# Synthesis of Watershed Characterization for Making Remediation Decisions

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## ABSTRACT

The Abandoned Mine Lands Initiative combines expertise from each division of the U.S. Geological Survey. The watershed orientation of the initiative leads to a synthesis of information from many areas of study. Geologic and geochemical studies contribute information about mineral deposits, their role in premining conditions, and their potential for contributing metals to mine drainage. Hydrologic and geochemical studies indicate the transport and transformation of metals from the sources to the streams. Biological studies show the effects of metals on the aquatic organisms and habitats, and help to establish goals for improving the habitats. All of these studies are unified by the application of geographic information systems and information management methods to enable a synthesis for regulatory and land management agencies.

## INTRODUCTION

Accomplishing the objectives of the Abandoned Mine Lands (AML) Initiative requires the synthesis of information from many disciplines. I want to start out with the "water" view. Often, the water approach to watershed studies often has revolved around data collection at the outlet to the watershed (fig. 1a). This view of the watershed serves several important purposes. It provides the integration of solute sources and watershed processes--it provides the results of the watershed "machine." Decisions about remediation, however, require detailed information about specific sources of mine drainage within the watershed, their relative significance, and their effects on the stream ecosystem. The view of the watershed from the outlet does not provide such source- and process-based information, even if the information from the outlet is combined with many individual samples at mine-drainage sources.

Influences of acid mine drainage occur on different scales. An individual mine might affect a single hillside, a small tributary, or the entire watershed downstream. Each site may contribute to the metal load of a watershed. Because of the legal requirements for waste discharge permits, there commonly is documentation of the location and chemistry of drainage from individual mining activities in a watershed. However, this leaves us without a context for understanding how individual sources interact and contribute to metal loads on a watershed scale.

Upland watersheds in mining districts generally contain many areas disturbed by mining activity, not just one site (fig. 1b). Estimates of the number of mines in the Rocky Mountains on public and private land are in the tens of thousands. Remediation currently must proceed on a site-by-site basis. The expense of this remediation would be more than private landowners or the public could bear. Remediation on this scale needs a comprehensive approach; an approach at the watershed scale. If water-quality standards can be achieved for the watershed by remediation of a select, limited number of sites, there could be great savings of money, and limited resources could do the most good. If we have to make expensive choices, then we want to choose those sites that will produce the greatest results for cleaning up the water. This is the approach of the AML Initiative.

So how do we identify those principal sources in a watershed? If we can identify a source as being a major contributor, what do we need to know about that source? How do each of the principal sources affect the stream ecosystem? These are not just hydrologic questions, but they are questions that require the combined efforts all the divisions of the U.S. Geological Survey (USGS). The answers require more than the "water" view.

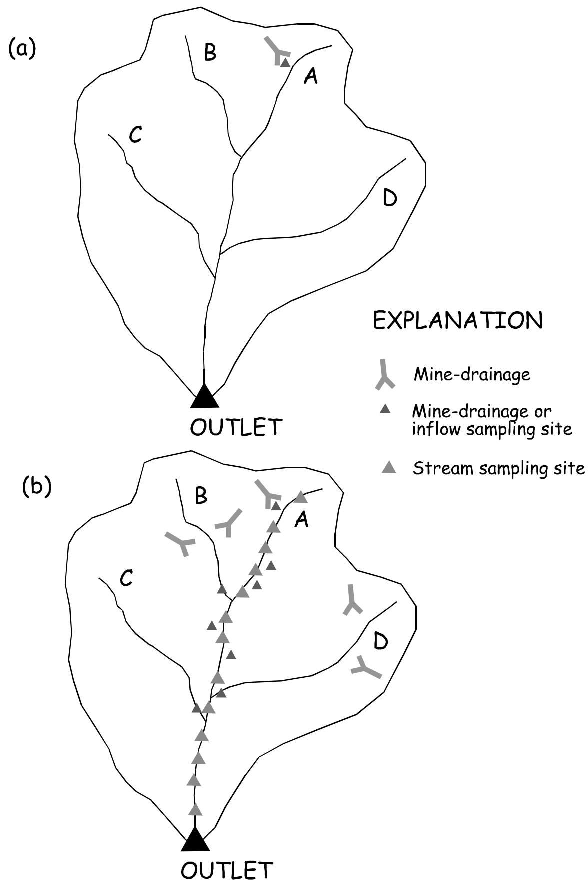


**Figure 1.** (a) Schematic watershed views showing (a) data collection at the watershed outlet verses (b) the detail of information needed for remediation decisions.

## SYNTHESIS FOR THE WATERSHED APPROACH

The depth of the many scientific disciplines within the USGS provides the expertise for a comprehensive understanding of metals from mining (Buxton and others, 1997). The watershed concept brings all the disciplines together to understand premining levels, sources, transport and transformations, and biological effects of metals. When all of this information is synthesized, land management agencies will have a better scientific basis for making decisions and choosing sites for remediation.

### Metal Sources and Premining Conditions

Not all mineral deposits were created equally. Differences in mineralogy give rise to different potential contributions of acid water and metals to streams. A classification of mineral deposits and their potential contributions has provided the basis of maps that are helpful for selecting watersheds to be studied in the AML Initiative. Remediation currently must proceed on a site-by-site basis.

The delivery of acid and metals from a source to a stream greatly depends on the geologic structure around the mineral deposit and the catchment hydrology. Mineral deposits that are associated with faults and fractures may have a direct route to a stream through ground-water inflows. Deposits that are more or less sealed from the stream may contribute to streams only through surface drainage from an adit. The amount of surface drainage that enters the ground and then affects the stream by diffuse seepage is also a geologic and hydrologic question. The geologic structure of a site might make remediation very difficult or might actually contribute to successful remediation.

The nature of premining conditions is always an important consideration for mine-drainage issues. Did mining cause current conditions, or were these conditions present naturally before mining occurred? In mineralized belts, the potential for natural acidic, metal-rich drainage is great. Establishing estimates of likely premining conditions can help establish reasonable remediation goals.

The question of premining conditions is being approached through several disciplines.

The geomorphology of a stream reveals much about past sedimentation and changes that could have occurred with the onset of mining. Isotope geochemistry of sediment cores reveals changing sources of lead and the chronology of sedimentation. Aqueous isotope geochemistry also may hold keys to distinguishing sulfate contributed by mining from natural weathering of sulfide minerals. Another promising avenue to past environmental conditions may be through paleobotany. Studying pollen, plants, and insects from cores may reveal the health of past habitats.

## Transport and Transformation of Metals

A watershed is more than a pipe transporting solutes downstream (Bencala and others, 1993). Streamflow in a mountain watershed generally is down a steep gradient and through pools and riffles in cobble-bottomed streams. These physical conditions lead to a continuous interaction of the stream with the hyporheic zone—formally defined as that part of the alluvium that contains at least 10 percent stream water (fig. 2). This hydrologic condition complicates the measurement of loads for planning remediation because actual loads of metals include both surface and hyporheic flow. When flow from a tributary enters the stream, the additional load is more than any visible tributary flow entering the stream. The actual effect of any given metal source, for example, from an adit drainage far from the stream, is tied to the total load that enters the stream, not the total load that leaves the source.

The geochemical consequences of the hyporheic zone are important to the transformation of solutes (Harvey and Fuller, 1998). Hyporheic conditions can cause extensive interaction with minerals, bacteria, and even reducing conditions. These interactions may improve water-quality conditions by removing solutes or changing the dominant chemical species of a toxic metal. The opposite could also occur; the interactions may create conditions that are more toxic. Because both outcomes are possible, it is very important to understand what is occurring in the stream. The full understanding comes from synthesis of hydrologic, geochemical, and biologic information.

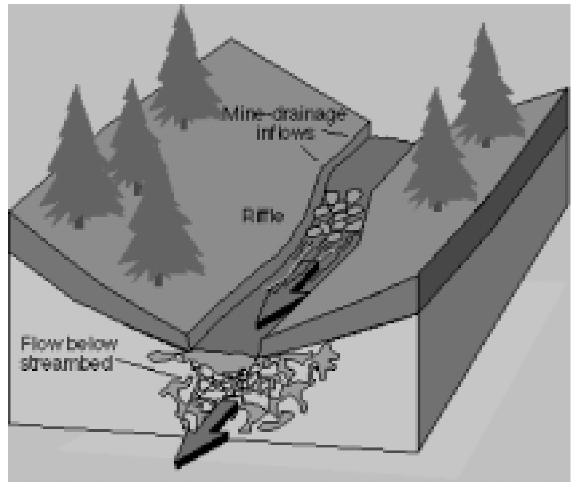


**Figure 2.** Schematic pattern of streamflow in upland watersheds. Much of the flow occurs below the streambed in the hyporheic zone.

Many transformations of metals occur in the water column during transport. These transformations are visually evident in streams affected by mine drainage because of the distinctive zones of color on the streambed. Mixing of metal-rich, acidic water from mine drainage with higher-pH water results in the rapid formation of iron and aluminum colloids in the water column. These submicron solids quickly aggregate and provide extensive surface area for the sorption of copper, lead, zinc, and other metals (Kimball and others, 1995). As the aggregated colloids are transported downstream they become trapped by algae growing on streambed cobbles and settle out of the stream in pooled areas. As this occurs, mine drainage gets its characteristic ochre color. Seasonal removal of the cobble coatings by snowmelt runoff also can release high metal concentrations at a critical time of year (Church and others, 1997).

## Biological Implications of Transformations

Transformations of metals transported in streams and hyporheic zones of streams can influence both the severity and mechanisms (fig. 3). Acute toxicity of metals, or effects that occur as a result of relatively short-term exposure, is typically related to the concentration of the dissolved species of a metal. Acute toxicity in a stream may occur as a result of an episodic event such as a spill of mining wastes or increased concentrations during high flow. Acutely toxic conditions, if frequent or persistent, can eliminate virtually all macroscopic life in severely contaminated streams. However, sensitivity to metals differs widely among different species of aquatic organisms, so episodic acute toxicity events may eliminate only the most sensitive species of algae, invertebrates, and fish, leaving a community consisting of relatively tolerant species. In contrast to the rapid loss of species typical of acute toxicity, chronic or long-term metal toxicity can lead to a community that contains fewer individuals, which grow more slowly, and may fail to reproduce. Such communities may be sustained only by constant immigration of organisms from less contaminated locations. Chronic toxicity results from long-term exposure to lower concentrations of metals, including exposure via diet as well as from water.

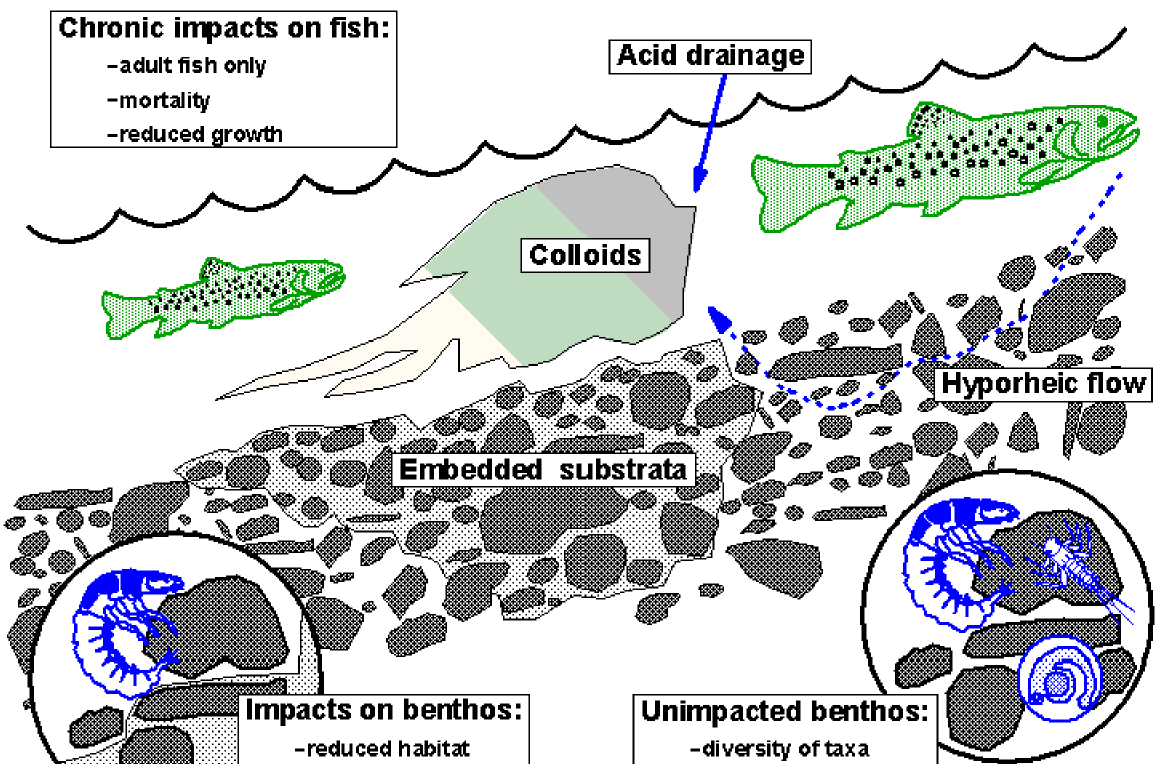


**Figure 3.** Schematic diagram showing relation of colloids to aquatic health and habitat.of adverse effects on stream ecosystems

The sorption of toxic metals to colloidal iron and aluminum reduces the threat of acute metal toxicity but does not make these metals completely unavailable to stream biota. When colloids become incorporated into the streambed coatings (known as periphyton or biofilm), which are the primary habitat for stream algae, they can be ingested and accumulated into the tissues of benthic invertebrates that graze on the algae. Metals associated with these grazers can become available to fish such as trout, which rely on benthic invertebrates for much of their diet in mountain streams. When grazers (or the larger invertebrates that prey on them) are eaten by fish, metals in colloids and in invertebrate tissues can dissolve in the acidic digestive tract of the fish. Mayer and others (1996) and Chen and Mayer (1998) have shown this to be a mechanism of metal delivery to fish. Metals absorbed via the gut can accumulate in internal organs such as the liver and kidney, which are the primary sites of chronic metal toxicity.

The incorporation of aggregated iron- and aluminum-rich colloids into stream gravels can adversely affect stream biota both by toxicity and by degrading benthic habitats. Aggregated colloids can also fill (embed) pore spaces in stream gravels, reducing or eliminating habitat that is inhabited by benthic invertebrates and is required by stream fish as spawning habitat. Accumulation of metal-rich colloids in stream sediments may result in metal concentrations in sediment pore water or in hyporheic flow that are greater than those in stream water. These elevated metal concentrations may be toxic to benthic invertebrates or to newly hatched trout. All of these processes can adversely affect fish populations by reducing survival, food availability (i.e. growth), and reproduction.

## SYNTHESIS FOR WATERSHED DECISIONS

The experience of the AML Initiative shows that significant spatial detail is necessary to make meaningful decisions about sources of mine drainage, transport and transformation of metals, and effects on aquatic organisms. Integration of the watershed by data collected at the outlet does not provide the detail needed. Integration of data from small sections of the watershed, however, carries the integration concept to the appropriate scale. This can be accomplished with tracer-injection studies and synoptic sampling of streams and inflows (Kimball, 1997).

Focusing on spatial detail in the watershed leads to a synthesis of geologic, geochemical, hydrologic, and biological information. The synthesis is aided by making the data available to GIS presentation and investigation. Often, exploring the data in their spatial context makes relations clear and solutions apparent. Another meaningful tool to evaluate the instream effects of alternate remediation choices is through solute-transport simulation. Simulations incorporate the best understanding of sources to the stream and instream processes and evaluate the extent to which remediation options can decrease concentrations of metals and colloids in streams.

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