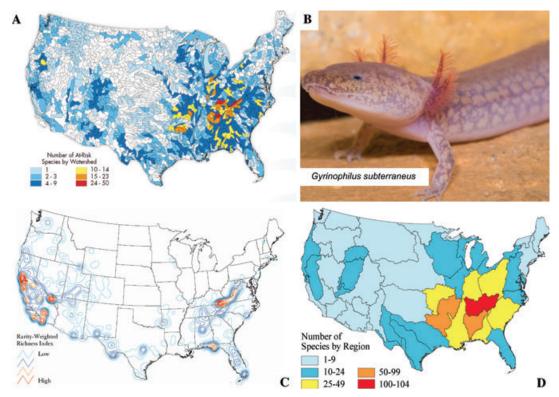


Figure 1. (A) Hotspots for at-risk fish and mussel species (from Master et al.⁷). (B) A Blue Ridge salamander (photo by J.S. Pippen). (C) Hotspots of rarity and richness. (D) Regional concentrations of aquatic biodiversity; both reprinted with permission from Precious Heritage, ©TNC and NatureServe, 2000.

concentrations of a variety of rock-derived chemicals to downstream rivers. Despite laws designed to regulate environmental effects from coal mining, such as the Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Refs. 2 and 3) and sections 402 and 404 of the Clean Water Act, examination of the known influences of MTVF on the environment has led some to designate the Central Appalachians as an "environmental sacrifice zone." While legal debates rage and court cases focused on the permitting and regulation of surface mining, particularly MTVF, continue to grow in number and complexity, our goal is to focus on the environmental impacts. In this review, we will describe how mountaintop removal mining affects aquatic ecosystems throughout the Central Appalachians.

Aquatic ecosystems of the Central Appalachians

The forests of the Central Appalachian ecoregion are rich in natural resources, including the produc-

tive temperate forests that characterize the region as well as rich reserves of bituminous coal. The Appalachian mountain region forms the headwaters for many major U.S. rivers including the Potomac, Susquehanna, and Ohio rivers, which collectively provide water resources to tens of millions of U.S. residents. Coal mining in this region has supported the growth of the U.S. energy economy since the early 19th century, and billions of tons of recoverable coal deposits are still contained within the region. In contrast to much of the rest of the eastern United States, much of this ecoregion remains forested, and the dominant land-cover change in the region results from surface mining.^{5,6}

Because the southern Appalachians escaped glaciation, these are among the oldest mountainous ecosystems on Earth. As a result of their antiquity and their topographic diversity, the landscape of the southern Appalachians supports among the highest levels of biodiversity and endemism in the temperate zone^{7,8} (Fig. 1). More than 2,000 species

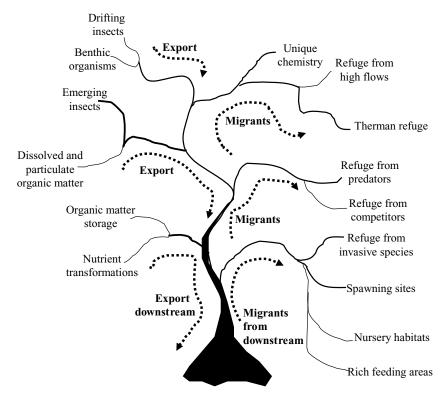


Figure 2. Factors that contribute to the biological importance of headwater streams in river networks. Attributes on the right benefit species unique to headwaters and also make headwaters essential seasonal habitats for migrants from downstream. On the left are biological contributions of headwater ecosystems to riparian and downstream ecosystems. From Meyer *et al.*¹²

of vascular plants have been recorded in the region, and the rivers and streams of the southern and Central Appalachians have been identified as the most biologically diverse freshwater systems in North America.⁸ The ecoregion is home to 10% of global salamander diversity and freshwater mussel diversity.^{7,9}

The burial of 2,000 km of Central Appalachian streams thus represents a significant loss of freshwater ecosystem habitat in the region. The role of headwater streams in supporting high levels of biodiversity has been emphasized in a great deal of scientific research. 10–12 These small streams provide habitats for a rich array of species, which enhances the biological diversity of the entire river system. Some of the species are unique—that is, the only place in a river network these species occur is in the headwaters. 13,14 They provide a refuge from predators and changes in temperature for some species 15 and can be important spawning and nursery grounds for others. 16,17 Meyer *et al.* 12 provide a succinct sum-

mary of why the protection of headwater streams is critical for preserving regional biodiversity, supporting downstream food webs, and reducing sediment and nutrient loading to downstream waters (Fig. 2).

Invertebrate diversity is particularly high in headwater streams.¹⁸ For example, Stout and Wallace¹⁴ sampled 23 intermittent Appalachian streams and recorded 86 insect genera from more than 47 families. Amphipods, isopods, copepods, cladocerans, and ostracods are particularly common, and the latter three may reach abundances of >10,000/m.2,19 Meyer et al. 12 documented that many of the smaller interstitial taxa such as rotifers, gastrotrichs, and oligochaetes are both diverse and abundant in headwater streams. Fish can also be abundant in headwaters, and while fish diversity generally increases with stream size, many headwater species are not found elsewhere in the river network—headwaters may disproportionately contribute to network-wide diversity and play a critical role in the genetics of fish populations.^{12,20} Generally, the species found in these small streams are small in body size—such as minnows, darters, and sculpins—but also may include salmonids such as those found in cold North Carolina headwaters.²¹

Where fish are absent in Appalachian streams, amphibians are common and are typically the top aquatic predators. Headwater seeps and ephemeral and intermittent streams provide vital habitat for amphibians, many of which are state and/or federally threatened and endangered.²²⁻²⁵ Salamanders are the most common vertebrate in headwaters of the region^{25,26} and appear to be particularly vulnerable to land-use change. Ford et al.27 documented that diversity and abundance of salamanders in the southern Appalachian mountains was reduced when forests are clear-cut, even after more than 75 years of regrowth. Loss of salamander populations from headwater streams can have ecosystemwide consequences since they influence insect population dynamics, regulate detritus food webs, and link stream and terrestrial food webs.²³

Stream ecosystem habitat loss through burial and degradation resulting from mining runoff occurs in the headwater streams "where rivers are born" (sensu Meyer et al.).12 Headwater streams are critically important components of river networks because their flow and associated biota, sediment, and dissolved constituents feed all downstream waters. Any major changes affecting headwater tributaries or any activity that isolates or cuts off these tributaries from the lower part of the watershed will have important consequences for hydrologic processes, sediment delivery, channel morphology, biogeochemistry, and stream ecology further downstream in the watershed.²⁸⁻³⁰ Surface mines and filled valleys deliver enormous quantities of miningderived sediments and solutes to downstream rivers, which fundamentally alters the biological communities and the biogeochemical cycling throughout the river network.

The coal mining process

Coal and coal impurities

Coal supplies nearly half of U.S. electricity needs annually.³¹ Coal minerals are a fossil fuel derived from the lithification of peats produced in wetlands millions of years ago and that were subsequently buried under sediments. Coal minerals primarily consist of densely packed organic carbon

that, when burned, produces energy. Coal minerals that have undergone more extensive lithification are denser and thus have higher energy production potential and greater economic value. Coal mining in the Central Appalachians produces high-grade bituminous coal with a high heat value.³² Along with the vegetation-derived carbon, coal minerals are also highly enriched in pyrite minerals produced as a byproduct of sulfate reduction in the anoxic sediments of ancient wetlands³³ as well as a variety of trace metals that accumulated in the original plant and microbial tissues. When coal minerals previously buried in bedrock are exposed to air and water, these pyrite minerals are oxidized, generating sulfuric acid and iron hydroxides. It is this reaction that generates the acid mine drainage problems associated with some coal mines. Throughout much of the Central Appalachians, carbonate parent material provides extensive internal buffering capacity so that many surface mines generate alkaline mine drainage, with mine runoff having elevated pH that is rich in the acid anion sulfate (SO_4^{2-}) and the base cations calcium and magnesium (Ca²⁺ and Mg²⁺). The sulfuric acid generated by pyrite oxidation facilitates rapid weathering of the surrounding rocks and leads to the leaching and export of trace elements to draining streams. When coal is burned, these trace elements can produce significant air quality problems—particularly through the production of the volatile SO_x and NO_x gases that generate acid rain³⁴ and the emission of mercury as an airborne pollutant.35

Mountaintop mining with valley fill operations

The advent of MTVF enabled surface mines to expand considerably in size.³⁶ MTVF practices involve the removal of the top 50-200 vertical meters of mountain summits and ridges to extract embedded coal strata.³⁷ To access the shallow coal seams embedded within the ridges, mining companies begin by clearing existing forests and then removing the topsoil. A combination of explosives and heavy machinery is then used to loosen and remove the dirt and rock material that covers coal seams (Fig. 3A). Mechanized draglines are then used to remove rubble to clear access to the now exposed coal seams on the rock face (Fig. 3C). MTVF produces large volumes of unconsolidated rock waste and coal debris, often referred to as "overburden." In the steep terrain of Appalachia, the cheapest



Figure 3. Photos of mountaintop mining activity. Panel A shows active and reclaimed portions of the Hobet mine in southern West Virginia; note the active explosion on the long wall at center left and the protection of the Berry Branch cemetery in the small forested ridge in the bottom left. Panel B is a photograph of a valley fill draining a portion of the Hobet mine. Panel C shows a dragline excavator at work on a long wall. These are the largest mobile machines built today, and they are capable of excavating 30–60 metric tons of material with every pass of the dragline bucket. Panel D shows iron precipitates coating the bed of a stream draining a mountaintop mining operation in Kentucky. Photos A&C are by Vivian Stockman, with the help of SouthWings.org. Photo B was taken by Ty Lindbergh, and Photo D was taken by Ken Fritz.

and most common disposal option for overburden is to push it into adjacent valleys, creating what are called valley fills. Individual valley fills can be hundreds of feet wide and more than a mile in length, and each fill buries the headwater streams of the former valley under tens to hundreds of meters of overburden (Fig. 3B). Most of the coal produced in the Central Appalachians is washed prior to extraction to reduce its sulfur content, a process that leaves behind large coal slurry ponds enriched in pyrite minerals and other trace elements leached

from coal.³⁷ Slurry ponds and coal washing facilities may be built on site in some mining operations, while other mines transport coal to centralized facilities. Once a surface mine permit area has been depleted of coal, mining companies are required to perform reclamation activities, including regrading and recontouring the land surface, adding a topsoil substitute, and seeding the area. Regulatory permitting requires that the burial of streams beneath valley fills and coal slurry ponds be mitigated by the construction of natural channels or near reclaimed

mines or the restoration of degraded streams within the watershed.

Mountaintop mining is widespread across the Central Appalachian Mountains and is particularly intense in southern West Virginia, eastern Kentucky and Tennessee, and southwestern Virginia. The U.S. Environmental Protection Agency (EPA) predicts that by 2012, mountaintop mining will have removed ~5700 km² of Appalachian forests and buried ~3200 km of streams. In fact, surface mining and mine reclamation activities are currently the largest driver of land-use change in the Appalachian region. See the Central Region of the Appalachian region.

The Central Appalachian region supplies ∼19% of U.S. coal production annually.³¹ Mountaintop mining is practiced by numerous companies in the region because it can be done at large scales, allows access to shallow coal seams, and generates greater profits than underground mining. The large size of MTVF mines (they can be many square kilometers in size) and the use of large machinery and explosives both reduce the number of workers needed and create economies of scale. Economic analysis shows that MTVF require far fewer workers per ton of coal produced than does underground mining;^{31,36} this allows Central Appalachian states to compete more effectively with western states in the extraction and sale of coal. Surface mining can be effectively accomplished with heavy machinery run by only a few workers. Indeed, the size of the coal mining workforce has dropped precipitously in the Appalachian region, falling from 171,000 workers in 1980 to 71,000 workers in 1993 without declines in production.³⁹ The extent of MTVF in the Central Appalachians increased markedly as a result of the 1977 and 1990 amendments to the Clean Air Act to curtail sulfur emissions, 40 because these regulations increased demand for the low sulfur coal characteristic of much of the Central Appalachians. MTVF target shallow coal reserves, often only a few feet thick, which are typically inaccessible to traditional underground mining practices.

The legal and regulatory framework governing MTVF

In the United States, debates over the social and environmental impacts of MTVF are conspicuous due to several high profile federal court cases, widely publicized exchanges between the EPA and the Army Corps of Engineers (ACOE) over permitting deci-

sions, advocacy by local and national nongovernmental organizations, and protests by miners related to Congressional hearings and pending legislation. Several federal laws and multiple government agencies regulate the practice of mountaintop mining. The federal laws that most directly relate to MTVF are the Surface Mining Control and Reclamation Act (SMCRA; 25 U.S.C. 1201) and the Clean Water Act (CWA; 33 U.S.C. 1252).41 The government agencies responsible for administering these laws are the EPA, the ACOE, and the environmental and natural resource departments of state governments. Enacted in 1977, the SMCRA requires the regulation and inspection of surface mines and the restoration or reclamation of abandoned mines. The CWA of 1972 is the central environmental statute protecting U.S. surface waters. The CWA aims to restore and maintain the physical, chemical, and biological integrity of streams, rivers, and water bodies. The CWA and its implementing regulations require that burying streams with discharged materials should be avoided and, if unavoidable, mitigation must render nonsignificant the impacts that mining activities have on the structure and function of aquatic ecosystems. Section 404 of the CWA regulates discharge of fill material into waterways by establishing a permit process administered by the ACOE and overseen by the EPA. Regulators and environmental advocacy groups have interpreted the language of the CWA differently, with numerous lawsuits challenging agency permitting.^{41,42}

Environmental impacts

MTVFs have both local and regional effects on aquatic ecosystems. The most obvious impact of MTVF on aquatic ecosystems is the local destruction of stream segments that are buried beneath valley fills, mined through or converted to waste treatment systems in the form of ponds at the base of fills. Streams that have been filled no longer exist thus, MTVF lead to a net loss of stream habitat and stream and riparian ecosystem function in the watersheds in which it occurs. In addition, MTVF have far-reaching downstream impacts through the export of sediments and dissolved substances (solutes) from mined watersheds. Furthermore, the removal of vegetation from mined watersheds, the flattening of valley contours, and the compaction of soil on mined sites fundamentally alters the patterns of water flow through impacted valleys and changes the delivery of water and the composition of dissolved and particulate materials provided to larger receiving streams.

Effects at the local scale

Lost streams. Individual surface mines in the Central Appalachians can range in size from a few square kilometers to the 40 km² Hobet mine in southern West Virginia, the largest individual surface mine in Appalachia. Typically, mining companies apply for a single permit that allows them to mine coal in multiple adjacent headwater valleys. The first step in initiating a new MTVF mine is to convert a portion of the draining stream into a sediment pond that will collect sediments generated during the mining operation. Ultimately, the sediment pond will sit at the base of a newly generated valley fill. The original draining stream will continue to receive all of the surface runoff generated from the watershed; yet the headwaters will be eliminated; instead, water will flow over and through blasted rock and through the increasingly thick valley fill and into a settling pond en route to the stream network. Settling ponds are critical because new mines immediately begin to generate sediment pollution as mine access roads are built and forests are cleared. The rate of sediment export only increases as a result of blasting along the ridges and the disposal of rock waste directly into the stream drainage network.

Lost soils. One of the most severe and long-lasting consequences of surface mining is the permanent loss and homogenization of the forest soils. Some mining operations attempt to preserve soil and store it to replace on the mine surface following mining, but even with careful management, a large volume of soil will inevitably be lost via erosion, burial within overburden, and oxidation by soil microbes. What soil remains will be homogenized so that organic and mineral soils are mixed, significantly altering soil horizons that developed over prior centuries. In addition to the significant losses of soil carbon associated with soil removal, 43 soil macro- and micronutrients are also lost. Thus, the surface of a reclaimed mine will at best be covered with a thin layer of very altered soils overlaying crushed and compacted rock. This change in the vertical profile of soils is coupled with massive changes in topography at the scale of the catchment, both of which have important implications for the hydrology and vegetation structure of the recovering watershed

and its draining stream; these changes persist indefinitely. The landscape left behind after surface mining operations cease must undergo a primary succession sequence similar to that following glacial retreat. 44-46 Many decades are required for forests to reestablish in the thin or nonexistent soils over newly exposed rock (Fig. 4B). In addition to the challenge of growing in thin soils, vegetation must establish roots in alkaline soils, which can inhibit tree growth. 47,48 Without thick soils and sufficient nutrients, there is little evidence to suggest that native trees characteristic of the region can be cultivated or maintained on reclaimed mines. 36,43 There are few peer-reviewed reports of forest growth on reclaimed mine sites in the Central Appalachians, and their conclusions are divergent. Several studies^{49,50} have reported limited woody tree recruitment and growth in a series of MTVF sites reclaimed under the SMCRA, while Rodrigue et al.51 and Amichev et al.52 estimated similar levels of forest productivity between 14 surface mine sites reclaimed prior to the 1977 enactment of the SMCRA and adjacent unmined stands. Revegetation is required under the SMCRA, but this has typically involved hydroseeding the recontoured landscape with a mixture of grasses⁴⁴ so that forest regrowth depends upon dispersal and recruitment. Recent studies demonstrate that the forests and grasslands growing on reclaimed surface mines sequester and store far less carbon than unmined sites, both in vegetation biomass and in the soil. 43,48,53

Altered hydrology. As a result of reduced vegetation and evapotranspiration, surface-mined watersheds typically have higher annual water yields than their forested counterparts.⁵⁴ Mining also leads to significant changes in watershed hydrographs.^{55–57} Recent work analyzing hydrological changes as a function of the amount of a watershed that has been surface mined showed that peak flows increase linearly with the percent of the watershed mined, even if the land has been reclaimed.⁵⁸ These hydrologic changes persist because reclamation using earth-moving machinery compacts soil layers thus decreasing porosity and water infiltration.⁵⁹ Compared to regions that have not been mined, infiltration may be as much as an order of magnitude lower^{60,61} so that mined sites respond to rainfall more like urban watersheds, where impervious surfaces lead to high surface runoff during storms.⁵⁸

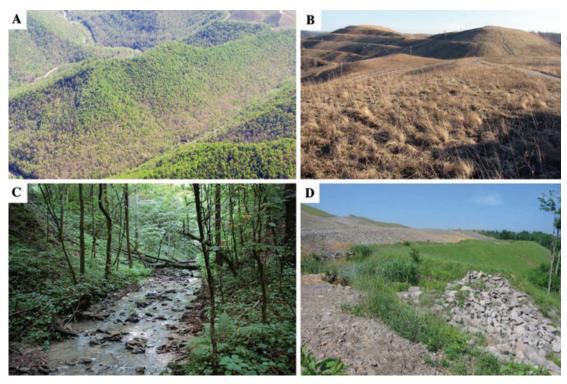


Figure 4. At top a photo of the (A) unmined landscape of the central Appalachians juxtaposed against (B) a photo of a reclamation site on the Wind River mine after more than 20 years of reclamation. Both photos by Vivian Stockman with the help of South-Wings.org. At bottom (C) a photo of a typical central Appalachian stream juxtaposed against (D) a photo of a created stream built to mitigate for stream burial by mining overburden. Photo C by Jack Webster. Photo D excerpted from a Technical memorandum: Ecological Functions in Created Stream Channels Prepared by Ecology and Environment, Inc. Source caption reads: "Example of a stream creation project 15 years post-creation (NPDES Outlet). Nicholas County, WV."

Longitudinal impacts

Three fundamental scientific principles are critical to understanding why cumulative impacts of MTVF on downstream aquatic resources are so important. First, changes at the watershed scale influence stream hydrology throughout the catchment.⁶² The timing and magnitude of stream flows result from complex interactions between rainfall, plants, topographic relief, and soil properties of all land above a drainage point.⁶³ Once vegetation is lost and soil is compacted, as occurs on mined and even reclaimed mine land, hydrological changes negatively affect stream biota and water quality.^{53,58} Second, stream water chemistry is shaped by processes that occur as rainwater infiltrates the ground and moves through pore spaces and soil on its way to streams. 64,65 Water emerging from valley fills carries with it dissolved constituents that are toxic or damaging to biota (discussed extensively later in this review). Third, the downhill movement of water and one-way flow in

stream networks means that whatever happens on land or in first- and second-order streams (headwaters) not only determines sediment and water flow in the immediately impacted streams and rivers, but also determines ecological structure and functions of larger waterways into which these tributaries flow.⁶⁶

Therefore, individual mines not only profoundly affect stream water quality, community structure, and ecosystem functions immediately downstream of valley fills (Fig. 3D), but multiple mining operations within larger watersheds have cumulative effects on larger downstream rivers through increased loading of dissolved substances derived from alkaline mine drainage.

Sulfate. Just as coal burning for power generation produces sulfur aerosols (SO_x) , the exposure of coal seams during coal mining provides many opportunities for the leaching of sulfate (SO_4^{2-}) from coal

wastes into surface waters. Unlike SO_x emissions that distribute sulfur aerosols regionally, mining activities lead to a localized point source of SO_4^{2-} to the drainage network. As a consequence of regional SO_x emissions, freshwater systems throughout North American and Europe have had tenfold or greater increases in SO_4^- concentrations. As a result of mining activities, impacted streams in West Virginia often have 30- to 40-fold increases in SO_4^{2-} concentrations,^{67,68} with some streams reported to have SO₄ - concentrations higher than found in seawater.⁶⁹ The relationship between mining activities and high sulfate concentrations is so well established that the 2008 WVDEP West Virginia Integrated Water Quality Monitoring and Assessment Report suggested that SO_4^{2-} concentrations $> 50 \text{ mg L}^{-1}$ could be used as an indicator of mining activity.⁷⁰

The headwater mountain streams of the Central Appalachians that are being impacted by mountaintop mining were historically dilute and oligotrophic. Earlier studies in major watersheds of West Virginia directly linked increases in river sulfate load to increasing coal production in the watershed² and used time-series analysis to show that sulfate concentrations in streams continue to increase after mining activities end.² Likewise, a U.S. Geological Survey National Water-Quality Assessment Program study found that in the Kanawha-New River Basin, total iron (Fe) and manganese (Mn) decreased in streams draining watersheds with ongoing coal production between 1991 and 1998, while sulfate concentrations continued to increase.⁵⁷ Both of these studies documented an increase in $SO_4{}^{2-}$ loading to major river systems that corresponded to increases in coal extraction within their watersheds.

This fundamental change in the chemistry of headwater streams can have important local- and watershed-scale impacts on aquatic organisms and ecosystem functions. Elevated sulfate concentrations will stimulate microbial sulfate reduction in stream and wetland sediments. In this reaction, microbes use SO_4^- in place of oxygen in their consumption of organic matter. The sulfur (S) in sulfates is converted to sulfide (HS⁻)—this is the reaction that gives salt marshes and wetlands their characteristic rotten egg (sulfurous) odor:

$$SO_4^{2-} + 2CH_2O \rightarrow HS^- + HCO_3^- + CO_2 + H_2O.$$

As sulfate concentrations increase, the production of sulfide also increases, and this has important

implications for the receiving ecosystems. Sulfide is directly phytotoxic to many aquatic plants.^{71–74} Elevated sulfide also has important biogeochemical impacts. Sulfide binds strongly with Fe in sediments, converting it to pyrite minerals. While this has positive benefits in terms of reducing Fe concentrations in sulfate-rich mine drainage, it also has implications for nutrient pollution. Much of the phosphorus (P) present in freshwater ecosystems at any given time is bound to iron minerals. In environments with high sulfide concentrations, sulfide interferes with the Fe-P bonds and P is released to the water column. 75,76 By this mechanism, sulfate additions can lead to the eutrophication of freshwater streams, wetlands, and lakes without any additional nutrient loading (so-called indirect or internal eutrophication). 74 High sulfate loading can also make freshwater ecosystems more sensitive to nutrient pollution by preventing abiotic reactions from sequestering P in inaccessible forms in the sediments. High sulfide can also inhibit nitrification (the process by which ammonium is converted to nitrate) in sediments and thereby dramatically reduce denitrification rates—again contributing to a reduced nitrogen removal efficiency within S-polluted sediments and promoting or enhancing nitrogen eutrophication.⁷⁷

Co-occurring contaminants. While an increase in sulfate loading is the most predictable and welldocumented water quality consequence of mountaintop mining in the Appalachians, many other substances are released to surface waters as a result of mining activity. Throughout much of the Central Appalachians, the presence of significant carbonate and base cations in parent material neutralizes the acidity of sulfuric acid released from weathered coal deposits, but the neutralization leads to dramatic increases in Ca²⁺, Mg²⁺, and HCO₃⁻ ions. This natural acid buffering potential can lead to an increase in the pH of receiving streams (rather than the more well understood acidification associated with acid mine drainage). The release of these ions contributes to dramatic increases in the electrical conductivity and total suspended solids within the water column of receiving streams.⁶⁷ An analysis of all small streams in West Virginia sampled by the West Virginia Department of Environmental Protection found that sulfate concentrations were highly correlated with conductivity, Ca, Cl, Fe, Mg, and Hardness—all of which contribute to

heightened ionic stress in these impacted streams.⁶⁹ The abundance of Al, Mn, and Se was also found to increase with SO_4^{2-} concentration.⁶⁹

Elevated conductivity. Recent studies 67,68,78 found that specific conductivities in streams below individual valley fills were 2–10 times higher than found in nearby unmined, reference streams. Typical specific conductance levels in low-order streams in West Virginia ranged from 13 to 253 μS/cm, 68,79 while valley fill-impacted streams were found to far exceed these values (502–2540 μS/cm). 67,68

For many streams, it is the cumulative or additive impact of elevated concentrations of multiple stressors that leads to biological impairment, and this is undoubtedly a part of the reason that conductivity (a cumulative measure of ionic strength) is such an effective predictor of biological impairment.⁸⁰ The ionic stress associated with high conductivity can have direct toxicity as well as providing an indication of the additive impacts of a variety of solutes. High conductivity can be directly toxic to aquatic organisms by disrupting osmoregulation.^{81,82} This is particularly important for aquatic insects with high cuticular permeability. Mayflies in particular are highly sensitive to ionic stress as they regulate their ion uptake and release using specialized structures within their gills, their integument, and internally via Malphigian tubules.⁸³ For these sensitive taxa, large increases in certain ions can disrupt water balance and ion exchange processes and cause stress or death. Tests for conductivity toxicity for mayflies have often proved inconclusive, 82,84-87 yet these studies are typically based on lab toxicological tests with hardy organisms that are easy to rear in lab settings (i.e., Hexagenia, Centroptilum, Cloeon, Isonychia) and are likely to be less sensitive than the mayfly genera that appear especially susceptible to ionic stress (e.g., ephemerellids, heptageniids).^{68,88} Rather than being directly lethal, high conductivity may encourage sensitive taxa to drift downstream from polluted reaches⁸⁹—an effect that would not be measured in the closed vessels of laboratory trials, but that could strongly alter community composition in the field.

The clear patterns linking high conductivity to a loss of mayfly (Ephemeroptera) taxa has ecosystem-scale importance since mayflies often account for 25–50% of total macroinverte-

brate abundance in the least-disturbed Central Appalachian streams.^{68,80} The finding that entire orders of benthic organisms are nearly eliminated in MTVF-affected streams suggests that alkaline mine drainage is fundamentally changing the structure of aquatic macroinvertebrate communities.^{68,80,90}

It is widely recognized that individual contaminants rarely exist alone, and although many ecotoxicological studies examine the impacts of single contaminants on laboratory organisms, it is the actual combined toxicity of constituents in field settings that is of interest. 91,92 In cases where an association of contaminants is well characterized (e.g., the trace metals and cations associated with alkaline or acid mine drainage or the road runoff associated with high-traffic volume corridors), a concentrationaddition method should be applied to assess their cumulative impact.92-95 Classic laboratory toxicological tests have largely failed to find toxic effects of any single component of alkaline mine drainage pollution. In contrast, the weight of field evidence suggests that mining activities in watersheds often degrade downstream water quality and lead to dramatic alterations in macroinvertebrate community structure. 36,68,69,80,90 Mine sites may vary considerably in the extent to which they affect legally regulated solutes in downstream waters, yet the valley fill operations studied to date are clearly causing heightened conductivity and high SO_4^{2-} concentrations. These increases in conductivity and sulfate are associated with a loss of sensitive macroinvertebrate taxa from affected stream reaches. 68,69,80,90 Current statistical and empirical work suggests that for Central Appalachian streams, conductivities above $300 \ \mu S \ cm^{-1}$ represent a threshold for sensitive invertebrate taxa. 68,80

All available data show that it becomes increasingly unlikely to find an unimpaired aquatic benthic community as conductivity increases. ^{36,68,69,80,96} As conductivity (and the associated SO₄²⁻, Ca²⁺, Mg²⁺, HCO₃⁻, and trace metals) increases in Central Appalachian streams, the biological community becomes less diverse and sensitive species (especially Ephemerellidae and Heptageniidae mayflies) are lost. High conductivities and high sulfates can persist long after mining activities cease, ^{2,57,68} and there is no empirical evidence documenting recovery of macroinvertebrate communities in the streams impacted by alkaline mine drainage.

Effects at the landscape scale

The EPA predicts that by 2012, an area over 5600 km² of Appalachian forests will have been impacted or destroyed by mountaintop removal mining (see Ref. 36 EIS, Appendix I). Surface mining is converting the large expanses of interior forest found in Central Appalachia into a fragmented patchwork of smaller forest patches with a higher proportion of forest edge habitat. In numerous studies examining the impacts of urban development or agricultural intensification on streams, authors have suggested that land-cover alteration affecting more than 10% of the watershed area leads to significant losses in stream biodiversity. To date, there have been no studies that explicitly link the cumulative extent of mountaintop mining to the water quality and biological community structure of impacted streams. Such information is critically important for guiding regulatory decision making. New research by Petty et al.90 suggests that mining severity (proximity to stream and extent of mining) is tightly linked to degradation of steam biological communities providing strong evidence of cumulative impacts.

Reclamation, remediation, and mitigation of MTVF

The CWA 404 guidelines mandate permit applicants to avoid, minimize, and mitigate impacts on the waters of the United States to prevent significant degradation of the nation's waters. When impacts are unavoidable, stream habitat and functions lost through mining and filling are subject to amelioration through mitigation. Because mitigation actions must replace lost stream resources and ecological functions, the value of those natural resources and functions must be assessed prior to their loss. This value is then used to determine how much mitigation is required.

Compensatory mitigation for MTVF generally includes efforts to create streams on the mining site and sometimes to also restore or enhance degraded streams in nearby watersheds. The SMCRA regulations require that watersheds impacted by surface mines be returned to a semblance of their former shape at the conclusion of mining activities. Yet the resulting manmade valleys are flattened, hydrologically altered grasslands with rock-lined drains flowing downslope. It is often these former drains that are restored to mitigate for newly permitted

stream burial even though the hydrology and the vegetation of the reclaimed mines are very different from their premining state. Stream creation proposals typically involve regrading mined land and reconfiguring mine drains or building new channels that are similar in physical form (e.g., width, depth, sinuosity) to the streams that were buried (Fig. 4C & D). Structural complexity of these channels may then be increased by adding wood or arranging rocks to help create physical habitat. Assessments developed by the regulatory authority are then required; these usually involve a focus on the physical structure of the stream even though structural and functional assessments are legally required. Stream mitigation efforts that meet a series of simple requirements for stream channel shape, streambed characteristics, and riparian vegetation survival are deemed adequate for mitigation. Mitigation credit can be earned for restored streams regardless of whether the constructed channels hold water for any time during the year, support any aquatic organisms, or perform any aquatic ecosystem functions. 97,98 The compensatory mitigation assessments⁹⁸ required by the ACOE have been successfully challenged in district court, but these rulings have been overturned upon appeal (see summary in Ref. 97).

Perhaps the most fundamental problem with the current regulatory framework is that permitting agencies fail to consider the cumulative impacts of issuing multiple mining permits in the same basin, and the impacts of mining outside of the permit boundaries are considered to be minimal, or to be taken care of through the National Pollutant Discharge Elimination System (NPDES) permitting. NPDES permit violations in the region are frequent, and when fines are levied, the costs are minimal relative to mining profits. ⁹⁹

Deficiencies of current mitigation practices

Failure to address ecosystem function

As described above, healthy streams are living, functional systems that support a number of critical ecological processes including the processing of nutrients; the decomposition of organic matter; and microbial, primary, and secondary production. ^{100–102} To date, mitigation plans associated with mountaintop mining have not used readily available methods for directly measuring ecological functions; however, these processes must be measured

in order to determine how and whether they may be brought back to the right levels and direction through mitigation. There are now abundant scientific studies outlining how to make and interpret such measurements 103,104 and how such measurements should be used to evaluate the success of a restoration project. 105–109

The use of well-accepted methods for measuring ecological functions¹¹⁰ is important because ecological functions evaluate dynamic properties of ecosystems that underlie an ecosystem's ability to provide vital goods and services. 102,103,108,111,112 Functions reflect system performance, and their measurement requires quantification of ecological processes such as primary production or nutrient uptake. 110 This should be reflected in the mitigation plan if the plan is to mitigate functions that are lost due to the mining through or filling streams. Functional measures have been used to compare degraded versus restored versus reference streams in many settings, 105-107,113,114 but research on ecological functions of created or restored MTVF streams is in its infancy. 115

Stream creation versus stream restoration

MTVF projects destroy healthy streams that are often in minimally disturbed, forested watersheds. Many mitigation plans propose to regrade the land and then construct a channel that has similar dimensions (width, depth, slope, sinuosity, etc.) to the one destroyed. Thus, the goal is to create a stream; however, all the natural flow paths and landscape topography have been destroyed. As "evidence" that stream creation is a routine practice, mitigation plans often cite projects that are actually channel reconfigurations or projects that have spatially shifted a section or meander of a channel these are not the same as stream creation because, for most restoration projects, the natural flow paths are still intact. In practice, ecological stream restoration varies along a continuum from removing ongoing impacts to a stream (e.g., preventing toxic inputs) and letting the system recover on its own; to enhancing habitat in the stream or its surrounding riparian zone (e.g., adding coarse woody debris to streams and planting vegetation); to fullscale restoration that involves manipulations of an existing stream channel (e.g., regrading banks and planting trees along a stream with eroding banks), 116-118

Some mitigation plans refer to channel creation projects as "restoration" or "reconstruction," dramatically broadening the definition of restoration with no evidence that historic ecological conditions can actually be restored, 119 but while a constructed channel may occupy the same map coordinates as a previously filled stream, virtually every aspect of this new channel and its watershed will be dramatically altered by surface mining operations. In particular, hydrologic connections between the watershed and its stream will be profoundly disrupted. As a result, built channels may not receive, contain, or exchange surface waters for any substantial period of time, and what water makes it to the channel will likely carry with it high sediment loads and substantially increased solute concentrations. Even well-constructed channels are thus highly unlikely to provide habitat that mimics or matches unmined streams in the region.

Between 2002 and 2005, we developed the first comprehensive database on stream and river restoration for the United States. 120,121 From our extensive work with scientists and restoration practitioners, 122 we do not know of a single case (of 38,000 projects in our database) in which stream creation, as proposed by many MTVF compensatory mitigation plans outlined, has been shown to recreate stream hydrology, much less to support the ecological functions lost when streams are filled. Contrary to suggestions made in many mitigation plans, the very concept of creating streams with levels of ecological functioning comparable to natural channels on sites that have been mined through remains untested. 123 No peer-reviewed scientific studies document a case where the critical features of stream ecosystems (flow, biota, and nutrient and material processing) have been created in a surface-mined landscape. Even with far less damage to their watershed, stream restoration projects that involve channel modification have a low probability of promoting recovery of geomorphic processes or biological communities. 124-126

Structure and function are not equivalent

Most mine permit compensatory mitigation plans that include stream enhancement or restoration are based on the Natural Channel Design (NCD) approach, ¹²⁷ but the NCD approach to stream restoration is not an ecological restoration approach and it has never been shown to promote ecological

recovery. In fact, results from recent studies point in the opposite direction. 126 Evidence to date suggests that extensive channel engineering, which is typical of the NCD approach, may in fact cause damage to streams in need of restoration; for example, species diversity may actually decrease following restoration and may decrease over time. 128 The NCD approach is fundamentally focused on channel form (structure), not ecological function. This approach was designed by David Rosgen¹²⁷ to address channel stability based only on building a channel structure (shape, slope, etc.) that is able to transport the sediment and water inputs that are expected to be delivered to the stream. There is no scientific evidence supporting the assumption that restoration of channel form will lead to full restoration of function. 111,129,130 How a stream looks (its form) is simply not the same as how it processes materials and supports life (its function).

Most MTVF stream mitigation plans assume that selection of a channel type from a channel classification scheme such as the NCD approach will necessarily result in full ecological restoration, but they also assume that use of the NCD approach guarantees successful creation of a channel from a geomorphic and hydrologic perspective. However, channel designs based on a classification system that has not been fully evaluated at the site can lead to serious failures, 125,131 because the specific processes and history of the river under study were not adequately understood. If mitigation projects fail and channels are unstable, this could cause new environmental degradation. Even if created channels are geomorphically stable, this cannot be taken as evidence that ecological functions have been restored. Indeed, the NCD scheme of classification does not deal with ecological functions at all.

While use of the NCD scheme for stream restoration has been very common in the past, current science has documented numerous reasons that use of this scheme for restoration can be extremely problematic. 125,131–138 The NCD method in no way takes into account a whole array of biophysical factors that determine the ability of the channel to support all of the living resources in pristine streams in the area. Such factors include the intensity and duration of sunlight reaching the stream, which is determined in part by the vegetative structure; inputs of organic matter upon which the food web depends; and on nitrogen and carbon levels in the soil and streambed.

In fact, an analysis of > 75 channel reconfiguration projects overwhelmingly showed that these projects failed to restore or even markedly change stream biodiversity. ¹²⁸ The fundamental problem with classification-based restoration approaches is that they assume fixed end points and rigid classification schemes in which the type of stream desired can be achieved by constructing a specific channel form.

Existing mitigation approaches fail to include any mechanisms that will reduce the export of SO_4^{2-} , HCO₃⁻, Ca²⁺, Mg²⁺, Fe, and trace metals from mined sites, or that will remediate these impacts for the water columns of constructed channels. Regardless of the structural similarity between constructed channels and reference sites, if the water flowing through these mitigated channels comes into contact with overburden, it will contain the characteristic signature of alkaline mine drainage. Thus, the capacity for even a channel that is structurally and hydrologically similar to reference streams to support a diverse aquatic fauna and an ecosystem functional capacity similar to those lost when unmined streams are buried will be limited due to the severe water quality degradation associated with water flowing through mined landscapes. The mitigation projects associated with MTVF are not designed to actually mitigate for the water quality impacts generated, and these long-term, long-distance impacts represent unmitigated stressors to the stream reaches below valley fills and to the full river network extending downstream.

Importance of ephemeral and intermittent streams

Often, mitigation plans propose to mitigate for the burial of ephemeral or intermittent headwater streams through the restoration or creation of perennial streams. While it may be tempting to view intermittent streams as harsh environments because they are dry during parts of the year, diverse assemblages are adapted to such conditions and may recover from flood and drought disturbances more quickly than biota only found in perennial reaches. Headwater streams contribute to the aquatic ecosystem in important ways that make them different from perennial streams. Intermittent and ephemeral streams have unique characteristics that distinguish them from perennial streams. The most obvious difference is

hydrological—surface water is only present part of the year, and this attribute leads to the support of unique species and characteristic communities of organisms that would not exist if flow were perennial. In particular, intermittent and some ephemeral streams provide unique habitat for a diverse population of insects and other animals, from macroinvertebrates to salamanders. ¹⁴² Because intermittent and ephemeral streams have a seasonal mosaic of habitat types, they typically support fauna that may be poor competitors with the taxa found in perennial reaches. ¹⁴³

The interaction of groundwater and surface water that takes place in the uppermost stream segments within river networks helps regulate downstream water quality, affecting both aquatic life and water quality below. Intermittent and ephemeral streams are critical to biogeochemical processes that have watershed-scale impacts, and streams that go through wet and dry cycles may support high rates of denitrification. 144 Furthermore, intermittent and ephemeral streams supply water and sediments that are important to downstream perennial reaches. 143 Finally, these smallest of streams act as a link between terrestrial ecosystems and perennial reaches, and when they are rewet following dry periods, the inundation of dry organic matter (especially in forested region) may release large amounts of dissolved organic matter to fuel downstream ecosystems. 143

Altered energetics in constructed channels

The energetic basis of the stream food web of mountainous Appalachian streams is leaf litter from the surrounding trees. 30,145 For most of the year, bacteria, fungi, and aquatic insects consume the leaves and wood that fall or are washed into the stream from the surrounding forest. 146 There may be brief periods of the year (between snowmelt and leaf out and between autumn litterfall and first snow) when aquatic plants (algae) are important food resources. Constructed channels on or below valley fills are in high-light environments with early vegetation consisting primarily of short-stature grasses. Thus, while the forested streams in the region are typically fueled by leaf litter from the surrounding forest, created streams will likely be fueled by algal production.¹⁴⁷ Without a forest canopy, water temperatures in the constructed channels will be significantly hotter in summer and significantly colder in winter than in the forested streams.

Furthermore, there is no evidence provided that diversion of water flow to ditches or low-lying points creates a stream. Subsurface and surface flow paths to natural streams may be complex, and the residence time of the water in the groundwater varies before it reaches streams. 148-150 Without a thorough scientific study including hydrological analysis of groundwater, surface water, and hyporheic interactions (rates of flow and flow paths), there is no evidence that the water resources left after the mining and mitigation will compensate for what was lost. Yet there is abundant scientific evidence that these hydrologic interactions determine ecosystem functions including rates of whole stream metabolism, nutrient processing, organic matter decomposition, productivity, and reproduction of invertebrates and fish. 151-153 Successful restoration requires that key processes and linkages beyond the channel reach (upstream/downstream connectivity, hillslope, floodplain, and hyporheic/groundwater connectivity) also be considered. 154-159 The importance of these linkages is without question; water, sediment, organic matter, nutrients, and chemicals move from uplands, through tributaries, and across floodplains at rates and concentrations that downstream organisms have evolved to depend upon.

Conclusions

In summary, the environmental impacts of MTVFs in the Central Appalachians are severe, large scale, and long lasting. In addition to the permanent burial and loss of headwater streams directly impacted by mining, many additional river miles are being degraded by the cumulative impacts of altered flows and increased pollutant from both past and present mining activities in the region. Whether or not individual component ions within mining-derived runoff reach streamwater concentrations that are individually lethal or toxic to aquatic life, the cumulative effect of elevated concentrations of multiple contaminants is clearly associated with a substantial reduction in water quality and biological integrity in streams and rivers below mine sites. All research to date indicates that conductivity is a robust measure of the cumulative or additive impacts of the elevated concentrations of multiple chemical stressors from mine sites that lead to biological impairment of streams. Each constituent pollutant increases conductivity and they may have additive or multiplicative ecological impacts. To date, mitigation practices and restoration efforts have not been effective in ameliorating water pollution from MTVF sites. Furthermore, efforts to reclaim vegetation and restore the full diversity of plant species in mined watersheds have not proved successful to date.

Conflicts of interest

The authors declare no conflicts of interest.

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