Potential for Successful Ecological Remediation, Restoration, and Monitoring

By Susan E. Finger, Stanley E. Church, and Paul von Guerard

Chapter F of

Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

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Abstract

Historical mining has adversely affected the water, sediment, and biological resources in the Animas River watershed study area. Remediation has been ongoing in the watershed since the early 1990s, and monitoring information suggests an improvement in water quality at several sites. Because a substantial amount of the metal load to the watershed is derived from weathering of rock that has not been disturbed by mining, recovery of the ecosystem to premining conditions is not feasible. The recovery goal is, therefore, to improve the overall health of the aquatic ecosystem and the surrounding landscape and reestablish a viable trout fishery. More than half the high priority sites identified by the U.S. Geological Survey have been remediated. Remediation has also occurred at 23 sites identified by the Animas River Stakeholders Group. Sources of dissolved copper, which represents a major ecological risk to trout in the river, have been reduced in areas such as Mineral Creek. Some recovery of the aquatic community is occurring at specific sites. However, copper and several other constituents remain near 1994 to 1996 baseline concentrations at the A72 gauging station on the Animas River, which best reflects the effects of upstream remediation. Additional activities such as rehabilitation and restoration might be appropriate to enhance the ecological recovery.

Introduction

Historical mining has resulted in contamination of land, water, and biological resources in many parts of the Animas River watershed study area. Other chapters in this volume have characterized the extent and severity of this contamination (Nash and Fey, Chapter E6; Mast and others, Chapter E7; Kimball and others, Chapter E9; Wright, Simon, and others, Chapter E10; Leib and others, Chapter E11; Church, Fey, and Unruh, Chapter E12; Besser and Brumbaugh, Chapter E18; Anderson, Chapter E20). In general, historical mining and associated activities in the Animas River watershed study area have substantially degraded the water quality and adversely altered the aquatic habitat, resulting in severely impaired biological communities in a major portion of this complex area. In addition, weathering of sulfide minerals in mines and in deposits of mine wastes has increased acid drainage (Nash and Fey, this volume; Mast and others, this volume). A substantial volume of mill tailings was also released into the surface streams and has physically and chemically altered the substrate, resulting in a loss of productive aquatic and riparian habitat. Historically, the only native fish species known to occur in the Animas River watershed study area was the Colorado River cutthroat trout (*Oncorhynchus clarkii pleuriticus*), although one account suggested that the mottled sculpin (*Cottus bairdi*), a species that occurs commonly in downstream reaches, may have occurred in portions of the watershed study area. An early account of the area by ichthyologist David Starr Jordan (1891) referred to deep pools full of trout in the Animas River canyon. At present, mining activities have degraded stream conditions (Bove and others, this volume, Chapter E3), and little to no aquatic life occurs in the upper Animas River, the entire length of Cement and Mineral Creeks, and several smaller tributaries. South Fork Mineral Creek and several tributaries of the upper Animas River, which drain basins that provide substantial acid-neutralizing capacity, support populations of brook trout and a even few cutthroat trout. The Animas River between Maggie Gulch and Cement Creek in Silverton supports brook trout and a substantial invertebrate community, suggesting that water and habitat quality in this reach is improving. The Animas River watershed study area is a highly complex system whose complexity is increased by more than 5,300 inactive mine, mill, and prospect sites (Church, Mast, and others, this volume, Chapter E5). Planning for the ecological recovery of this system requires an understanding of premining baseline conditions as well as the hydrological processes, the geological and geochemical characteristics, and the biological limitations of this watershed. Although the scope of the scientific investigations contained in this volume will not be feasible for all basins containing mining-affected sites, the many parameters measured in these studies can be used to develop models that will guide the outcome of remedial and restoration activities in other watersheds.

Remediation, reclamation, rehabilitation, and restoration are all terms referring to activities that attempt to alter and improve the biological and physical conditions at a degraded site. These terms are closely linked, but they refer to distinct phases in the process of ecological recovery. Because of the high cost associated with reparation of ecologically impaired areas, an understanding of these processes and how they may complement each other is critical to success. Practiced independently, these activities will lead to different endpoints in ecological succession, and it is thus important to clearly delineate goals and objectives for watershed recovery during the initial project planning process.

Remediation is the cleanup of a contaminated area. Remedial actions remove or isolate contaminants from the environment. These actions are critical to promoting the recovery of both the terrestrial and aquatic ecosystems. Remediation at mine sites can involve the in-place treatment or physical removal of mine waste and mill tailings from a stream, its associated flood plain, and the surrounding landscape. Remediation can also involve the reduction or elimination of metal and acid loading from draining mines. The actual cleanup activities can result in ecological injury and should be addressed early in the planning process, because some remedial actions may preclude successful ecological restoration. Successful remedial actions result from risk-management decisions based on cost-benefit analysis that evaluates the potential outcome of several alternatives. These alternatives range from a simple "no action" alternative to a much more costly and complicated one such as complete removal of contaminated material. Performance measures for successful remediation might include:

- Major sources of contamination in the watershed have been reduced or eliminated
- Trace-element concentrations in water no longer exceed acute or chronic criteria for aquatic life
- Trace-element concentrations in streambed sediment no longer exceed sediment-quality guidelines
- Stream banks have been stabilized and erosion has been minimized, or
- Flood-plain revegetation has reduced or eliminated the transport of contaminated sediment, mine waste, or mill tailings downstream.

Reclamation is a term commonly used in association with mined lands. The main objective of reclamation is the stabilization of terrain, improvement in landscape appearance and esthetics, and the return of land to what might regionally be defined as a useful purpose. Revegetation is usually a component of reclamation, but revegetation commonly includes establishing only a few species for the main purpose of site stabilization to reduce erosion and runoff, rather than restoring ecological value.

Rehabilitation is most similar to restoration in that rehabilitation planning uses preexisting ecological conditions as models or references. Rehabilitation seeks to recreate ecosystem processes, productivity, or services, but does not emphasize the establishment of preexisting species composition and diversity. Specifically, rehabilitation does not attempt to return the landscape to its prior baseline state or, in this case, does not attempt to reestablish premining ecosystems. As is true of the Animas River watershed study area, restoration may be impossible in many mining-affected areas of the West, because of anthropogenic and natural factors that may limit ecological recovery. However, if remediation, reclamation, and rehabilitation are ecologically based, they will lead to more timely and ecologically functional restoration.

Restoration is the process of returning an ecosystem to a close approximation of its historical or premining condition prior to physical or chemical disturbance (National Research Council, 1992). Therefore, premining conditions are the ideal starting point. Although an injured ecosystem may never return to conditions identical to those in the past, it can recover to conditions that are functionally equivalent to those of the previous environment. The underlying goal of restoration is ecological recovery. This goal must be realistic given the geologic, hydrologic, and biologic characteristics of the ecosystem. Therefore, in an area affected by historical mining, an understanding of premining conditions in the watershed is required. In the Animas River watershed study area, weathering and release of metals from hydrothermally altered, unmined areas (Bove and others, this volume) limited the biological community in some areas. Such complexity caused by geology and hydrology must be understood in any restoration effort. Although successful remediation actions, such as physical removal of mine waste and mill tailings or reduction in acidic mine drainage, may be part of the restoration process, these remedial steps do not necessarily ensure that ecological recovery will occur. Restoration may require such actions as creation of viable fisheries habitat, restocking a stream with fish, reintroduction of aquatic invertebrates and terrestrial species, or revegetation of the flood plain to compensate for ecological losses. Performance measures for successful restoration might include:

- Self-sustaining populations of fish occur throughout the watershed
- Colonies of nesting birds are successfully reproducing, or
- A healthy riparian corridor is present.

Both restoration and rehabilitation can produce a system with a high degree of ecological integrity.

Monitoring is a critically important but an often undervalued and underutilized tool for determining the success of remedial measures and evaluation of ecological recovery. Adequate and appropriate monitoring procedures are the most direct measure of the success of remedial strategies and the resulting rates of recovery for populations, communities, or ecosystems. However, monitoring rarely receives the attention and funding necessary for development and implementation of a successful restoration plan. Kondolf and Micheli (1995) indicate that despite increased commitment to stream restoration, post-restoration monitoring has generally been neglected. Monitoring plans need not be exhaustive or complex. However, they must be designed to address specific objectives and applied over the entirety of the project in a consistent manner. They will not only offer a measure of success for the project, but they will also provide information useful in predicting restoration outcomes at other sites.

Purpose and Scope

In this chapter, we describe the factors that influence successful ecological restoration and recovery of the aquatic community in the Animas River watershed study area. Successful restoration is a result of both the removal of the residual levels of contamination and the establishment of physical or chemical conditions that will support desired or realistic biological communities. Although the desire of land-management agencies may be for ecological recovery to a preexisting baseline or premining condition, this may not be economically attainable or feasible. Remediation or removal of the contaminated materials and reduction of the amount of contamination in the stream may result in a measurable improvement of water quality. However, the biological community may need additional changes before it can respond. Numerous factors must be considered before the restoration alternative with the highest probability of success can be identified. The success of any restoration effort can be best documented through a well-designed monitoring program that collects physical, chemical, and biological information to provide a comparison with conditions prior to cleanup activities. Necessary monitoring activities are recommended to chart the progress of aquatic recovery following remediation and restoration efforts.

Remediation Activities in the Animas River Watershed Study Area

More than 30 years ago, the Colorado Division of Wildlife attempted to replenish the fisheries in the Animas River by stocking rainbow trout, brook trout, and brown trout in the watershed. Observational data suggest that neither rainbow nor brown trout were able to reproduce upstream from the Animas River canyon reach, but brook trout, which are more tolerant of low pH and toxic metal exposure than the other species, have persisted. Brook trout is the predominant fish species in the Animas River watershed study area, despite no documented stocking of this species since 1985. By the early 1990s, interest in reducing the environmental effects of the many inactive mines and prospects in the Animas River watershed study area began. In 1991–1992, a preliminary water-quality sampling of the major streams in the Animas River watershed study area was coordinated by the Colorado Department of Health and Environment. The Colorado Division of Mines and Geology, the USDA Forest Service, and the Bureau of Land Management (BLM) inventoried and ranked inactive mines in the study area (Wright, Simon, and others, this volume).

The Animas River Stakeholders Group (ARSG) and Federal land-management agencies began planning for cleanup activities in the mid-1990s. Sunnyside Gold, Inc., implemented a number of remediation activities in the watershed study area as a condition for terminating its discharge permit at the American tunnel (site # 96, fig. 1). Sunnyside Gold, Inc., has completed numerous remediation projects, including removal of tailings deposits in the upper Animas River between Eureka and Howardsville, removal of mine dumps at the Longfellow mine (site # 77) and Koehler tunnel (site # 75), construction of hydrologic controls to prevent surface runoff from flowing overland through dump and tailings piles, and the plugging of the numerous portals and adits (fig. 1; table 1). Most of this remediation work on Sunnyside properties was completed by 1996. Remediation activities by BLM include mine drainage collection and diversion at Joe and Johns mine (site # 87), acid-mine drainage collection and hydrologic controls at the Lark mine (site # 86), acid-mine drainage collection and passive wetland treatment at the Forest Queen mine (site # 195), hydrologic controls and capping of the mine dump at the May Day mine (site # 181), acid-mine drainage collection and removal of waste rock at the Bonner mine (site # 172), and the removal of tailings from the Animas River flood plain at the Lackawanna Mill site (site # 287). Other remediation work has been done by the San Juan Resource and Conservation District, Silver Wing Mining Company, Gold King mine, Office of Surface Mining, Salem Minerals, and Mining Remedial Recovery (William Simon, Animas River Stakeholders Group, written commun., 2005; Robert H. Robinson, Bureau of Land Management, written commun., 2005).

Remediation work that has been completed in the Animas River watershed study area through 2004 is summarized in figure 1 and table 1. Of the more than 5,300 mine, mill, and prospect sites, information in this volume suggests that about 80 sites are responsible for 90 percent of the metal loads to surface water. Of the 39 priority sites identified by Nash and Fey (this volume), 9 (23 percent) have been remediated. Of the 61 high-priority sites identified by the ARSG, 14 (23 percent) have been remediated. The ARSG is actively working with Federal, State, and local funding sources to remediate these sites and reduce the metal loading in surface water in the watershed study area.

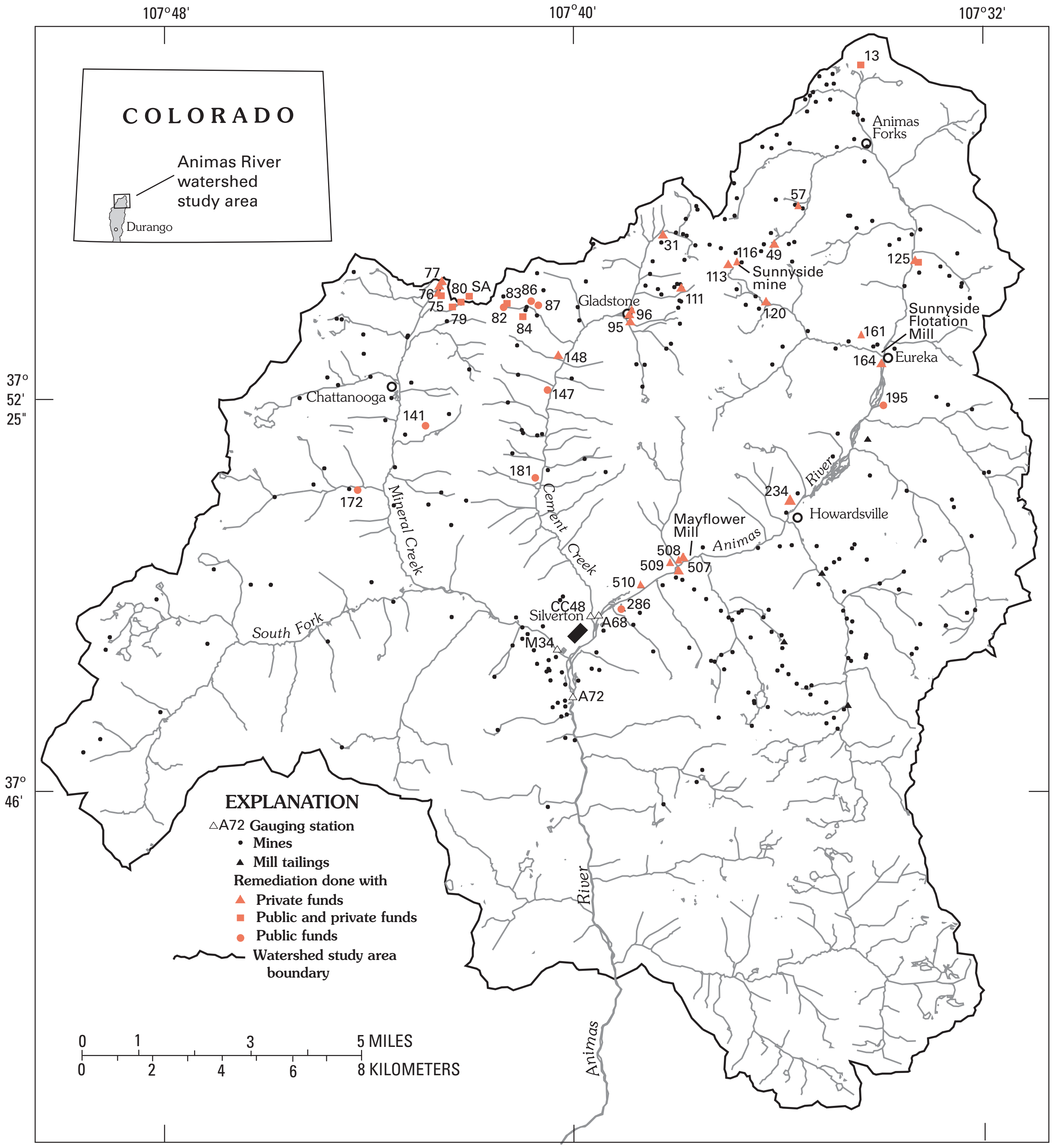

Figure 1. Locations of sites remediated in the Animas River watershed study area through October 2004 (data from table 1, William Simon, ARSG, written commun., 2004). Sites designated by sources of funding for remediation work (private, public, or both). Numbers are AMLI_MINE_ID site numbers in the Animas River watershed database (Church, Mast, and others, this volume, Chapter E5; Sole and others, this volume, Chapter G). SA, San Antonio mine (table 1).

Table 1. Summary of remediation projects completed, Animas River watershed study area, 2004.

[San Juan R. C. & D., San Juan County Resource and Conservation District; ARSG, Animas River Stakeholders Group; U.S. OSM, U.S. Department of the Interior, Office of Surface Mining; U.S. BLM, U.S. Department of the Interior, Bureau of Land Management; U.S. FS, U.S. Department of Agriculture (USDA) Forest Service; mine site locations from Church, Mast, and others, this volume; mill site locations from Jones, this volume, Chapter C; yd^3, cubic yards of material; data provided by William Simon, Animas River Stakeholders Group, written commun., 2004, and by Robert H. Robinson, BLM, written commun., 2005. Site numbers are AML_MINE_ID numbers in the Animas River watershed database]

Project sponsor	Project site	Location (fig. 1)	Type of remediation	Date project completed	Improvement (actual or anticipated)
			Private funds		
Sunnyside Gold, Inc.	Lead Carbonate Mill.	Gladstone, South Fork Cement Creek, site # 95.	Removal of 27,000 yd^3 of mill tailings from stream bank.	1991	Reduce loading of metals to Cement Creek and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Mayflower Mill	Mayflower Mill tailings, sites # 507–509.	Re-contour inactive mill tailings ponds and cap; 625,000 yd^3 of mill tailings and overburden moved.	1992	Mined land remediation—reduce loading of metals to Animas River and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Lake Emma Sunnyside Basin	Sunnyside mine collapse, site # 116.	Fill mine subsidence at Lake Emma, remove 240,000 yd^3 mine waste and re-contour.	1993	Mined land remediation and reduce loading of metals to Animas River.
Sunnyside Gold, Inc.	American tunnel waste dump.	Gladstone, on bank of South Fork Cement Creek, site # 96.	Remove 90,000 yd^3 waste dump and underlying historical mill tailings.	1995	Mined land remediation and reduce loading of metals to Cement Creek and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Sunnyside Eureka Mill, tailings at town site.	On banks and in flood plain of Animas River, downstream of site # 164.	Remove 112,000 yd^3 of mill tailings	1996	Reduce loading of metals to Animas River and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Sunnyside mine hydraulic seal project.	Sunnyside mine, sites # 116, # 120, # 96.	Bulkheads placed in Sunnyside mine to restore hydrologic regime to approximate premining hydrology and eliminate drainage from adits.	1997	Place mine workings under water to reduce oxidation, restore groundwater movement around mine workings and eliminate need for perpetual water treatment.
Sunnyside Gold, Inc.	American tunnel	American tunnel at Gladstone, site # 96.	Divert and treat Cement Creek, fill Sunnyside mine pool to mitigate any short-term impacts of remediation projects.	8/1996 to 12/1999	Reduce loading to Animas River to offset any short-term impacts of remediation of other sites.
Sunnyside Gold, Inc.	Mayflower Mill tailings, Boulder Creek.	Mill tailings at site # 509, flood plain of Boulder Creek.	Remove 5,700 yd^3 of mill tailings	1997	Reduce loading of metals to Animas River and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Ransom mine adit.	Eureka town site, site # 161.	Bulkhead seal to stop deep mine drainage and remediate portal.	1997	Restore hydrologic regime and reduce rate of ore oxidation by placing mine workings under water to reduce metal loading to Animas River.
Sunnyside Gold, Inc.	Gold Prince mine waste and mill tailings.	Placer Gulch, site # 49.	Bulkhead seals to stop deep mine drainage, consolidate mine waste and mill tailings, removed 6,000 yd^3 mine waste and construct upland diversions.	1997	Reduce exposure to water to reduce metal loading to Animas River.
Sunnyside Gold, Inc.	Longfellow-Koehler	Headwaters of Mineral Creek, Longfellow mine, site # 77; Junction mine, site # 76; Koehler tunnel, site # 75.	Remove Koehler mine-waste dump (32,100 yd^3), consolidate Junction mine dump and Longfellow mine dump and cap, capture adit drainage, construct diversions, conduct feasibility study of wetland treatment of Koehler tunnel acidic drainage.	1997	Reduce metal loading to Mineral Creek and erosion transport of mine waste.
Sunnyside Gold, Inc.	Pride of the West mill tailings.	Howardsville, site # 234.	Remove 84,000 yd^3 of mill tailings	1997	Reduce metal loading to Animas River and transport of mill tailings by erosion.
Sunnyside Gold, Inc.	Sunnyside mine	Sunnyside mine, American tunnel treatment, site # 96.	Inject 652 tons of hydrated lime into the Sunnyside mine pool to provide increased alkalinity and reduce oxygen available in mine for pyrite oxidation.	1997	Improve initial conditions as water table is restored by installing bulkhead to stop acidic mine drainage.

Table 1. Summary of remediation projects completed, Animas River watershed study area, 2004.—Continued

Project sponsor	Project site	Location (fig. 1)	Type of remediation	Date project completed	Improvement (actual or anticipated)
			Private funds—Continued		
Sunnyside Gold, Inc.	Mayflower Hydrological Control.	Mayflower Mill tailings pond #1, site # 507.	Capture and divert three upland drainages that provide supply to ground water upgradient of mill tailings.	1999	Minimize potential for contact of runoff with mill tailings and reduce potential for metal loading to Animas River.
Sunnyside Gold, Inc.	Mayflower mill tailings pond #4.	Mayflower Mill tailings pond #4 drainage modification, site # 510.	Install lined diversion ditch to capture surface runoff and prevent infiltration through mill tailings.	1999	Minimize potential for contact of runoff with mill tailings and reduce potential for metal loading to Animas River.
Sunnyside Gold, Inc.	Mayflower mill tailings pond #4.	Divert ground water upgradient from mill tailings pond #4, site # 510.	Capture ground water and divert around mill tailings impoundment, tailings pond #4.	1995, 1999	Minimize potential for contact of ground water with mill tailings and reduce potential for metal loading to Animas River.
Sunnyside Gold, Inc.	Power plant flats.	Animas River near old power plant, east of site # 509.	Removed mill tailings to tailings pond #4, site # 510.	2003	Reduce metal loading to Animas River.
Sunnyside Gold, Inc.	Mogul mine bulkhead.	Cement Creek, site # 31	Install bulkhead in Mogul mine to stop acidic drainage.	2003	Reduce metal loading to Cement Creek.
Sunnyside Gold, Inc.	Koehler tunnel bulkhead.	Koehler tunnel (site # 75)	Install bulkhead in Koehler tunnel to stop acidic drainage.	2003	Reduce metal loading to Mineral Creek.
Sunnyside Gold, Inc.	Reactive barrier	Animas River flood plain below Mayflower Mill, mill tailings pond #4 (site # 510).	Passive treatment of contaminated ground water before entering Animas River.	2003	Reduce metal loading to Animas River.
Gold King Mines, Inc.	Gold King mine	North Fork Cement Creek, site # 111.	Hydrologic controls for workings and mine waste.	1998	Reduce metal loading to North Fork Cement Creek.
Gold King Mines, Inc.	Gold King mine	North Fork Cement Creek, site # 111.	Pipe Gold King adit discharge to Gladstone for active treatment of acidic drainage.	2002	Reduce metal loading to Cement Creek.
Mining Remedial Recovery.	Sunbank group	Placer Gulch, site # 57	Anoxic drain, settling pond, waste consolidation, bulkhead.	1995	Raise pH from draining adit, reduce metal loading to Animas River from adits and mine waste.
Salem Minerals.	Mammoth tunnel	Cement Creek, site # 148	Settling ponds for mine drainage	1999	Reduce iron load to Cement Creek.
Silver Wing Mining Co.	Silver Wing mine	Animas River, site # 125	Collect acidic mine water, install hydrologic controls.	1995	Divert acidic drainage around mine-waste dump, reduce metals loading to Animas River.
			Private and public funds		
Silver Wing Mining Co.	Silver Wing mine	Animas River, site # 125	Install anoxic drain, settling pond, and bioreactor.	2000	Reduce metal loading to Animas River.
San Juan R. C. & D., ARSG.	Carbon Lake–Phase I.	Carbon Lake mine, Mineral Creek, site # 80.	Removal of 1,900 yd^3 of waste rock from stream channel.	Phase I–1999	Reduce loading of metals, especially cadmium, copper, iron, lead, manganese, and zinc, to Mineral Creek.
San Juan R. C. & D., ARSG.	Carbon Lake—Phase II.	Koehler tunnel, Mineral Creek, site # 75.	Reduce flows from Koehler tunnel by reducing infiltration into surface mine workings.	Phase II–2001	Reduce metals loading to Mineral Creek by reducing infiltration of water into old mine workings.
San Juan R. C. & D., ARSG.	Carbon Lake—Phase III.	Congress mine, Mineral Creek, site # 79.	Complete removal of Congress mine-waste dump.	Phase III–2003	Reduce metals loading to Mineral Creek by removal of mine wastes and beneficiation.
San Juan R. C. & D., ARSG.	Carbon Lake—Phase III.	Carbon Lake, site # 80, ditch reclamation.	Diversion ditch, wetlands, and stream reclamation, water rights purchased and water diverted to Uncompahgre River watershed restored to Mineral Creek drainage.	Phase III–2003	Reduce metals loading to Mineral Creek by removal of mine wastes and site beneficiation.
San Juan R. C. & D., ARSG.	Galena Queen and Hercules mines.	Prospect Gulch, sites # 82 and # 83.	Remove mine waste, install hydrologic controls, add soil amendments, and revegetation.	2001	Elimination of surface water leaching of toxic metals. Reduce metal loading to Cement Creek.

Table 1. Summary of remediation projects completed, Animas River watershed study area, 2004.—Continued

Project sponsor	Project site	Location (fig. 1)	Type of remediation	Date project completed	Improvement (actual or anticipated)
Private and public funds—Continued					
San Juan R. C. & D., ARSG.	San Antonio Project.	San Antonio mine	Install hydrologic controls, remove wastes from stream, consolidate wastes and neutralize, revegetation.	2004	Reduce metal loading and acidity to Mineral Creek; stabilize site, remove mine wastes, restore streambed and riparian habitat.
San Juan R. C. & D., ARSG.	Handies Peak Project.	Lucky Jack mine, site # 13	Hydrologic controls, remove wastes from fen, consolidate, neutralize, and revegetation; adit and shaft closures.	2004	Reduce metal loading and acidity to upper Animas River; uncover fen and restore.
U.S. BLM and Duke Energy.	Henrietta mine	Prospect Gulch, site # 84	Hydrologic controls and mine waste removal.	2004	Reduce metal loading to Cement Creek.
Public funds					
U.S. OSM	Galena Queen mine	Prospect Gulch, site # 82	Waste consolidation and hydrologic controls.	1998	Reduce surface water leaching of toxic metal loading to Cement Creek.
U.S. BLM	Joe & Johns mine	Prospect Gulch, site # 87	Mine drainage collection and diversion.	1999	Collect acidic drainage for later treatment project development, reduce metal loading to Cement Creek.
U.S. BLM	Lark mine	Prospect Gulch, site # 86	Install collection system for acidic water, hydrologic controls.	1999	Collect acidic drainage for possible treatment, remove surface water from site, reduce metal loading to Cement Creek.
U.S. BLM	Forest Queen mine	Animas River near Eureka, site # 195.	Install collection system for acidic water and passive wetland treatment.	1999	Reduce metal loading to Animas River.
U.S. BLM	May Day mine	Cement Creek, site # 181	Hydrologic controls, cap top of mine-waste pile.	1999	Reduce surface water leaching of toxic metals.
U.S. BLM	Lackawanna Mill tailings.	Animas River near Silverton, site # 286, site # 181.	Removal of mill tailings from flood plain to May Day dump for consolidation and capping.	2000	Reduce metal loading to Animas River.
U.S. BLM	Elk tunnel	Cement Creek, site # 147	Install limestone drain	2003	Reduce metal loading to Cement Creek.
USDA FS.	Bonner mine	Middle Fork Mineral Creek, site # 172.	Install collection system for acidic water and diversion, move waste rock from avalanche path.	2000	Reduce metal loading to Mineral Creek.
USDA FS.	Brooklyn mine	Mineral Creek, site # 141	Hydrologic controls and mine-waste removal.	2004	Reduce metal loading to Mineral Creek.

Identifying Sites for Remediation

One of the major goals of the Abandoned Mine Lands (AML) Initiative was to identify and prioritize contaminated sites for remediation that would provide the greatest benefit to the ecological recovery of the watershed study area. Because fiscal resources are limited, land-management agencies must invest their funds where remediation has the highest probability of success. The geographic extent of the Animas River watershed study area, the large number of inactive mine, mill, and prospect sites, and the complexities of the geology and hydrology of the region increased the challenges of identifying specific cleanup sites that will contribute to the most efficient and effective recovery of the aquatic system. In prioritizing sites in the Animas River watershed study area, planners must acknowledge that both mined and unmined areas contribute significantly to the in-stream load for the major constituents of concern.

Prioritizing mine-site remediation at the watershed scale requires an understanding of how multiple sources of acidic, metal-rich drainage affect the streams in the watershed and how the stream will respond if those sources are reduced or removed. Kimball and others (this volume) have demonstrated that using a combination of tracer-dilution and synoptic water-quality sampling provides the information on discharge and concentration necessary to evaluate mass chemical loading both spatially and temporally in an aquatic ecosystem. Mass-loading studies are also useful when those loads enter the environment directly from a specific source such as a tributary or when they are released in a diffuse manner through ground water. For example, this approach was instrumental in determination of remedial measures for the Mineral Creek basin by demonstrating that the Mineral Creek basin was a primary source of copper for the Animas River and thus a critical target for remediation. Eight sites in Mineral Creek have been remediated by removal of mine waste (table 1), and as a result, copper concentration and loading were reduced (J.R. Owen, written commun., 2005; http://www.waterinfo.org/arsg/). Identification and minimizing of this source of copper were also important in terms of ecological recovery, as the assessment of surface water-quality effects on aquatic life had demonstrated that dissolved copper posed the greatest risk to brook trout, the dominant species of fish in streams (Besser and others, this volume, Chapter D). Remediation of the Mineral Creek basin also resulted in a reduction in zinc and cadmium concentrations.

Reactive transport models developed during the AML Initiative provide an approach to anticipate changes that could occur in the water column following implementation of remedial measures. These models not only predict the change at a specific site, but also can assess potential downstream effects on loading. Evaluation of different remedial alternatives using these reactive-transport models can influence decisions prior to implementation of expensive engineering solutions. Information on tracer-dilution discharge and synoptic sampling from the Mineral Creek basin described previously was used to evaluate two water-treatment alternatives (Runkel and Kimball, 2002). Option 1 simulated conditions where only ferric (not ferrous) iron was removed. Option 2 evaluated total removal of iron. The model indicated that both options increased pH and reduced total and dissolved concentrations of aluminum, arsenic, copper, and ferrous and ferric iron. Dissolved lead concentrations were reduced by 18 percent in option 1. Lead and iron were removed in option 2. However, the model for option 2 indicates that the removal of all iron will ultimately result in increased loading of lead in Mineral Creek because downstream lead sources will not be attenuated by sorption to iron colloids. In addition, the model indicated that zinc concentrations would not be reduced by either option. Given the long-term costs of operating a water-treatment facility, these predictive models provide an extremely important tool for cost-benefit analysis in the decision-making process.

In prioritizing sites, scientists and land-use managers must also consider the biological community that is dependent on the habitat for survival. Using a risk-based approach, Besser and others (this volume) categorized areas in the watershed as low risk, moderate risk, high risk, and severe risk. Focusing on remedial measures for stream improvement in regions of moderate to high risk offers an optimum potential for measurable biological response. Besser and others (this volume) and Anderson (this volume) both offer biologically based indices to rank or assess the environmental impact of mining. Indices such as these that measure injury to the biological resources also provide a means to gauge recovery after remedial or restoration options have been implemented.

Monitoring Strategies and Tools for Evaluation of Ecological Recovery

Monitoring is an essential tool for evaluation of the success of remediation and restoration efforts and assessment of the overall status of ecological recovery. Without collecting and analyzing comprehensive monitoring data, land managers cannot objectively evaluate the success of a remedial or restoration action or determine whether remediation and restoration goals have been met. As a tool, monitoring provides information for four basic purposes:

- Performance evaluation: used to evaluate project implementation and ecological effectiveness
- Trend assessment: includes an extended sampling plan to identify changes across spatial and temporal scales
- Risk assessment: used to identify hazard sources, causal relationships, and resource injury within an ecosystem
- Baseline characterization: used to quantify ecological conditions prior to an actual disturbance. It may also be used to collect information at a reference site to estimate premining baseline conditions for a comparable disturbed habitat.

The type and extent of monitoring necessary will depend on specific management objectives (Kondolf, 1995). In the case of a historical mining area, the strategy most appropriate for evaluation of the success of remediation and restoration would be performance evaluation. The three components of performance evaluation include:

- Implementation monitoring
- Effectiveness monitoring
- Validation monitoring.

Implementation monitoring addresses the question: “Were the remediation and restoration measures done correctly?” Exploring this relatively simple question may yield valuable information that will help with potential refinement of remediation or restoration practices.

Effectiveness monitoring addresses the question: “Did remediation and restoration measures achieve the desired results?” Monitoring variables should be sensitive enough to detect changing conditions and have statistical validity. This level of monitoring is more time consuming than implementation monitoring. However, if monitoring data indicate that goals are not being met, problems can be evaluated in a timely manner, and adjustments can be made to the remediation and restoration designs.

Validation monitoring addresses the question: “Are the underlying assumptions used in the remediation and restoration designs and the cause-effect relations correct?” This is the most costly level of monitoring and is usually performed when the desired results of the remediation or restoration actions are not occurring and when further corrective action has not achieved the desired results. This level of monitoring requires specific scientific expertise to design and implement.

Monitoring involves the measurement of chemical, physical, and biological parameters to evaluate the magnitude of change that occurs following remedial and restoration activities and to estimate the rate of recovery of an ecosystem. A comprehensive list of all potential variables available for use in a monitoring program would be overwhelming. Therefore, in this section, we present a refined list of the types of monitoring variables that are applicable to an ecosystem affected by historical mining activities. An ideal monitoring program would include a combination of these chemical, physical, and biological variables.

Biological communities provide an integrated response to environmental conditions, and therefore, understanding the effect of remediation and restoration activities on biota is often the most important part of monitoring. Physical and chemical variables that may significantly affect the quality of aquatic habitat include temperature, turbidity, dissolved oxygen, pH, alkalinity/acidity, hardness, nutrients, streamflow, channel characteristics, spawning gravel/interstitial space, pool/riffle ratio, shade, in-stream cover, bed-material load, dissolved constituents, and suspended solids. For a remediated historical mining area, chemical variables would include measures of trace-element concentrations in water, streambed sediment, and biota that during the assessment phase of the project have been identified as being impaired. For the chemical analysis of water, measurement of the fraction (total recoverable or dissolved) that relates specifically to national or State water-quality criteria or that may be linked to bioavailability is most valuable in determining potential habitat improvement.

Ultimately, the goal of mine- and mill-site remediation is to restore a healthy self-sustaining ecosystem. In the Animas River watershed study area, this will not be possible in several stream reaches because of naturally acidic metal-rich conditions or limited suitable physical habitat. Recovery following remediation may be achieved more efficiently by changes that would increase the quality of the substrate for the benthic community, expand and enhance the aquatic habitat to increase the reproductive success of trout, or alter physical conditions to provide expanded overwintering habitat for adult trout (Milhous, this volume, chapter E21). Successful recovery can only be documented through measurement of biological endpoints (table 2). Selection of biological measurements is generally determined by the response of the predominant species needed to achieve the restoration goals. For example, in the Animas River watershed study area, both the ARSG and land managers are interested in establishing a healthy ecosystem that would support a successful trout fishery. In this case, measures of successful ecological restoration could include assessment of fish population densities, predominantly of brook trout, survival and health of individual fish (Karr, 1981; Farag and others, 2004), trace-element concentrations in biofilm and invertebrates, and indices of health of the aquatic invertebrate community (Klemm and others, 1990; Pflakin and others, 1989). In addition, avian species such as the white-tailed ptarmigan, which occurs near Silverton, may also provide a means to evaluate ecosystem recovery. Larison and others (2000) correlated renal damage in ptarmigan with dietary exposure to cadmium and suggested that consumption of cadmium-contaminated willow (*Salix* spp.) from the Silverton area created potentially life threatening conditions for older ptarmigan. Monitoring the population status of these birds and evaluating the concentration of cadmium and the overall health of the kidney offers a means to assess watershed recovery. Given that the pathway of exposure appears to be through consumption of willow, monitoring the concentration of cadmium in willow leaf buds and in recently grown shoots and stems provides an indication of changes in the birds' food source that might occur following remediation of the habitat.

Monitoring Success in the Animas River Watershed Study Area

Monitoring provides the information required to determine the changes in water and sediment quality and improvement in or deterioration of the status and health of the ecological community. Initial awareness of the impaired fisheries in the Animas River was documented through surveys conducted by Federal and State agencies in the 1960s and 1970s. In the reach of the Animas River upstream of Silverton, only one trout was recovered in an electrofishing survey in 1968 (U.S. Department of the Interior, unpub. data, 1968). Beginning in 1973, twenty years of fish stocking by the Colorado Division of Wildlife provided no evidence of reproductive success in rainbow or brown trout. Only brook trout were successful. More recent surveys of fish and benthic macroinvertebrates (Peter Butler, Robert Owen, and William Simon, Unpublished report to Colorado Water Quality Control Commission, 2001; Anderson, this volume; Besser and Brumbaugh, this volume; Milhous, this volume) indicate that, although many parts of the study area remain adversely affected by water and habitat quality, some trout populations may show signs of recovery following site-specific remedial activities. South Fork Mineral Creek and several tributaries of the upper Animas River support brook and cutthroat trout. Brook trout also occur in the Animas River between Maggie Gulch and the confluence with Cement Creek. However, mining effects and continued drainage of naturally acidic water from hydrothermally altered areas in the headwaters (Bove and others, this volume) have resulted in little to no aquatic life in the Animas River upstream of Eureka and in the entire reach of both Mineral and Cement Creeks even prior to mining.

Table 2. Examples of biological components and corresponding parameters that may be measured to evaluate progress of ecological recovery.

Biological component	Parameter
Primary productivity	Periphyton or biofilm density
	Aquatic macrophytes species and density
	Concentration of trace elements
Aquatic invertebrate community	Species composition
	Numbers of individuals
	Diversity
	Biomass
	Concentration of trace elements
Fish community	Species composition
	Age class distribution
	Fish health assessment
	Population density
	Concentration of trace elements
	In-stream exposure experiments
Riparian wildlife/terrestrial community	Amphibian/reptile species composition
	Amphibian/reptile population density
	Mammal species composition
	Mammal population density
	Mammal health assessment
	Passerine bird species composition
	Passerine bird population density
	Passerine bird reproductive health
	Fish-eating bird species composition
	Fish-eating bird health and population density
Riparian vegetation	Species composition
	Condition
	Successional changes
	Soil toxicity assessment

Water-quality monitoring has provided important insights into the effects of remedial measures. J.R. Owen (written commun., 2005; http://www.waterinfo.org/arsg/) has assessed progress towards meeting water-quality goals (established for the watershed study area by the Colorado Water Quality Control Commission) using water-quality data collected at the gauges from 1994 to 2004. During that 10-year period, water-quality samples were collected approximately at monthly intervals. A stream-flow regression model was used to account for changes in constituent concentrations with seasonal flow (Leib and others, 2003). The period between 1994 and 1996, prior to remediation in the watershed study area (table 1), provided baseline concentrations for this analysis. Changes in aluminum, cadmium, copper, zinc, manganese, and sulfate concentrations were measured at four USGS gauging stations in the watershed (A68, A72, CC48, and M34; fig. 1). To summarize the effects of remediation:

In the Mineral Creek basin, eight sites have undergone remediation (table 1), which has resulted in decreased concentrations of all constituents except manganese and iron. Iron remained near the baseline concentration, and the manganese concentration appears to experience a site-specific increase.

In the Cement Creek basin, remediation occurred at 15 sites in the basin (table 1). Concentrations of aluminum, cadmium, manganese, and copper dropped markedly following initial water treatment at the Gladstone portal on Cement Creek, but metal concentrations have fluctuated around the baseline values since 1999, when water treatment was discontinued by Sunnyside Gold, Inc., at the American tunnel (site # 96). Sulfate concentrations dropped substantially after final installation of the plugs eliminated acid mine drainage from the American tunnel.

The upper Animas River basin was the major contributor of dissolved manganese and zinc loads in the Animas River. Sunnyside Gold, Inc., has completed major long-term remediation projects at multiple sites on their properties (table 1). Although manganese concentrations have remained elevated, zinc concentrations have decreased to baseline values. Cadmium concentrations have remained generally above baseline values.

The Animas River downstream of Silverton at the gauge (A72, fig. 1) integrates the effects of all upstream remediation efforts. It also is the point of compliance established by the Colorado Water Quality Control Commission for instream concentrations of aluminum, cadmium, copper, iron, manganese, and zinc. At this location, cadmium and sulfate concentrations have fluctuated around the baseline values, whereas copper concentrations were below baseline values until 2004 when concentrations increased, probably related to increases in the load from Cement Creek. Manganese concentrations continue to be higher than baseline values observed before remediation began, probably because of the large amount of manganese in the mill tailings and stream gravel from sites (Vincent and Elliott, this volume, Chapter E22; Church, Fey, and Unruh, this volume) remediated on the upper Animas River (table 1).

Although some sites show measurable improvement, recovery is not dramatic. However, encouraging signs, such as the reoccurrence of benthic invertebrates in Mineral Creek downstream of the confluence with South Fork Mineral Creek, have been observed (William Simon, ARSG, written commun., 2005). Continued monitoring is essential to follow these long-term changes and relate them to biological improvement. Monitoring should include chemical, physical, and biological measures to evaluate the magnitude of change that occurs following remedial actions and to allow for the estimation of recovery rates so that lessons learned can be applied to other watersheds.

Summary

Historical mining practices have resulted in the degradation of fisheries and their supporting habitat in the Animas River watershed study area. Both mined and unmined areas contribute to the contamination. Many activities, including remediation, reclamation, rehabilitation, and restoration, are available for watershed recovery. At this point, the major activity in the Animas River watershed study area has been remediation (fig. 1). Although only half of the very high priority sites on Federal lands identified by Nash and Fey (this volume) and by Kimball and others (this volume) have been addressed, and 23 percent of sites identified by the Animas River Stakeholders Group, Bureau of Land Management, USDA Forest Service, and the U.S. Geological Survey have been remediated through various engineering options (table 1), some improvement in water quality has been demonstrated by the water-quality data analysis. Individual sites have responded to the remediation work done, as evidenced by the improved water chemistry at individual sites (William Simon, ARSG, written commun., 2005). Remediation work conducted by the Federal agencies, the ARSG, Sunnyside Gold, Inc., and other private parties has addressed water-quality issues caused by acid drainage and runoff from some of the largest contaminated sites in the watershed study area. Because a substantial amount of the metal load in the surface drainages is derived simply from weathering of hydrothermally altered rock that has not been disturbed by mining (Kimball and others, this volume; Wirt and others, this volume, Chapter E17), recovery of the watershed to premining conditions may not be an attainable goal; that is, it is simply not possible to remove all of the metal loading contributed by historical mining. Steady improvement in water quality should continue as dynamic equilibrium is reestablished following remediation activities. Some recovery of aquatic life in designated stream reaches is already occurring. The ability of an ecosystem to support a viable fishery depends not only on water quality, but also on availability of an uncontaminated food source and suitable habitat. Removal of major sources of contamination in the watershed will provide improved conditions for survival and reduce the potential for fish to encounter acutely toxic conditions. However, chronic water or dietary exposure of trout may persist in areas with residual contamination and may delay the recovery of the benthic community as well. Sublethal effects resulting from chronic exposure can be documented through the measurement of the same biological endpoints that were used to evaluate the adverse ecological effects prior to remediation. These parameters should include measurement of dissolved-metal concentrations (aluminum, cadmium, copper, zinc, and sulfate), benthic community surveys, periodic in-stream larval fish exposure studies, and fish health and population surveys. Monitoring sites should remain consistent with past sites with the potential addition of sites near newly remediated areas.

At this point, recovery in the Animas River watershed study area has been predominated by remedial measures. Future planning may include ecological restoration alternatives that will enhance the recovery of the biological community. The Society for Ecological Restoration (2004) has defined nine attributes that "provide a basis for determining when restoration has been accomplished." Some attributes can be easily measured, whereas others can only be assessed indirectly and may require "research efforts that exceed the capabilities and funds of most restoration projects." However, these nine attributes provide a means to evaluate progress of ecological recovery following remediation, reclamation, rehabilitation, and restoration of a site.[1]

1. The restored ecosystem contains a characteristic assemblage of the species that occur in the reference ecosystem and provide appropriate community structure.

2. The restored ecosystem consists of indigenous species to the greatest practical extent. In restored cultural ecosystems, allowances can be made for exotic domesticated species and for non-invasive ruderal and segetal species that presumably co-evolved with them. Ruderals are plants that colonize disturbed sites, whereas segetals typically grow intermixed with crop species.

[1]Material in quote marks, and the nine attributes, are quoted with the acquiescence of Society for Ecological Restoration International.

3. All functional groups necessary for the continued development and (or) stability of the restored ecosystem are represented or, if they are not, the missing groups have the potential to colonize by natural means.

4. The physical environment of the restored ecosystem is capable of sustaining reproducing populations of the species necessary for its continued stability or development along the desired trajectory.

5. The restored ecosystem apparently functions normally for its ecological stage of development, and signs of dysfunction are absent.

6. The restored ecosystem is suitably integrated into a larger ecological matrix or landscape, with which it interacts through abiotic and biotic flows and exchanges.

7. Potential threats to the health and integrity of the restored ecosystem from the surrounding landscape have been eliminated or reduced as much as possible.

8. The restored ecosystem is sufficiently resilient to endure the normal periodic stress events in the local environment that serve to maintain the integrity of the ecosystem.

9. The restored ecosystem is self-sustaining to the same degree as its reference ecosystem, and has the potential to persist indefinitely under existing environmental conditions.***As in any intact ecosystem, the species composition and other attributes of a restored ecosystem may evolve as environmental conditions change.

The severity of the injury to the ecological community and the complexities of the Animas River watershed study area make ecological recovery a distant goal. Although source reduction will improve water quality so that the aquatic community no longer encounters acutely toxic exposures, biological recovery may still be limited by the availability of suitable habitat for spawning and overwintering of trout or by the chronic exposure of individual organisms through water, sediment, and diet. As funds remain limited for remediation and additional restoration options, reduction of the sources of contaminants is a positive step toward improving the environmental conditions in the Animas River watershed study area. Continued monitoring of water, sediment, and biological resources will provide the information necessary to determine if recovery is proceeding in an acceptable time frame or whether additional remediation or restoration measures are required. If monitoring data indicate that goals are not being met, adjustments can be made to the remediation and restoration designs.

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