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Analysis of the Transport and Fate of Metals Released from the Gold King Mine in the Animas and San Juan Rivers

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Notice

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Executive Summary

On August 5, 2015, a field investigation of the Gold King Mine (GKM) near Silverton, CO, inadvertently triggered an estimated release of 3 million gallons of acidic, mine-impacted waters into the Animas River. These waters had been dammed by a collapsed mine structure and rock at the mine entrance, causing the waters to back up and become pressurized. This report is a scientific evaluation that focuses on understanding the river conditions before the GKM release; the movement of the GKM release through the river system; and what has happened to the river since the time of the event.

Specifically, EPA looked at: (a) the GKM effects on water quality after the release; (b) whether or not the water quality returned to pre-event conditions; (c) whether or not there was a second wave of contamination following storms and/or spring snow melt when high flows could remobilize deposits; and (d) whether or not any remaining GKM impacts could be detected given the legacy contamination from historic mining in the region.

The initial GKM release first flowed into nearby Cement Creek. Cement Creek flows 12.5 km (8 mi) into the Animas River near Silverton, CO. The Animas River then flows 203 km (126 mi) where it joins the San Juan River near Farmington, NM. The San Juan river flows 347 km (215 mi) until it flows into Lake Powell in Utah. The GKM release crossed three state lines and three tribal lands over a 9-day period for an approximate total distance of 550 km (342 mi). This river system has a long history of leaking mine waste contamination from hundreds of old and abandoned mines throughout the region. Acid mine waste contamination historically has settled along these river banks and in the sediment beds. High river flow or snow melt can remobilize the contaminants, impacting water quality throughout the river system to Lake Powell.

Historically, mine waste had been piled up outside the Gold King mine entrance for many years. The initial load of metals contained in the GKM release increased significantly as the mine water traveled down the hillslope and along Cement Creek, picking up additional metals from the waste pile and streambed along the way. EPA estimates that approximately 490,000 kg (close to 540 tons) of metals, mostly iron and aluminum, entered into the Animas River over the 9-hour period of the release. The iron and aluminum reacted with the river water to cause the characteristic bright yellow color that was visible for days as the plume traveled down the river system.

EPA estimates that one percent of the metals came from inside the mine itself while 99 percent of the metals were scoured from the waste pile on the hillslope and the Cement Creek streambed. Approximately 15,000 kg, or 3 percent, of the original total metal mass was initially in dissolved form and 475,000 kg was in a fine,

GKM Release

9 hours of pressurized mine impacted waters scoured the hillside with approximately **1% total metal load** coming from inside the mine and **99% total metal load** from a waste pile located on the hillslope outside the mine.

EPA estimates that **approximately 490,000 kg (close to 540 tons) of metals**, dominated by iron and aluminum, entered into the Animas River over the 9-hour period of the release.

The total amount of metals entering the Animas River following the release was comparable to the amount of metals carried by the river in one to two days of high spring runoff.

Historical Sampling Data

EPA researchers analyzed hundreds of water quality samples and approximately 50 sediment samples provided by USGS

Post Gold King Mine Release Data

EPA researchers analyzed:

- 1758 total and dissolved water samples collected by EPA, states and tribes through August 2016
  - Approximately 56% of samples came from the Animas River and 44% from the San Juan River
- 963 sediment samples collected by EPA, states and tribes through September 2016
  - Approximately 66% of samples came from the Animas River and 34% from the San Juan River and Lake Powell
- Samples were collected from 294 sites throughout the total River system.

Animas River in Colorado

(River km 0 to 150):

• returned to pre-event levels in the weeks after the release

• stayed at pre-event levels through the winter

Animas River in New Mexico

(River km 150 to 192):

• Initially returned to pre-event levels after 15 days

• Most dissolved metals increased after the August 2015 storm

San Juan River

(River km 193 to 540)

• Increased Aluminum and Iron in Animas were carried into San Juan

clay-like solid form. Generally, dissolved metals are considered more toxic, more reactive, and more mobile than solid metals.

EPA analyzed data from samples collected by EPA, states and tribes from the affected rivers during and after the GKM release to estimate where and when the plume passed, and what happened to the metal contaminants as it flowed, like historic acid mine contamination, through the river system to Lake Powell. To allow for a robust comparison to historic conditions, EPA scientists reviewed U.S. Geological Survey (USGS) historic studies of acid mine drainage under similar high flow scenarios. According to the analysis, the volume of the GKM release was equivalent to four to seven days of ongoing GKM acid mine drainage. The total amount of metals entering the Animas River following the release was comparable to the amount of metals carried by the river in one to two days of high spring runoff; however, the concentration of metals during the peak of the plume passage was much higher than historic spring runoff conditions.

As the plume traveled downstream, the metal concentrations within the plume decreased as it was diluted by river water and as some of the metals in the plume settled to the river bed. EPA estimates that approximately 90 percent of the solid metal load initially settled in the Animas River bed and that dissolved metal concentrations decreased to pre-event conditions by the time the plume flowed into the San Juan River. Although the GKM metal deposits were highly visible as a bright yellow color, they were on average similar to existing metal concentrations stored in the river sediments from years of mining activity in the region.

The GKM plume flowed into the sediment-rich San Juan River where the small amount of remaining solid metals mixed with the large existing sediment load. The San Juan River bed naturally has low metal concentrations; however, the river has a very large amount of mobile sediment during storms and high flow events. Because of this, water quality in the San Juan River is strongly related to the amount of sediment in the water; the concentrations of metals in the sediment in the San Juan River can exceed the concentrations of all the metals found in the GKM plume. On the day the GKM plume passed, lead and arsenic were found to be elevated relative to background levels of the San Juan River. Relatively higher levels of lead, and to a lesser extent arsenic, were characteristic of the GKM release metals. Although elevated, these metals were not uniquely higher than what is typically seen in high flow periods such as a major storm or spring snowmelt.

Data indicate that water quality returned to pre-event conditions within two weeks after the GKM plume passed. Three weeks after the mine release, a large storm centered in Aztec, NM, flushed some of the deposited GKM metals from the lower Animas River and the San Juan River to Lake Powell. After the storm flushed these deposits, water sampling showed elevated levels of dissolved aluminum and iron in both rivers that persisted through the 2015 fall months. During this time, the dissolved metals exceeded tribal aluminum human contact-related criteria, and Utah aquatic chronic criteria, and New Mexico irrigation criteria.

Samples collected did not exceed EPA's recreational screening levels. Some metal concentrations contributed to sporadic exceedances of state and tribal water quality criteria at times for nine months in some locations. EPA and states establish water quality standards based on the use of the water to protect human health and aquatic life. In addition to these factors, tribal standards also consider tribal cultural uses, and are often more stringent than state or federal standards. Thus, tribal standards were exceeded more often, even during average flow periods because of historical background contamination. Metals from the GKM release also may have contributed to some exceedances during the 2016 spring snow melt. Other exceedances may reflect longstanding issues of mining wastes in the region as well as natural levels of common elements such as aluminum and iron in soils and rocks in the area. EPA will continue to work with states and tribes to interpret and respond to these findings.

There were no reported fish kills in the affected rivers, and post release surveys by multiple organizations have found that other aquatic life do not appear to have suffered harmful short-term effects from the GKM plume. Longer-term monitoring continues to evaluate potential chronic impacts from the GKM release deposits that may have been added to ongoing impairment from legacy mining activity.

As part of the monitoring study, EPA explored whether or not the metals from the GKM release could have potentially contaminated water supply wells in the floodplain aquifers of the Animas. There are hundreds of water supply wells located in the floodplain of the Animas River in Colorado and New Mexico. EPA analysis showed that only a small number of wells potentially draw in water from the river because groundwater in this area generally flows into the river, rather than the river water flowing into the wells. The concentrations of metals in well-water samples collected after the plume passed did not exceed federal drinking water standards.

The 2016 spring snowmelt period remobilized metals that had settled in the sediment in the river system. EPA's analysis showed concentrations of metals in the water and sediment were elevated throughout the Animas and San Juan Rivers. While some of the metals in the upper Animas were expected from regional acid mine drainage contamination as established by the USGS in earlier studies, there was strong evidence that a portion of the metals came from recent streambed deposits associated with the GKM release. Concentrations were low, but the duration of snowmelt strongly implies that the mass of GKM metals that had settled in the river beds was moved downstream to Lake Powell by the end of the snowmelt period. Monitoring through the summer and fall of 2016 shows that metal concentrations in water and sediment have returned to pre-event conditions throughout the Animas and San Juan Rivers. Monitoring throughout spring 2017 should confirm our finding that, similar to historic acid mine contamination, the remaining contamination from GKM has flowed through the river system to Lake Powell. The USGS and state partners will be studying core samples from Lake Powell to evaluate metal contamination in the sediments.

Summary of key findings from the fate and transport of the GKM event:

- This river system has a long history of leaking mine waste contamination from hundreds of old and abandoned mines throughout the region.
- EPA analysis indicates as of Fall 2016 contamination of metals from the GKM release have been transported through the Animas and San Juan River system to Lake Powell.
- The GKM release included aluminum, iron, manganese, lead, copper, arsenic, zinc, cadmium, and a small amount of mercury.

- The Gold King Mine release was equivalent to four to seven days of ongoing GKM acid mine drainage. The total amount of metals entering the Animas River following the 9-hour release was comparable to the amount of metals carried by the river in one to two days of high spring runoff. However, the concentrations of metals were higher than historical acid mine drainage.
- Samples collected did not exceed EPA's recreational screening levels. Some metal concentrations contributed to sporadic exceedances of state and tribal water quality criteria at times for 9 months in some locations. EPA and states establish water quality standards based on the use of the water to protect human health and aquatic life. In addition to these factors, tribal standards also consider tribal cultural uses, and are often more stringent than state or federal standards. Thus, tribal standards were exceeded more often, even during average flow periods because of historical background contamination. Metals from the GKM release also may have contributed to some exceedances during the 2016 spring snow melt. Other exceedances may reflect longstanding issues of mining wastes in the region as well as natural levels of common elements such as aluminum and iron in soils and rocks in the area. EPA will continue to work with states and tribes to interpret and respond to these findings.
- The 2016 spring snowmelt remobilized the metals that had settled in the sediment throughout the river system. This was expected based on historic observations. Some of the metals were due to the GKM release. Concentrations of metals in both sediment and water returned to pre-event concentrations by the end of the snowmelt period.
- Ground water modeling suggests that a few wells located in the floodplain within 100 meters of the Animas River had the potential to draw river water, possibly including dissolved metals, during the time the GKM release plume passed. Most ground water in the affected area flows towards the river rather than from the river toward the wells. The concentrations of metals in well-water samples collected after the plume passed did not exceed federal drinking water standards.
- Results from this analysis will inform future monitoring by EPA, states and tribes, including decisions about what is monitored; where monitoring takes place; and when monitoring takes place.
- EPA is committed to working with States and Tribes in the areas affected by the Gold King Mine release to ensure the protection of public health and the environment.

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Acronyms and Abbreviations

Ag	silver
AEM	analytic element method
AES	atomic emission spectrometry
Al	aluminum
$AL(OH)_3$	aluminum hydroxide
AMD	acid mine drainage
AnAqSim	Analytic Aquifer Simulation (AnAqSim)
As	arsenic
ASTM	American Society for Testing and Materials
Ba	barium
BAFs	bioaccumulation factors
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BASS	Bioaccumulation and Aquatic System Simulator
Be	beryllium
BLM	Bureau of Land Management
BMI	benthic macroinvertebrates
BOR	Bureau of Reclamation
Ca	calcium
CaCO3	calcium carbonate
$CaMg(CO_3)_2$	dolomite
$CaSO^4 \bullet 2H_2O$	gypsum
Cd	cadmium
CDPHE	Colorado Department of Public Health and Environment
CFARM	City of Farmington
Cfs	cubic feet per second
Cr	chromium
Cu	copper
Co	cobalt
D	day
DF	Dupuit-Forcheimer
DRMS	Division of Reclamation, Mining, and Safety
EPA	U.S. Environmental Protection Agency
EPA R	U.S. Environmental Protection Agency Region
Fe^{2+}.	ferrous iron
Fe^{3+}	ferric iron
$Fe(OH_3)$	iron(III) hydroxide
FeO(OH),	goethite

Fh	ferrihydrite
ft	foot
gal	gallon
GIS	geographic information systems
GKM	Gold King Mine
gpm	gallons per minute
GPS	global positioning unit
H_2O_2	hydrogen peroxide
HCl	hydrochloric acid
HCO_3	bicarbonate
HFO	hydrous ferric-oxide
HNO_3	nitric acid
hr	hour
ICP	inductively coupled plasma
K	potassium
kg	kilogram
km	kilometer
km/h	kilometer/hour
L	liter
m	meter
mg	milligram
Mg	magnesium
mi	mile
min	minute
mL	milliliter
Mn	manganese
Mo	molybdenum
mph	mile per hour
m^3/s	cubic meter per second
MS	mass spectrometry
MSI	Mountain Studies Institute
Na	sodium
NGO	non-governmental organization
NHD	National Hydrography Dataset
Ni	nickel
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
NMED	New Mexico Environment Department
NNEPA	Navajo Nation Environmental Protection Agency
ntu	Nephelometric Turbidity Unit
ORD	Office of Research and Development
Pb	lead

QC	quality control
RCWWN	Rivers of Colorado Water Watch Network
RK	river kilometer
s	second
Sb	antimony
SC	specific conductance
SO_4	sulfate
STORET	STOrage and RETreival
SUIT	Southern Ute Indian Tribe
TAL	Metal/Cyanide Analyte List
TDS	total dissolved solids
UDEQ	Utah Department of Environmental Quality
µm	micrometer
UMUT	Ute Mountain Ute Tribe
USGS	U.S. Geological Survey
WASP	Water Quality Analysis Simulation Program
WhAEM	Wellhead Analytic Element Model
yd	yard
Zn	zinc

Units of Conversion

Length

To / From	mi	km	ft
mi	1	1.609	5,280
km	0.621	1	3,281
ft	0.0001894	0.0003048	1

Area

To / From	mi^2	km^2	acre	ha
mi^2	1	2.590	640.0	259.0
km^2	0.386	1	247.1	100.0
acre	0.001563	0.004047	1	0.405
ha	0.003861	0.01	2.471	1

Volume

To / From	ft^3	m^3	gal	liters	Million gal
ft^3	1	0.02832	7.481	28.319	0.000007
yd^3	9	.76455	202	764.6	.000202
m^3	35.315	1	264.2	1,000	0.000264
gal	0.134	0.003785	1	3.7854	0.000001
liters	0.035	0.001	0.264	1	0.0000003
Million gal	133,681	3,785	1,000,000	3,785,412	1

Flow Rate

To / From	cfs	cms	mgd
cfs (ft^3/s)	1	0.02832	0.646
cms (m^3/s)	35.315	1	22.825
mgd	1.547	0.044	1

Acknowledgments

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CHAPTER 1 INTRODUCTION

1.1 Overview of Mining Activities

More than 50,000 inactive hard-rock mines located on public lands, and many more on private lands, have left a legacy of acid drainage and toxic metals contamination across mountain watersheds in the western United States (BLM 2007). More than 40 percent of the watersheds in or west of the Rocky Mountains have headwater streams in which the effects of historical hard-rock mining are thought to represent a potential threat to human and ecosystem health through the persistent release of acidity and metals into water bodies (von Guerard *et al*. 2007).

One of those areas lies within the southern extent of the Colorado Mineral Belt in the headwaters of the Animas River, which originates in the San Juan Mountains in southwest Colorado (Figure 1-1). The geologic stratigraphy of this area consists of a Precambrian crystalline basement overlain by Paleozoic to Tertiary sedimentary rocks and capped by a thick sequence of Tertiary volcanic rocks (Luedke and Burbank 2000).

In a series of regional volcanic eruptions that took place during the late Paleogene (28–23 million years ago), magma intruded into a northeasterly-striking shear zone. Over geologic time, hydrothermal processes altered the pre-existing volcanic and sedimentary rocks, forming orebodies containing economically-valuable minerals and extensive areas of naturally-acidic rocks and soils (Luedke and Burbank 2000; Besser *et al*. 2007; von Guerard *et al*. 2007). Mineralized relict features remain from the volcanism, including the Silverton caldera, just north and west of the town of Silverton, Colorado (Figure 1-2). The highly-mineralized Silverton caldera is bounded by the Animas River to the east and is drained exclusively by Mineral Creek to the south.

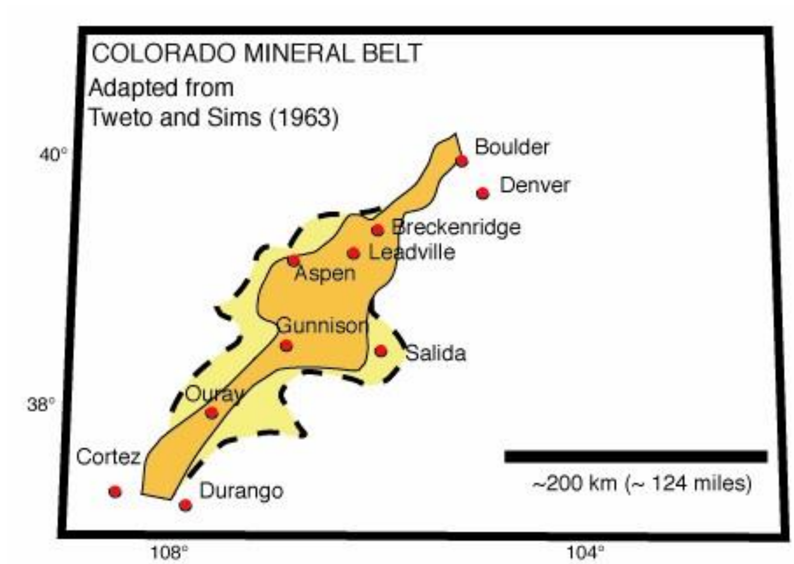
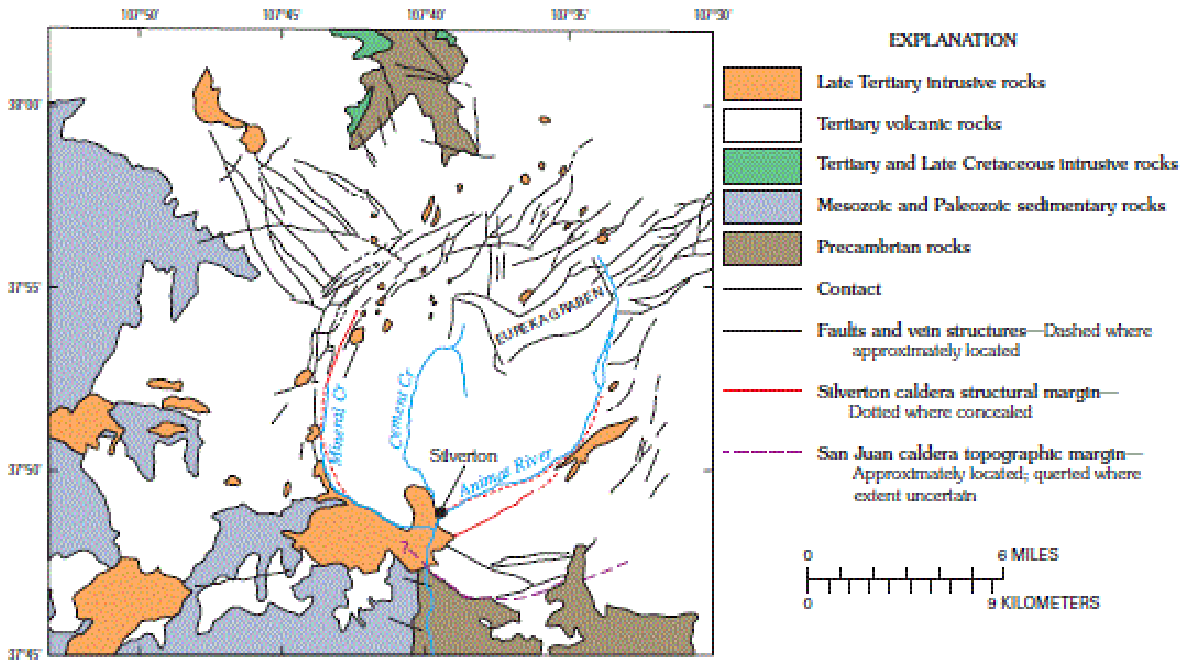


Figure 1-1. Map of southwest Colorado, showing the general locations of the Colorado mineral belt.

The metal rich ores within the caldera are mainly vein-type deposits with extensive volumes of pyritized rock around the vein zones. The sulfide deposits are largely composed of iron (e.g., pyrite), copper (chalcopyrite), lead, zinc, mercury, and arsenic (Luedke and Burbank 2000). Gold and silver are present in varying concentrations. A detailed geologic map of the headwaters of the Animas watershed from USGS Professional Paper 1651 is shown in Figure 1-3.

A)



B)

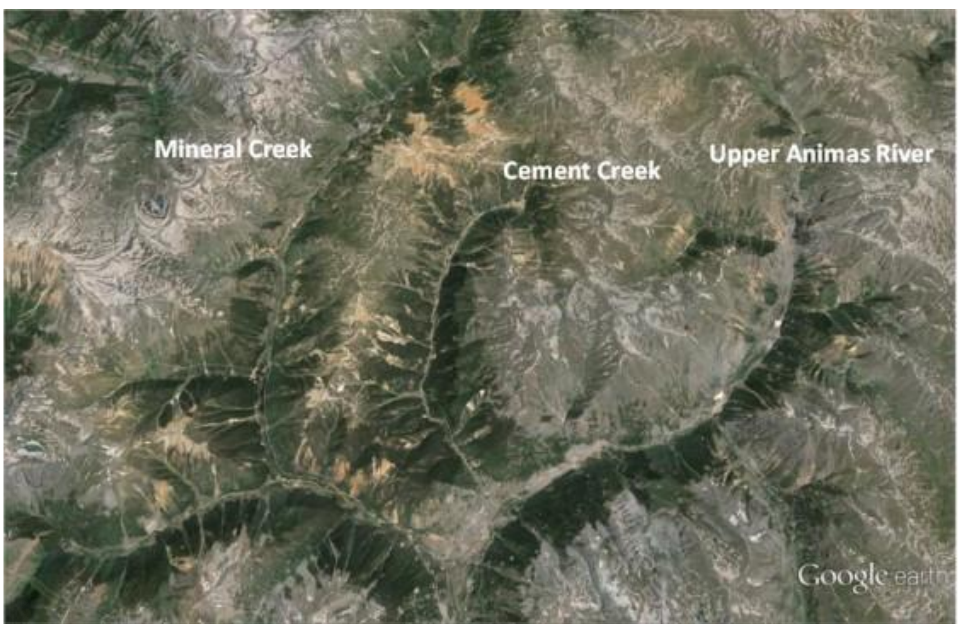


Figure 1-2. A) Generalized regional geology map of Animas River headwaters and surrounding regions near Silverton, Colorado. (Taken from: Yager and Bove 2007). B) Aerial view of the Silverton caldera area and the three main tributaries to the Animas River; Silverton is located in the center bottom of the image (Source: GoogleEarth).

The region was subject to extensive mining from 1871 until 1991, but mining has not been economically-viable in the region since the early 1990s (Figure 1-4). During those 120 years of activity, more than 300 large mines and thousands of smaller claims produced silver, lead, gold, zinc, and copper from 18.1 million short tons of ore extracted primarily from hard-rock mines burrowed into the rugged mountains (Jones 2007). Many of those mines are now abandoned, but continue to leak acid mine drainage to surrounding surface waters, impairing water quality throughout the area and in downstream receiving waters.

1.2 Mining Impacts on Water Quality

Along with the veins of mineable metals, the natural geological conditions in the orebodies create extensive areas of naturally-acidic rocks and soils within the upper Animas basin. Acid drainage occurs when either surface water or groundwater seepage intersects with the sulfide-rich ores in-situ or the wastes left by mining (e.g., overburden, waste piles, tailings, etc.), under conditions with sufficient oxygen to oxidize and dissolve the sulfide minerals. A chain of reducing reactions generates acidic drainage (typically sulfuric acid) with a pH between 2 and 5 that is laden with a concentrated mixture of metal ions dissolved from the ores. These mixtures typically include some combination of iron, aluminum, zinc, cadmium, copper, lead, arsenic, nickel, and other trace metals dissolved in an acidic mixture (Wirt *et al.* 2007). This acidic drainage is referred to as “acid mine drainage” or AMD, even though some acidity is present naturally.

Acid Mine Drainage (AMD). AMD presents two general areas of concern for water quality in receiving waters: 1) acidity and acid generation and 2) mobilization of high concentrations of metals in dissolved and colloidal phases. Many metals occur ubiquitously in soils and water in trace amounts and are essential to life. In higher concentrations, metals can adversely affect human or ecosystem health. EPA, states, and tribes have identified concentrations for short- and long-term exposures to metals in water and sediment that are protective of human and ecological health. In portions of the upper Animas River, pre- and post-spill concentrations of a number of metals exceeded levels of concern for acute and chronic toxicity for aquatic life (Besser *et al*. 2007). These metals included dissolved forms of aluminum, zinc, copper, and cadmium, as well as dissolved and colloidal aluminum. The persistence of acid drainage in the headwaters has led to relatively reduced aquatic communities and water that cannot be used for human consumption in most of the Animas River above Silverton (Besser *et al*. 2001, 2007).

Acidic drainage from mines and natural rock formations has been extensively studied in the headwaters of the Animas River at Silverton (watershed area 346 km^2), where the majority of mineralized rock and mining has occurred. Taking a watershed approach, a team of investigators from the U.S. Geological Survey’s (USGS’s) Abandoned Mines Initiative studied the geological and anthropogenic sources of acid drainage, hydrologic mechanisms and volumes delivered to streams, and the biological impacts of metals in the acidic waters in fine spatial detail. A decade of multidisciplinary research is summarized in USGS Professional Paper 1651 (Church *et al*. 2007). Patterns and processes leading to acid drainage are very complex and spatially varied within this area, reflecting local variations in geology and mineralization and mining activity (Schemel and Cox 2005; Bove *et al*. 2007; Church *et al*. 2007).

Hard-rock mining activity has contributed significantly to the generation of AMD in streams (Church *et al*. 2007). Mining excavations created many miles of underground workings that have significantly altered subsurface hydrology at a hillslope scale. The mining voids collect and provide preferential flow paths for groundwater. The voids collect water as groundwater seeps through the hillslopes, providing an ideal environment for oxygen enrichment that triggers the acid-producing reactions in the ore deposits. Acidic drainage accumulates to some extent in most mines and is a source of significant effluent from some (Church *et al*. 2007). At active or remediated mines, AMD is pumped out and treated with a pH-neutralizing agent, such as calcium carbonate ($CaCO_3$); this stimulates the formation of iron and aluminum oxides, which precipitate as solids (often referred to as sludge) and are then disposed of. Closed and untreated mines collect water that may leak from the mine entrances or seep slowly via subsurface pathways to streams. More rarely, AMD spills catastrophically with failure of aging and unmaintained infrastructure (BOR 2015).

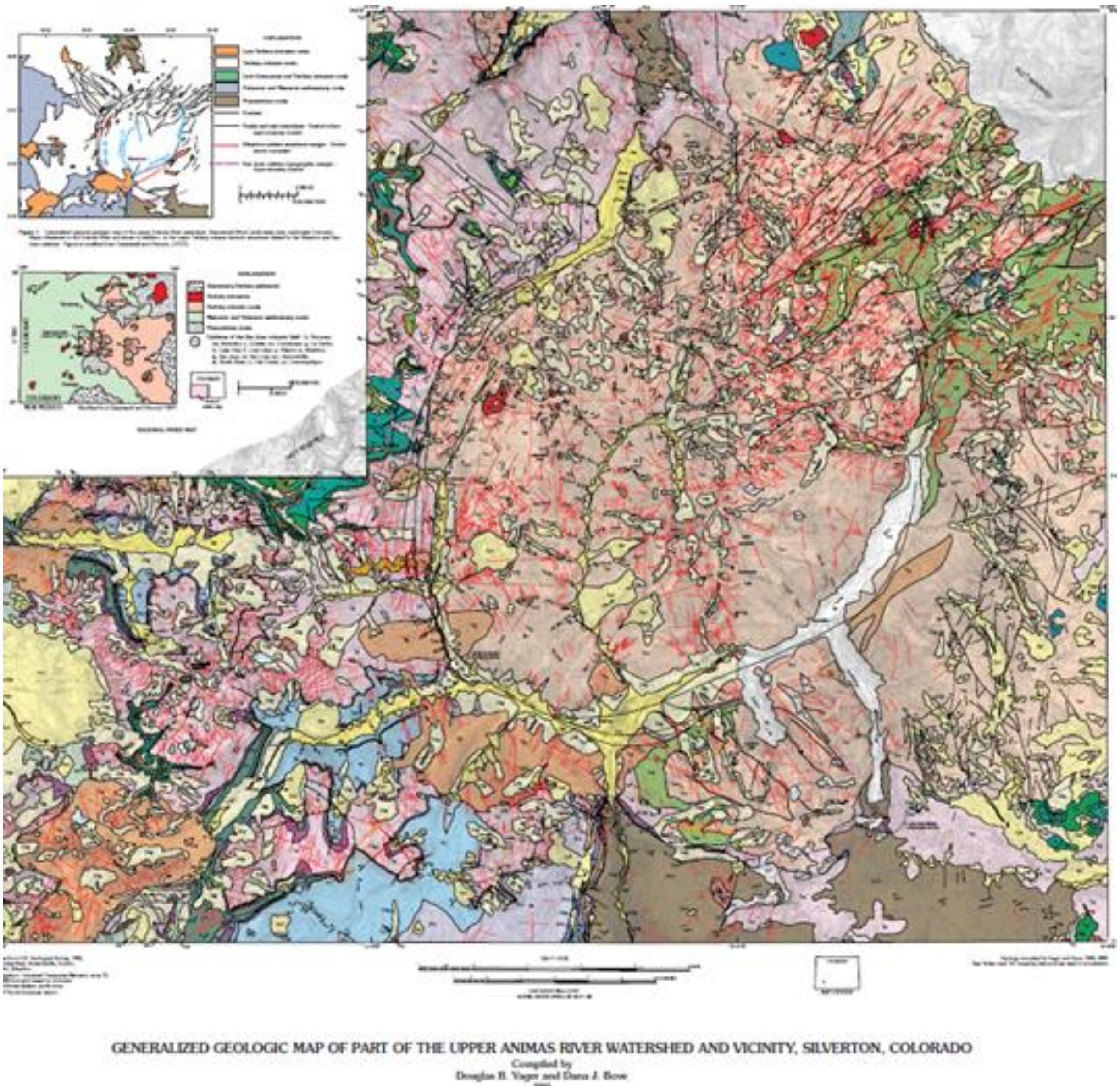


Figure 1-3. Geologic map of the area surrounding Gold King Mine (Source: Yager and Bove 2002). Mapping units are lost in this image due to reduction from the original scale, but the outline of the Silverton caldera, in which Gold King Mine is located, is visible, as is the Animas River to the east and Mineral Creek to the south. For a full scale map with legend see https://pubs.usgs.gov/pp/1651/downloads/plates/pl_1.pdf.

In addition to drainage from inside the mine, excavations often leave large volumes of tailings, which have been pulverized to remove sulfide ores, outside the mines (von Guerard et al. 2007). Mine waste piles at mine and milling sites magnify the surface area exposure of pyrite ores to oxidation and water, increasing potential for runoff of AMD and exacerbating acidic drainage concerns.

The three main headwater tributaries of the Animas that converge near Silverton are characterized by high to moderate acidity and high concentrations of dissolved metals due to natural processes and mining activities. Cement Creek naturally has the lowest pH as it dissects the Silverton caldera (Figure 1-2A), giving drainage water the greatest exposure to sulfide ores. Both upstream and downstream of Cement Creek, the upper Animas River branch is buffered by the moderate alkaline pH of sedimentary bedrock that is comprised of abundant carbonate and chlorite minerals.

The mixing of AMD with these alkaline waters changes the water chemistry. As AMD flows southward from the headwaters, dissolved-metals concentrations are generally suppressed as the acidic waters mix and dilute with inflow from moderately-alkaline, well-buffered pH in the Animas River. Increasing pH allows oxidizing reactions that reduce the solubility of metal ions such as aluminum (Al^{3+}) and ferric iron (Fe^{3+}). As these reactions progress, amorphous iron or aluminum (hydr)oxides and sulfates precipitate (Schemel *et al*. 2000; Schemel and Cox 2005). In turn, dissolved concentrations of trace metals decrease as they sorb or integrate into the iron and aluminum precipitates (Schemel *et al*. 2007; Wirt *et al*. 2007). Secondary iron sulfate minerals exist and form in acidic conditions due to oxidation typically accompanied by evaporation.

The colloidal solids formed from iron, aluminum or manganese oxidation cause a distinctive staining of the river, commonly called "yellowboy," which can be yellow, red, white, or black depending on the dominant metals (Schemel *et al.* 2000). Yellow staining is a persistent feature in the Animas River for several kilometers below its confluence with Cement Creek (Figure 1-5) due to the prevalence of iron (Besser *et al*. 2007). After sufficient aggregation/flocculation, typically in response to changes in ambient chemistry and/or time, colloids can be lost from the water column to the streambed (Schemel *et al.* 2000), where the insoluble aluminum and iron oxides and similar compounds form coatings on the streambed (Theobald *et al.* 1963; Chapman *et al*. 1983; Rampe and Runnells 1989). A combination of chemical, physical, and biological processes promotes their long-term retention in the sediment (Schemel *et al*. 2007).

Mining operations also affect impacted river sediments directly. It was common practice through much of the mining era to discharge mill tailings directly into water bodies. By the time mining ended, more than 8.6 million short tons of mill tailings and waste had been discharged directly into the Animas River and its tributaries (Jones 2007). Substantial amounts of the discarded waste were subsequently transported downstream and dispersed within the Animas sediments (Church *et al*. 1997; Vincent and Elliott 2007), while considerable amounts remain in place. Church *et al*. (1997) found bed sediments of the Animas River far downstream of the headwaters to be contaminated with metals that could be traced to the headwaters and its historical mining practices. Early in the 1900s, the people of Durango, Colorado built a new reservoir and delivery system that utilized water from the more distant Florida River to create a better public water supply source and avoid using water from the tailings-laden Animas River (Jones 2007, citing Durango Democrat, August 1-15 and November 18, 1902).

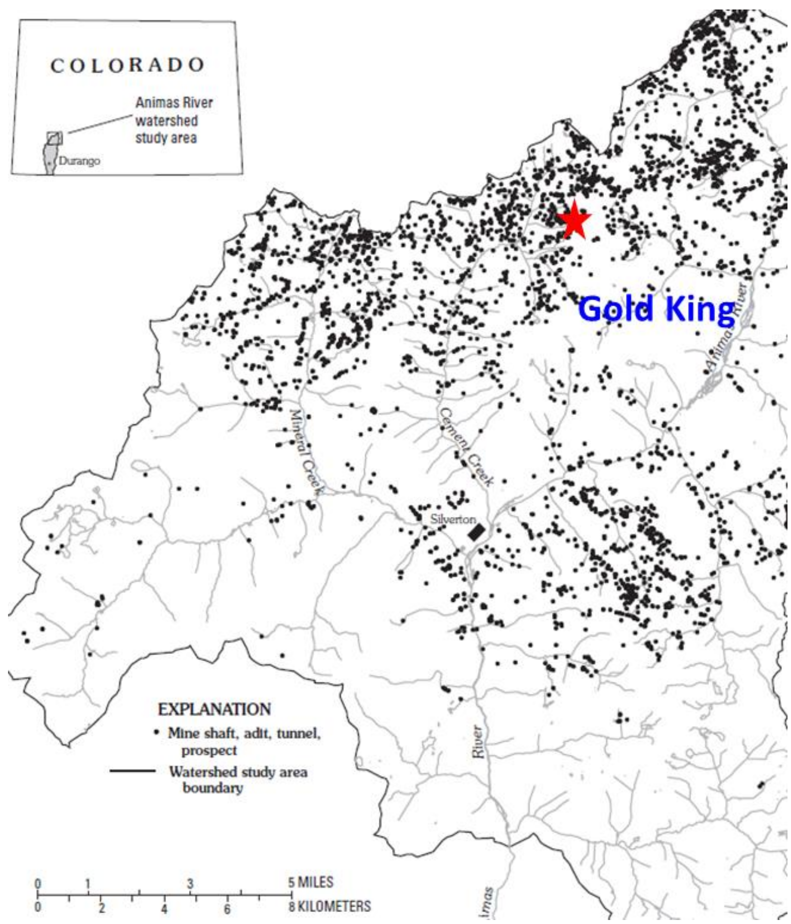


Figure 1-4. Mines within the Animas River headwaters, many of which are abandoned. Mining has not been economically viable in this area since the early 1990s. (Map modified from Church *et al*. 2007).

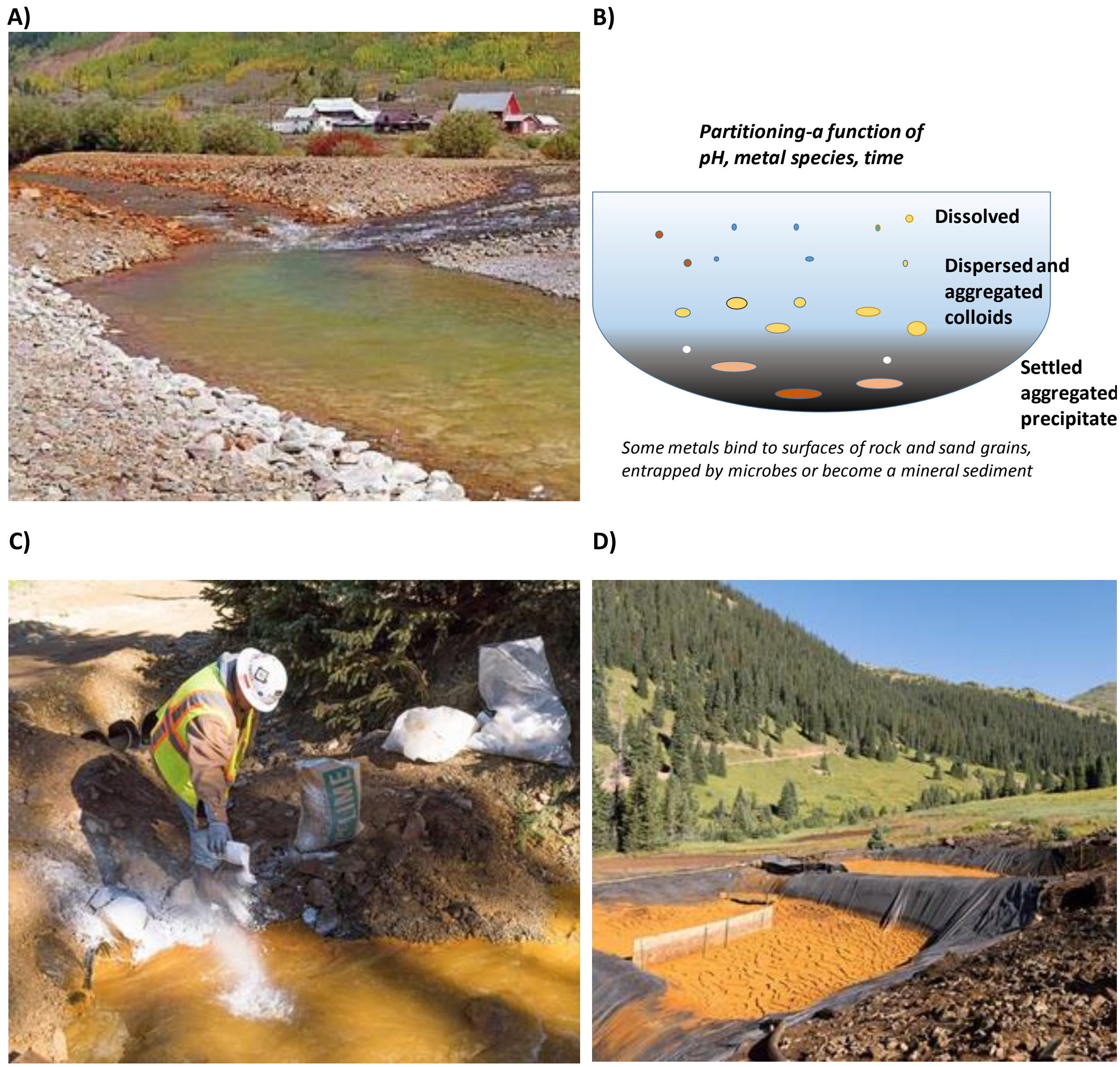


Figure 1-5. A) Acid mine drainage has routinely affected the Animas River at the confluence with Cement Creek in Silverton, Colorado. B) Iron and aluminum hydroxides form when the highly-acidic Cement Creek water mixes with the more alkaline Animas River; the yellowish color is colloidal precipitates, termed "yellow boy," which are small particles suspended in a liquid. The neutralization seen in Cement Creek is the same chemical process used to treat acid mine drainage (AMD), where C) basic materials are added to the AMD D) to neutralize and precipitate solids as sludge. The photographs of remediation at Gold King Mine were taken post release.

Remediation. For decades, stretches of the Upper Animas River and its tributaries have not supported healthy communities of fish and other aquatic life. Since 1998, Colorado has designated portions of the Animas River downstream from Cement Creek as impaired for certain heavy metals, including lead, iron, and aluminum. Colorado has developed water quality cleanup plans under the federal Clean Water Act to address mining contaminants. Numerous projects have been implemented to control "nonpoint sources" of mining waste on public and private lands with funding from EPA's nonpoint source control grant program (under Section 319 of the Clean Water Act) and other public and private sources (BLM 2007, BOR 2016).

The USGS AMD research project in the Animas River watershed was aimed at better informing remediation activities by identifying those mines that contributed the greatest to AMD pollution and that could be most readily reclaimed (Church *et al*. 2007; BOR 2015). The USGS study determined that the bulk of the metals loading to the Animas River was generated from about 80 of the thousands of mining-related sites inventoried in the watershed. The State of Colorado Water Quality Control Division and the EPA have also conducted studies to assess impairment and remediation opportunities.

1.3 Gold King Mine Release

The Gold King Mine (GKM), located in the Cement Creek basin of the Silverton caldera, is one of the 80 sites determined to be contributing to metals loading in the Animas River watershed. In the project remediation plan, the Colorado Division of Reclamation, Mining and Safety (DRMS) described this mine as one of the worst draining mines in the state of Colorado due to extremely poor water quality and very high outflow rates (see DRMS project summary provided in BOR 2015). Outflow rates have varied considerably over time, with most recent estimates varying from 300 to 480 gallons per minute (gpm). Using an outflow rate of approximately 300 gpm, as measured in 2006 (BOR 2015), the daily discharge of AMD from the Gold King Mine is approximately 432,000 gallons per day and almost 160 million gallons per year. The mine's effluent was treated at times in the past, but has been largely uncontrolled in the last decade. The EPA and DRMS initiated a comprehensive treatment project at Gold King Mine in 2014.

Figure 1-6. Equipment operator working at the entrance to Gold King Mine as the mine water is spilling from the mine entrance.

On August 5, 2015, equipment operators were performing excavations as part of a preliminary site investigation by the Colorado Department of Public Health and Environment (CDPHE) and EPA to develop plans for reopening the mine for active remediation. The mine entrance and a drain that had been previously installed were blocked by emplaced fill, as well as rock and soil debris that had slipped from the slope above (BOR 2015). As the equipment operator disturbed the pile at the mine entrance, a small trickle of water grew quickly into a flood that rapidly drained the mine pool collected behind the blockage (Figure 1-6). Over the next 7 hours, a large volume of water, with very low pH and high concentrations of dissolved metals, would drain from the mine into Cement Creek. Adding to the severity of the event, the initial flood of water eroded soil and rock debris from the mine portal and pyritic rock and soil from the adjoining waste-rock dump. The flood also swept away the road-embankment fill of several downstream, unpaved road stream crossings in its path to Cement Creek, increasing sediment loads (BOR 2015). The flood may have also entrained sediments and any associated metals from the Cement Creek channel.

1.3.1 Travel of the Gold King Mine Release Through the River System

Although the headwaters of the Animas River routinely receive acid mine drainage from hundreds of mines each day, this release event was unique, although not unprecedented (Jones 2007). The uncontrolled release at Gold King Mine occurred over a short period of time, sending a large volume of AMD traveling rapidly as a plume, carrying volumes of very acidic water contaminated with high concentrations of metals much farther downriver than had occurred in recent times.

As soon as the plume exited Cement Creek and joined the Animas River, the same geochemical reactions routinely observed near Silverton, Colorado began to neutralize the plume's acidity and trigger the geochemical reactions that form iron and aluminum oxides. The large volume of this release turned the river a bright yellow color, which intensified as the plume traveled (Figure 1-7). The plume of mine water subsequently worked its way through 190 km of the Animas River, where it joined the San Juan River at Farmington, New Mexico, 3 days later. From there, the plume continued 360 km westward towards Lake Powell. Plume visibility was lost through much of the San Juan River due to high sediment loads carried at the same time.

1.3.2 Impacts of the Gold King Mine Release on Water Quality

While the Gold King Mine release moved fairly quickly through the river system, it left behind deposits of metal contaminants that were visible long after the plume had passed. There was considerable public concern about these metal contaminants and their effects on water quality throughout the river system. The release potentially impacted many communities within the states of Colorado, New Mexico, and Utah and the tribal reservation lands of the Southern Ute Indian Tribe (SUIT), the Ute Mountain Ute Tribe (UMUT), and the Navajo Nation (Figure 1-8). Many communities and individual residences in the area of the release obtain their domestic source of water from the river or wells drilled into its adjacent floodplain. Irrigation also draws heavily from the Animas and San Juan Rivers in August (when the release occurred), especially along the alluvial valleys from Durango, Colorado through Farmington New Mexico. Recreational boating and fishing are popular on the Animas and San Juan Rivers and subsistence fishing from these waters is also important. The release and movement of the plume through the system was reported widely in the media as it occurred, and public awareness and concerns for water safety were very high; concerns for water safety remain very high, due to the potential for longer-term impacts.

Photo: Jerry McBride Durango Herald

Figure 1-7. Photograph of the Gold King Mine plume as it moved through the Animas River at Bakers Bridge north of Durango, Colorado. Chemical processes of acid neutralization were ongoing and the colloidal solids that formed stained the river an intense yellow color.

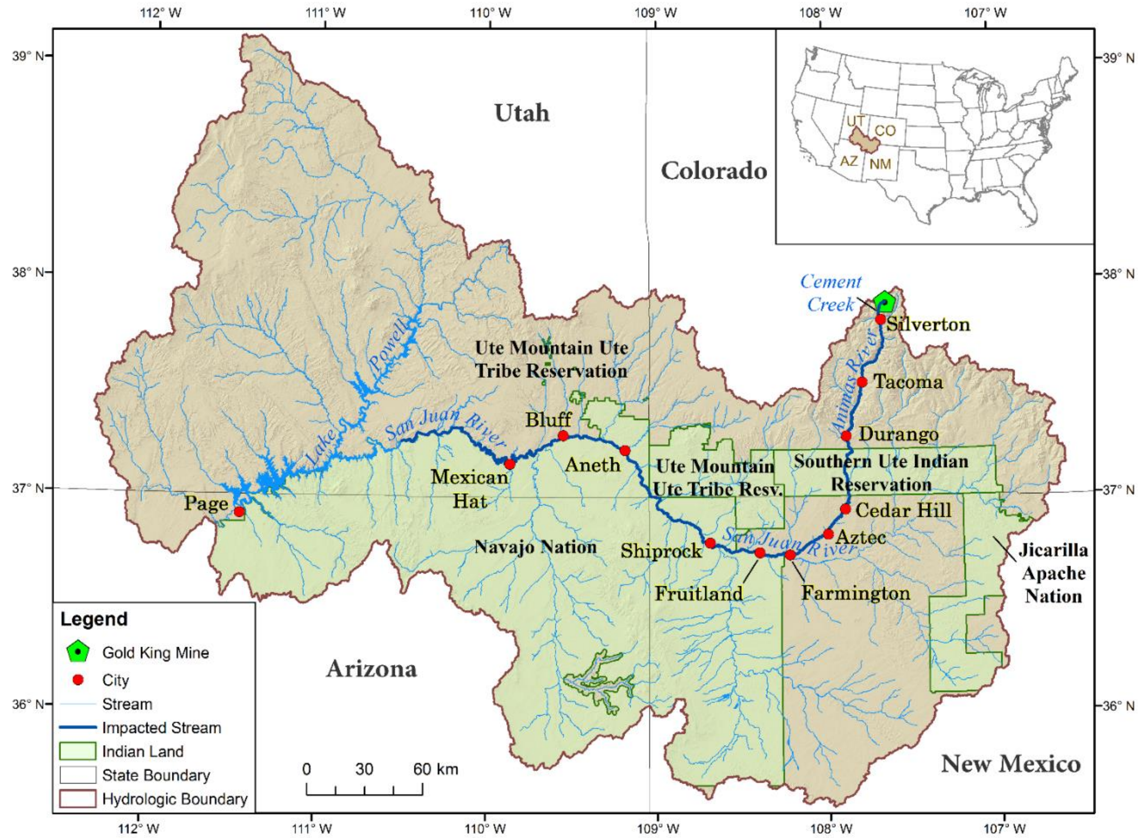


Figure 1-8. General map of the Animas River, San Juan River, and Lake Powell area affected by the Gold King Mine release. Many communities in this region rely on the rivers affected by the release for domestic water, water for agriculture and livestock, and recreation.

EPA established a Unified EPA Area Command that coordinated the activities of the three EPA Regions that serve the area (Regions 6, 8, and 9), state agencies, and communities and tribes. Water use for domestic supplies, irrigation, livestock, and recreation were curtailed while alternative water sources were provided for a number of days during and after the passage of the plume. The EPA, states, and tribes also mobilized monitoring programs to sample for metals contamination in the river water and sediments, irrigation ditches, and wells throughout the Animas and San Juan Rivers. The initial monitoring focused on determining the extent and duration of contamination to inform management decisions. Although the monitoring was largely uncoordinated among organizations, they used similar methods, following protocols already in place for various ongoing monitoring programs. Collectively, they amassed a significant data record of water and sediment quality during the plume and in the months afterward. Coordination increased with time, and these organizations have continued monitoring to assess the longer-term effects of the release in the year following the release.

Research Needs. There were many concerns regarding the Gold King Mine release and the plume of AMD that it generated as it passed through the 550 km of the Animas and San Juan Rivers. Important questions raised by the affected communities included:

- What was the composition and amount of contaminants released from the Gold King Mine?
- How was water quality affected?

- What was the short- and long-term fate of metals released to the river?
- What was the potential for water user exposure to adverse levels of metals?
- Will deposited material be released into the river and will it have delayed impacts?
- Were groundwater, drinking water, or irrigation sources impacted?
- Have metal concentrations in the water and sediment returned to pre-event levels?

In order to address these questions, it was necessary to reconstruct the type of metals and how much was introduced into the rivers during the release, characterize metals concentrations as the plume of materials traveled through the rivers, and determine how much material was deposited in the rivers and where. This is accomplished with analysis of monitoring data supported by software-based models that assist detailed predictions of water and metals movement and chemical transformations in natural environments.

1.4 EPA Gold King Mine Transport and Fate Study Report

Given the broad geographic scope of the Gold King Mine release and the dynamic reactions within the plume as it moved, there was a need to integrate the large amount of data collected by a number of organizations into a comprehensive analysis of the Gold King Mine release and its transport and fate within the river system. This report documents the results beginning with the release event and plume travel in August 2015 and assesses water quality effects through data received as of November 2016.

The objectives of the transport and fate study and the methods and data used are detailed in Chapter 2. Data analysis and modeling are divided into a series of chapters that follow. Information builds sequentially with each chapter, as the chapters utilize results from analyses presented in earlier chapters.

Information on data and the modeling approaches is introduced in Chapter 2. The initial Gold King Mine release volume and the mass and composition of the plume created during the release is assessed in Chapter 3. Chapter 4 discusses the characteristics of the plume dynamics as it moved through the Animas and San Juan Rivers, based on available data and modeling efforts. Metals concentrations and transformations within the river as the plume traveled through the river system are analyzed in Chapter 5, and Chapter 6 assesses mass transport, metals deposition, interaction with the streambed.

Chapters 7 through 9 of the report address the potential exposures to metals contaminants during the Gold King Mine plume, water and sediment quality impacts, and potential groundwater effects. The exposures analysis of the release event on river water quality is presented in Chapter 7. The potential impacts of the release from Gold King Mine, supported by plume simulations, is evaluated relative to beneficial uses via water quality criteria. Chapter 8 explores the potential for groundwater contamination due to the exchange of water between the river and the river alluvial floodplain where many wells draw water for a multitude of uses; the groundwater analysis is largely independent of other chapters. Trends observed in metals concentrations and their effect on water and sediment quality are assessed for the year following the release in Chapter 9. This analysis includes mobilization of material deposited in the river system by the Gold King Mine plume during the 2016 snowmelt period.

Chapter 10 provides a summary and synthesis of the fate and transport study and is followed by a list of references used in the study; appendices providing greater detail on the data sources, methods, and analyses conducted as part of the effort; and a glossary of key terms.

CHAPTER 2 STUDY OBJECTIVES, DATA, AND METHODS

Acidic water and metals were suddenly released in an event that drained a large volume of water from the Gold King Mine in the San Juan Mountains of southern Colorado over a matter of hours. The release sent a slug of metal contaminants into the upper reaches of Cement Creek that drains to the Animas River. The release then flowed as a plume for approximately 550 kilometers before eventually reaching its terminus in Lake Powell in Utah. Metals composition was dynamic in space and time during plume travel through the rivers and for some period after it passed. Transport and movement of the release would depend on hydrodynamic and geochemical processes that would determine deposition within the river system and subsequent water quality effects.

2.1 Goals and Objectives

A primary goal of this transport and fate study was to quantify and characterize the metals associated with the Gold King Mine release as they traveled through the river system and to evaluate the attenuation and later release of metals through deposition and resuspension processes. Another primary goal was to assess the impact of contaminants on water quality during the plume event and in the year following the event, as the affected rivers responded to plume material deposited on the riverbed. Specific study objectives were to:

- Quantify the release at the GKM source;
- Quantify transport and fate of metals in the Animas and San Juan Rivers;
- Characterize potential exposure to metal concentrations as the plume traveled through the system;
- Assess the status of metals in water and sediments in the months after the event; and
- Evaluate mobilization of metals deposited in the streambed during high flows in storms or seasonal snowmelt.

An activity central to achieving these objectives was to simulate the plume of released metals as it traveled through the Animas and San Juan Rivers. This was accomplished by combining empirical analysis of information assembled from multiple data sources with water quality modeling to characterize the release event and deposition of metals within the rivers.

To quantify the Gold King Mine release and transport of metals through the rivers, key characteristics of the contaminated plume had to be estimated at many river locations in the impacted rivers (Figure 2-1). These included:

- Time of travel, as it provided context to the water samples that were collected at each location;

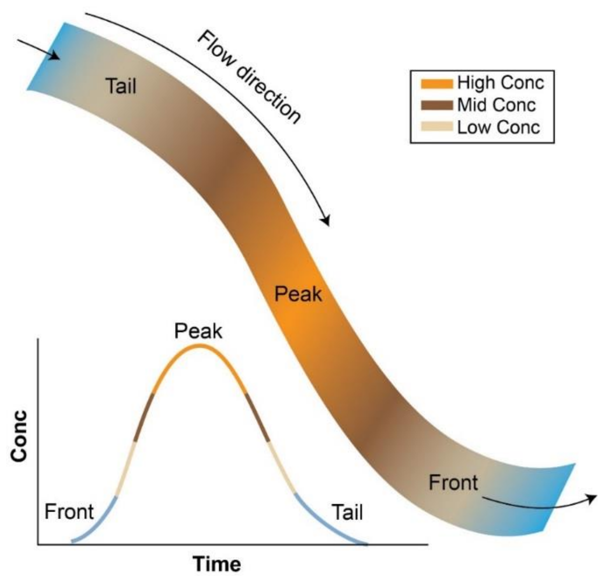


Figure 2-1. Conceptual drawing of what the Gold King plume was. The Gold King plume consisted of a slug of acid water with elevated concentrations of dissolved and colloidal/particulate metals, possibly including entrained sediments that travelled as a coherent mass through the Animas and San Juan Rivers. The plume had a beginning and end with peak concentration within that period. Plume characteristics and metal concentrations changed as it moved through the rivers. A central product of the analysis was simulation of the plume throughout the river system.

- Peak concentrations, as they carry the bulk of the metals mass;
- The trace of metals concentrations for the duration of the plume, as it determined potential exposure due to the magnitude and duration of metals concentrations.

The mass or weight of material that was released from the mine and transported during the plume and in transit through the rivers could be determined from these plume characteristics when combined with available streamflow volume. Study objectives were accomplished with a combination of empirical analysis of metals collected from river water and sediments and other relevant data during and after the Gold King Mine release.

A considerable amount of water and sediment data were collected during and following the release by multiple agencies and organizations, enabling the characterization of the Gold King Mine plume and assessment of post-event water and sediment quality conducted in this study. The spatial and temporal distribution of water and sediment sampling in the Animas and San Juan Rivers following the spill from the Gold King Mine was unprecedented in the annals of an acid mine drainage-related incident.

This chapter identifies the available data to characterize the Gold King event and subsequent water quality impacts and introduces the empirical and mechanistic modeling approaches used to simulate the Gold King plume.

2.2 Study Area

The study area included the Gold King Mine site, as the source of the release; Cement Creek, which initially received the release; the length of the Animas River between its confluence with Cement Creek and its confluence with the San Juan River in Farmington, New Mexico, and the San Juan River, from its junction with the Animas River to Lake Powell in western Utah. The total river length between Gold King Mine and Lake Powell is approximately 550 km.

Because this was a release event, the study focused on the river continuum within the affected river length and does not address general watershed inputs of water or metals, except as initializing conditions on water volume or constituent concentrations at key river junctions. River flow characteristics were obtained from multiple USGS gages distributed throughout the study area, precluding the need for watershed-scale modeling to generate streamflow. The study also investigated the river interaction with groundwater in the alluvial floodplains adjacent to the river, in several segments of the Animas River.

The rivers flow through many different geomorphic settings, which influenced the characteristics of the Gold King plume as it traveled and deposited material along its path (Figure 2-2). The entrance to Gold King Mine lies at an elevation of 11,400 feet in the San Juan Mountains. The release spilled into a headwaters tributary of the Animas River (i.e., the North Fork of Cement Creek) below the mine entrance and then traveled rapidly through 12.5 km of a steeper mountain stream before joining the Animas River in the valley where the town of Silverton is located. From there, the Animas River flows southward for approximately 50 km through a steep and narrow canyon carved into Precambrian basement rocks, where it is characterized by riffles, cascades, and falls. The river abruptly exits the canyon onto a wide alluvial valley at Baker's Bridge on Route 250, about 30 km north of Durango, Colorado. Upon exiting the canyon, the channel is heavily braided for about 10 km before establishing a meandering form that persists to Durango. The river becomes more tightly constrained and follows a straighter course within the incised valley from Durango, Colorado to Farmington, New Mexico, located 190 km from the Gold King Mine.

Headwaters of the Animas River

Animas River Canyon in San Juan Forest

Animas River south of Bakers Bridge, Colorado

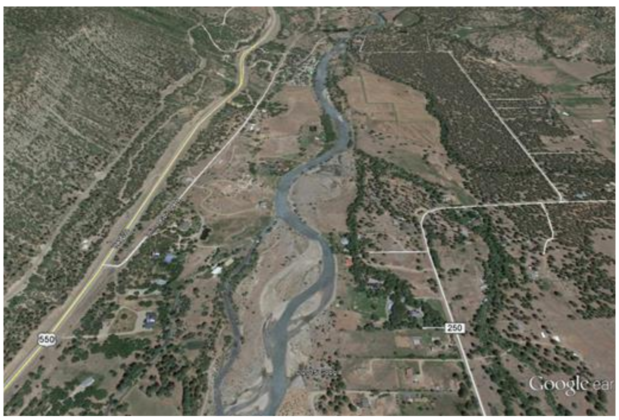


Image from GoogleEarth

Animas River south of Durango, Colorado

San Juan River upstream of Farmington, New Mexico

Photo: UDEQ

San Juan River west of Montezuma, New Mexico

Figure 2-2. Photographs of river channels in the Animas and San Juan Rivers. The Gold King Mine released a large volume of acid mine drainage into the headwaters of the Animas River in San Juan County near Silverton, Colorado. The plume of contaminated water traveled the length of the Animas River through a diverse river morphology that influenced where metals deposited. The Animas joins the San Juan River in Farmington, New Mexico. The plume traveled 550 km until it eventually flowed into Lake Powell in Utah.

Most of the population within the Animas River basin lives within or adjacent to the alluvial valley that includes the population centers of Durango, Colorado; Aztec and Farmington, New Mexico; and portions of the Southern Ute Indian Tribe (SUIT) reservation. Irrigated agriculture is a major land use in the middle and lower reaches of the Animas and San Juan Rivers, withdrawing water from the rivers through a system of ditches and canals. There are also numerous wells drilled into the river floodplains that supply public, domestic, and irrigation users.

The Animas River joins the San Juan River at Farmington, New Mexico. The San Juan flows through the states of New Mexico and Utah and the tribal lands of the Navajo Nation and Ute Mountain Ute Tribe (UMUT) (Figure 2-3). The river flows westerly towards its junction with the Colorado River within a valley that, for most of its length, is shallowly incised into a series of sedimentary rock formations at various depths. Flow upstream of Farmington is regulated by the Navajo Dam. Within this generally arid area, the river valley supports irrigated farming and communities downstream as far as Shiprock, New Mexico. A large canal that withdraws from the San Juan River near Waterflow, New Mexico between Fruitland and Shiprock supplies water to the area. The San Juan River is approximately 360 km from its confluence with the Animas River to where it ultimately flows into Lake Powell at approximately RK 550, created by the Glen Canyon Dam at Page, Arizona.

2.3 Water and Sediment Sampling and Laboratory Analysis

The Animas and San Juan Rivers were sampled intensively at many locations during passage of the Gold King Mine plume and in the next several months after it passed. Monitoring has continued at select locations in the spring and summer of 2016 at lower intensity than in the months after the event. These efforts focused on sampling water and sediments for concentration of the 23 metals on the priority Metal/Cyanide Target Analyte List (TAL), plus molybdenum (Mo).

2.3.1 Sampling Entities/Data Providers

Almost as soon as the Gold King Mine release occurred, the EPA mobilized field crews who sampled water quality and river sediments to be analyzed primarily for metals. Crews arrived at Cement Creek, in the headwaters where the spill occurred, within five hours of the release. Sampling was rapidly expanded to the rest of the Animas and San Juan Rivers.

EPA Regions 6, 8, and 9 coordinated sampling within their assigned geographies, and the Colorado Department of Public Health and Environment (CDPHE), the New Mexico Environment Department (NMED), and the Utah Department of Environmental Quality (UDEQ) collected water samples as the plume passed through each state. The Navajo Nation Environmental Protection Agency (NNEPA), Southern Ute Indian Tribe, and Ute Mountain Ute Tribe collected samples where the rivers traversed tribal lands. The U.S. Geological Survey (USGS) collected samples at several stream gages, and non-governmental organizations (NGOs) sampled water within the Animas River in the Durango area. We refer to these agencies and organizations (Table 2-1) collectively as “data providers”. The trnsport and fate analyses of the Gold King Mine release relied on data collected by these organizations.

2.3.2 Sampling Locations

Water and Sediment Field Sampling Locations. Collectively, the data providers sampled water and sediment quality at numerous locations covering the entire river length within the Animas and San Juan Rivers, as well as in some locations in Lake Powell during passage of the Gold King Mine plume and in the months following. The general location of the rivers and sampling locations are shown in Figure 2-3. Sampling location and frequency varied during the release and with implementation of the EPA (2016) conceptual monitoring plan.

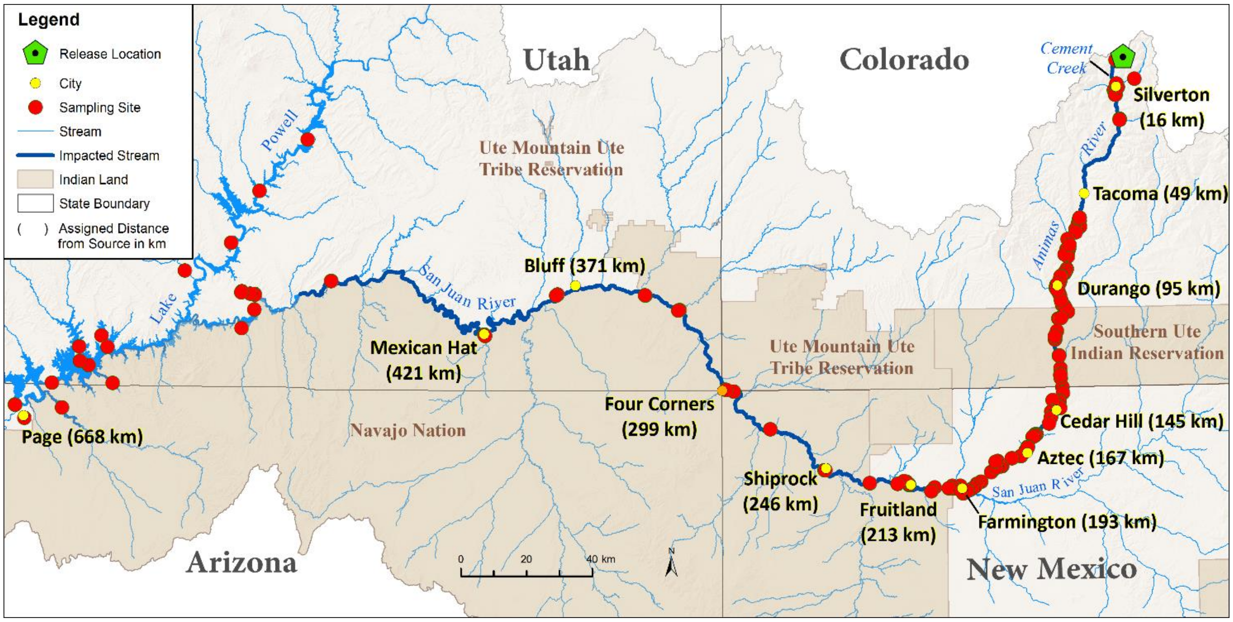


Figure 2-3. Water and/or sediment samples were collected at numerous locations along the Animas and San Juan Rivers by EPA Regions 8, 6, and 9, states, tribes, municipalities and NGOs. Red dots show locations where one or more samples were collected during the Gold King plume and in the year following the release.

Sampling from the mainstems of the Animas and San Juan Rivers has been the primary focus for monitoring since the GKM release. Approximately 180 river locations have been sampled either once or repeatedly. Sampling locations for surface water and sediment are shown by organization for the Animas River in Figure 2-4 and the San Juan River in Figure 2-5. Sampling sites were distributed throughout the river system, although populated areas such as Durango, Colorado and Farmington, New Mexico were sampled more intensively. There are long distances between sites in river segments that are very remote or with difficult access, including the canyon reaches of the upper Animas River and portions of the San Juan River.

A number of additional sites were sampled for a brief period during or immediately following the plume, as part of agency efforts to understand and manage public exposure to contaminants in the water and sediments. Short-term water sampling was conducted at 16 water supply intakes and off-channel ponds, and sediment was sampled in 68 irrigation ditches. Many of the irrigation sites were measured once or only a few times until it was determined that the water was safe to use. Some water supply intakes have continued to be routinely sampled.

Each data provider included the geographic coordinates (latitude, longitude) of sampling sites. A complete, integrated list of the 264 sampling sites is provided in Appendix A. Some analyses in this report focus on a subset of sites where sampling was more intensive during and since the release. Information for these sites, including assigned distance from the Gold King Mine, are provided in Table 2-2.

Monitoring of water and sediments has continued since the initial GKM release event. Longer-term sampling has focused on a more limited set of river sites to determine whether water and sediment metals concentrations have returned to pre-event conditions. Many of these locations are part of ongoing or historic monitoring programs implemented by the data providers for various objectives, including several in the headwaters of the Animas River that were initially part of the USGS Acid Mine Drainage research initiative (Church *et al.* 2007) and continue to be part of remediation studies.

Table 2-1. List of Data Providers and Contributed Data Used in the Gold King Mine (GKM) Transport and Fate Study

	Data Providers			Metals Sampling							
				Surface Water				Sediment			
	Entity	Abbreviation	Primary Sampling Area During GKM Plume	GKM Plume Event (Aug 5-20)	Post-Event (Aug 21-Oct) 2015	Spring 2016 Snowmelt through Fall 2016	Pre-Event/ Historic	GKM Plume Event (Aug 5-20)	Post-Event (Aug 21-Oct) 2015	Spring 2016 Snowmelt through Fall 2016	Pre-Event/ Historic
Federal	EPA Region 8	EPA R8	Upper and Middle Animas in Colorado	X	X	X	X[1]	X	X	X	X[1]
	EPA Region 6	EPA R6	Lower Animas in NM; Upper San Juan near Farmington. NM	X	X	X		X	X	X	
	EPA Region 9	EPA R9	Upper, Middle and Lower San Juan	X	X	X		X	X	X	
	U.S. Geological Survey	USGS	Upper and Middle San Juan in NM	X	X	X	X				X
State	Colorado Department of Public Health and Environment	CDPHE	Upper and Middle Animas in Colorado	X	X	X	X	X		X	
	New Mexico Environment Department	NMED	Lower Animas and Upper San Juan in New Mexico	X		X	X				X
	Utah Department of Environmental Quality	UDEQ	Middle and Lower San Juan in Utah	X	X	X	X	X	X		
Tribal	Southern Ute Indian Tribe	SUIT	Middle Animas on tribal lands	X	X	X	X				
	Ute Mountain Ute Tribe	UMUT	Middle San Juan on tribal lands	X			X				
	Navajo Nation Environmental Protection Agency	NNEPA	Upper, Middle, and Lower San Juan on tribal lands	X	X		X	X	X		
Municipal	City of Farmington	CoF	Water intakes on Animas at Farmington	X	X	X					
NGO[2]	Mountain Sudies Institute	MSI	Durango	X	X			X			
	Rivers of Colorado Water Watch Network	RCWWN	Mid Animas and Durango	X	X		X				

[1] SADIE Superfund data
[2] Non-governmental organization

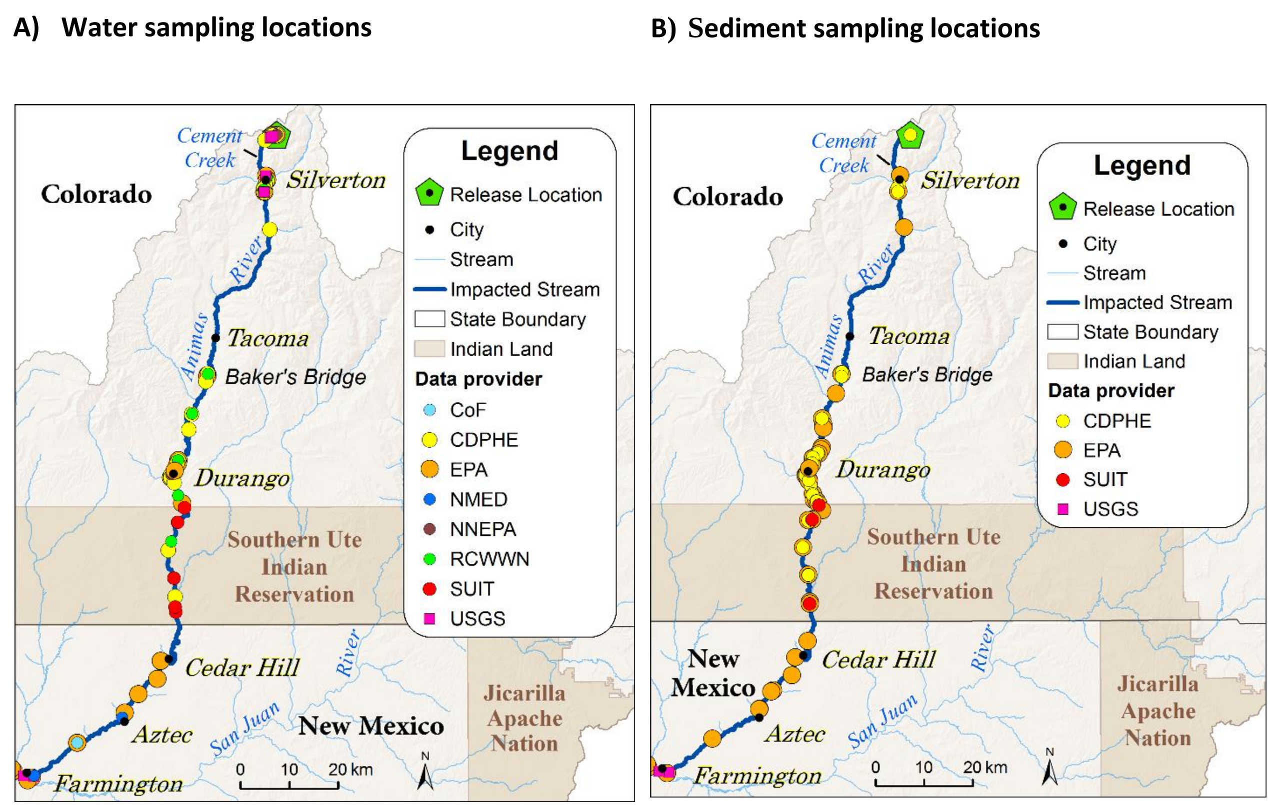
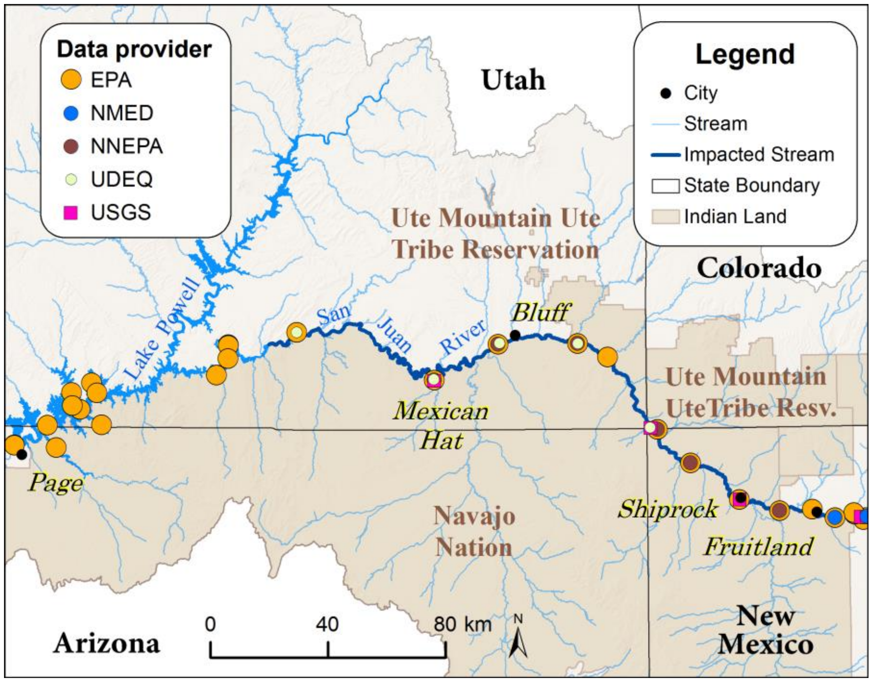


Figure 2-4. Location maps of sites where A) surface water and B) sediment were sampled in the Animas River, identified by data provider. Some locations were sampled in the same area by multiple agencies. See Appendix Table A-12 for a complete list of sites and associated information including data provider, media, and assigned distance from source.

A)



B)

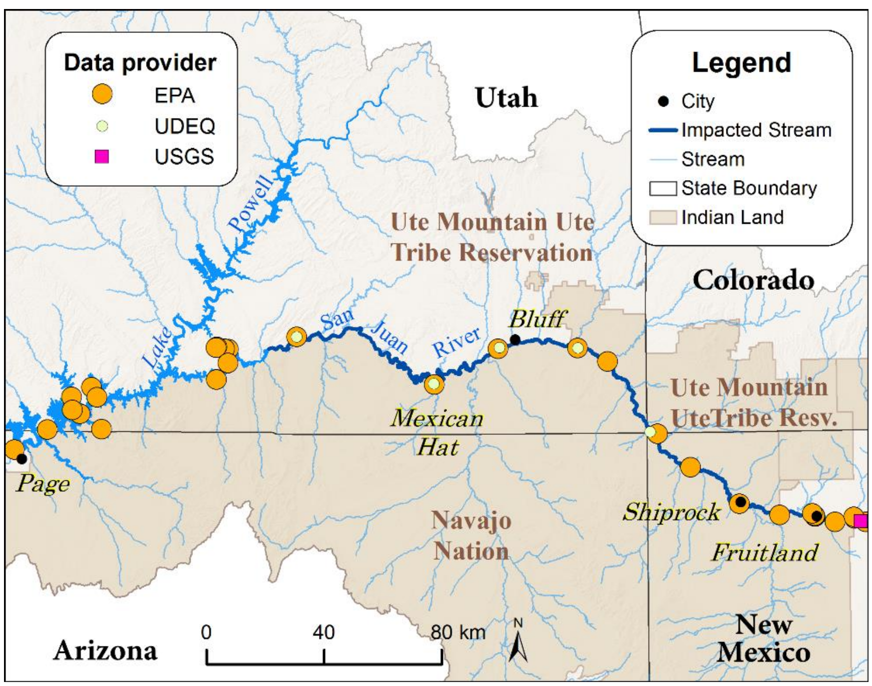


Figure 2-5. Location maps of sites where A) surface water and B) sediment were sampled in the San Juan River, identified by data provider. Some locations were sampled in the same area by multiple agencies. See Appendix Table A-12 for a complete list of sites and associated information including data provider, media, and assigned distance from source.

Table 2-2. Primary Water and Sediment Sampling Sites Assessed During the Gold King Mine (GKM) Plume Passage and in the Year Following the Event. (A complete list of sampled sites is in Appendix A.)

Agency	Landmark	Site ID	Distance from GKM Source (km)
EPA	Gold King Mine	CC06	0.0
EPA	Cement Creek	CC48	12.5
USGS	Cement Creek in CO	09358550	12.5
EPA	Below Silverton, CO	A72	16.4
USGS	Below Silverton, CO	09359020	16.4
USGS	Above Tacoma, CO	09359500	48.8
EPA	Bakers Bridge, CO	Bakers Bridge	63.8
EPA	32nd St. Bridge	32nd St Bridge	91.8
EPA	Durango, CO	ROTARY PARK	94.2
USGS	At Durango, CO	09361500	95.1
SoUtes		AR 19-3	104.2
SoUtes		AR 16-0	109.0
USGS	Near Cedar Hill, NM	09363500	129.6
SoUtes		NAR 06	131.5
EPA	Cedar Hill, CO	ADW-022	147.5
EPA		NSW-020	151.6
EPA		ADW 010	162.9
New Mexico	Aztec, NM	66Animas028.1	164.1
USGS	Below Aztec, NM	09364010	167.4
EPA		FW-012	176.6
New Mexico	Farmington, NM	66Animas001.7	189.4
USGS	Animas at Farmington, NM	09364500	189.6
EPA	Farmington, NM	FW-040	190.2
USGS	San Juan at Farmington, NM	09365000	193.0
EPA	Farmington, NM	LVW-020, SJLP	196.1, 196.2
New Mexico	Farmington, NM	67SanJua088.1	204.4
EPA		LVW-030	204.5
EPA	Fruitland, NM	SJFP	214.4
USGS	At Shiprock, NM	09368000	246.1
EPA	Shiprock, NM	SJSR	246.3
EPA		SJDS	272.5
EPA	Four Corners, NM	SJ4C	295.8
USGS	At Four Corners, CO	09371010	298.5
UDEQ	Four Corners, CO	160 Xing	298.7
EPA		SJME	333.2
UDEQ	Near Montezuma, UT	Utah near Montezuma	345.7
EPA		SJMC	345.8
UDEQ		Sand Island	377.1
EPA	Bluff, UT	SJBB	377.6
EPA	Mexican Hat, UT	SJMH	421.3
USGS	Near Bluff, UT	09379500	420.9
UDEQ	Mexican Hat, UT	Clay Hill Ramp	510.7

Table 2-3. Sonde Parameters. Six sondes were operated during the Gold King plume. NMED operated two sondes in the lower Animas between river kilometer (RK) 164 and 190 and one in the San Juan River at RK 204 during the plume. The Southern Ute Indian Tribe operated three sondes as the river flowed through tribal lands in the mid Animas between river kilometer (RK) 103 and 132.

Sonde Parameters	New Mexico Environment Department	Southern Ute Indian Tribe
pH	X	X
Specific Conductance	X	X
Temperature	X	X
Turbidity	X	
ODO, Saturated	X	X
ODO, Concentration	X	X

Sonde Locations. Sondes were deployed in six locations - five in the lower Animas River and one in the upper San Juan River - during the passage of the Gold King Mine plume. The New Mexico Environment Department operated two sondes in the lower Animas River between river kilometer (RK) 164 and 190 and one in the San Juan River during the plume. The Southern Ute Indian Tribe operated three sondes, as the river flowed through their tribal lands in the mid Animas River between RK 103 and 132 (Figure 2-6).

A sonde is a water quality monitoring instrument that may be stationary or move up and down in the water and typically measures multiple water quality parameters on a continuous basis and records them electronically. Each sonde had room for six onboard probes, which varied by data provider (Table 2-3).

Figure 2-6. Map of locations of continuously recording water quality measurement sondes during the Gold King plume.

Streamflow Gage Locations. Streamflow was essential to quantify the passage of the Gold King Mine release through the river system. There are 13 USGS stream gages located in the Animas and San Juan Rivers that were used to inform these analyses (Figure 2-7; Table 2-4). There is a USGS gage located in Cement Creek, where the spill occurred, that enabled accurate determination of the released volume. USGS flow data at the time of the start of the plume was used to initialize the boundary locations (i.e., Cement Creek, upper Animas River above Cement Creek, and the San Juan River above its confluence with the Animas River). Gage data from the 10-day period following the release were used to calibrate velocity of the river. Long-term gage records were used to simulate potential mobilization of metals during storms and spring snowmelt and to calibrate the water quality model.

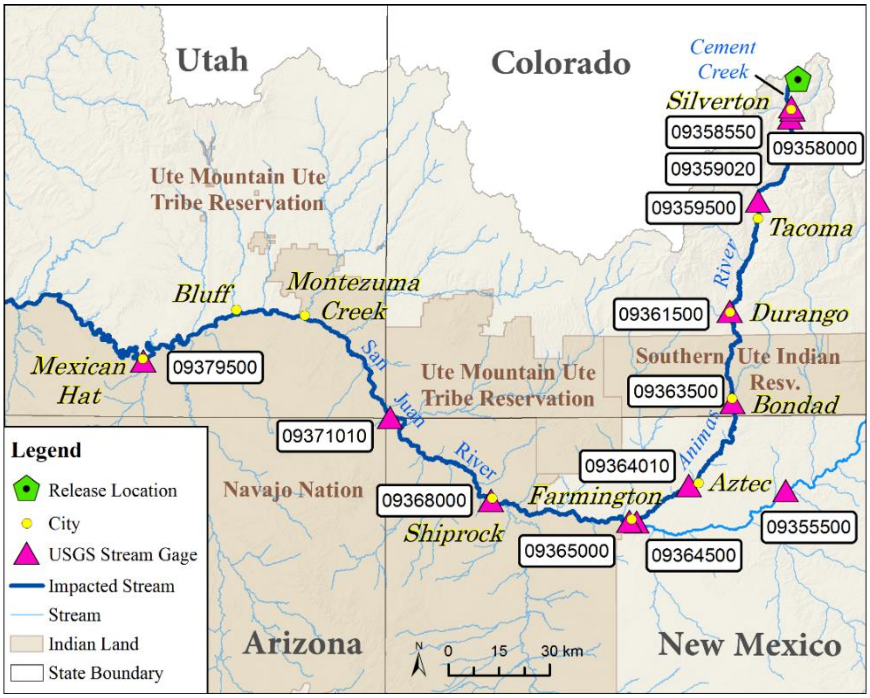


Figure 2-7. Map of USGS gage locations that supplied flow data for plume travel and volume modeling.

Table 2-4. US Geological Survey Streamflow Gages in the Animas and San Juan Rivers.

USGS Site Number	Station Name	State	Longitude	Latitude	River Kilometer	Contributing Watershed Area (mi^2)	Contributing Watershed Area (km^2)
09358550	Cement Creek at Silverton, CO	CO	-107.6636723	37.8197187	12.5	20	52
09358000	Animas River at Silverton, CO[1]	CO	-107.6592278	37.81110773	13.9	71	183
09359020	Animas River Below Silverton, CO	CO	-107.6675615	37.7902746	16.4	146	378
09359500	Animas River Above Tacoma, CO	CO	-107.7806204	37.57027662	48.8	348	901
09361500	Animas River at Durango, CO	CO	-107.8803445	37.27916882	95.1	692	1,792
09363500	Animas River Near Cedar Hill, CO	CO	-107.8742321	37.03805772	129.6	1,090	2,823
09364010	Animas River Below Aztec, NM	NM	-108.0197909	36.81833707	167.4	1,301	3,370
09364500	Animas River at Farmington, NM	NM	-108.2020184	36.72139183	189.6	1,360	3,522
09355500	San Juan River Near Archuleta, NM[2]	NM	-107.6981135	36.8013939	191.9	3,260	8,443
09365000	San Juan River at Farmington, NM	NM	-108.2256302	36.72278043	193.0	7,240	18,752
09368000	San Juan River at Shiprock, NM	NM	-108.7323112	36.79222043	246.1	12,900	33,411
09371010	San Juan River at Four Corners, CO	CO	-109.0339923	37.00555317	298.5	14,600	37,814
09379500	San Juan River Near Bluff, UT	UT	-109.864844	37.14694612	420.9	23,000	59,570

[1] Reference gage. Not in the path of the plume. Distance measured to the confluence of Animas River with Cement Creek.
[2] Reference gage. Not in the path of the plume. Distance measured to the confluence of the Animas and San Juan rivers.

2.3.3 Sampling Schedule

Water and sediment sampling began almost as soon as the Gold King Mine release occurred and continued on varying schedules for a year following the event. Initially, sampling was oriented to support risk assessment and management actions to protect public health. Once the plume passed, sampling became more oriented to monitoring for return to pre-plume water quality and potential secondary impacts from metals that were deposited within the river system. Sampling frequency reflected that transition. To meet study objectives, we generally organized metals and water quality data collected in the Animas and San Juan Rivers into five distinct time periods (Figure 2-8).

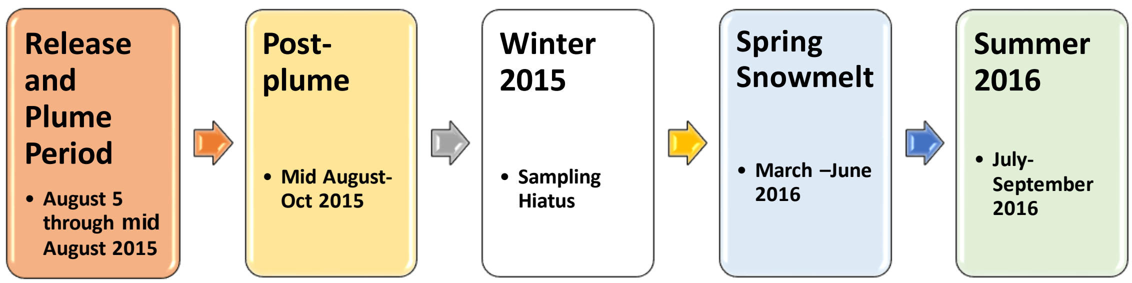


Figure 2-8. Time periods for Gold King release and post-event analyses.

Plume Period. The first sampling period included the time from the release event to the completion of the plume's movement through the Animas and San Juan Rivers. It took nine days for the plume to travel the distance from its start at the Gold King Mine in Colorado to Lake Powell in Utah, but only a few days to pass any specific location. During passage of the GKM plume, sampling frequency was at the discretion of each data provider and subject to objectives, personnel availability, and distances involved in visiting the sites they chose to sample. Timing of samples during plume movement was critical, as the bulk of the released metals moved past each location fairly quickly and concentrations rose and fell sharply within a narrow time window. Many sites were visited daily, while others were visited once or a few times. A select group of sites were sampled multiple times, in relatively short intervals, as field crews anticipated the arrival of the GKM plume. A few sites located in close proximity to one another were sampled by different data providers, whose combined visits collectively intensified sampling frequency during the plume. Analyses in this report combines samples from nearby sites, where applicable. This study largely relied on sites where metals were repeatedly sampled, a number of which have become long-term monitoring sites (Table 2-5).

Post-plume Period. The second phase of sampling, which considered the return of the river to pre-event conditions, began soon after the plume passed and continued through October 2015, when flows typically reach their lowest point. Sampling emphasis during this period was on monitoring water quality and sediment for trends and recovery at a smaller group of sites, with sampling performed daily to weekly.

Winter Sampling Hiatus. Sampling was curtailed during the low-flow winter months.

Spring 2016 Snowmelt. Observations and analyses showed that significant quantities of colloidal and sludge-like material were deposited through much of the length of the Animas River, in particular, as the GKM plume passed. EPA's (2016a) Conceptual Monitoring Plan called for more intensive monitoring during the spring snowmelt period, when flows would likely be high enough to mobilize Gold King Mine deposits and potentially generate a flush of metals contamination. State data providers resumed sampling between March and April 2016 at 1 to 2 samples per week and EPA sampled near the peak of the snowmelt hydrograph.

Summer Sampling. Periodic sampling occurred through September 2016 and is included in this report.

Pre-Event or Historic Data. Historic metals data collected prior to the GKM plume were assembled to compare and evaluate post-event trends in water quality relative to pre-existing conditions. Historic data were more variable in methods and analytes, as they had been generated for a variety of purposes over a long period of time. Metals concentration data were available at some of the same locations monitored by the data providers in connection with the GKM release. Monitoring and research conducted in the Animas River prior to the release identified pre-existing impairment and helped establish baseline conditions of water quality, sediment quality, and biological communities (e.g., Church *et al.* 2007).

Historic data were primarily available from EPA's STOrage and RETreival (STORET) database, where data providers deposit data for public access, or from the USGS. The USGS compiled all of its agency's data collected in the geographic area encompassing the Animas and San Juan River watersheds over 50+ years and made it available for support of Gold King assessments, referencing it as the USGS Gold King Mine Release Database (USGS 2016). Much of that data was not pertinent to this study's objectives, but it did provide metals concentration data from 500+ water quality and sediment samples that were helpful for trend comparisons.

2.3.4 Sampling Methods

Water Sampling. EPA field crews and other data providers primarily collected water samples by grab sampling, as illustrated in Figure 2-9. A sample bottle was dipped into the stream as far towards the middle of the stream as possible. Two samples were collected, one of which was filtered in the field and later processed for dissolved metals, and the other of which was not filtered and was later processed for "total" or "total recoverable" metals, which included dissolved and particulate fractions. Samples were preserved in the field with acid or were shipped immediately to the lab where they were acidified. Samples were held for 16 hours prior to processing. EPA laboratories checked pH upon receiving the sample, and if pH >2, acid was added and the sample was held an additional 24 hours. The complete list and links to sampling and testing methods used by individual data providers is available in Appendix A.

Table 2-5. Metal Sampling by Media for Each Data Provider. Data providers varied in metals routinely included in laboratory analysis. T is total recoverable water samples. D is dissolved water samples. S is sediment samples.

	Federal Agencies				States			Tribes		
Metal	EPA Region 6	EPA Region 8	EPA Region 9	U.S. Geological Survey	Colorado DPHE	New Mexico ED	Utah DEQ	Southern Ute Indian Tribe	Ute Mountain Ute Tribe	Navajo Nation NNEPA
Aluminum	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Antimony	T, D, S	T, D, S	T, D, S	T, D		T, D, S	T, D, S	T, D, S	T, D	T, D, S
Arsenic	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Barium	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Beryllium	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S		T, D, S
Cadmium	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Calcium	T, D, S	T, D, S	T, D, S	D	T, D	T, D, S	T, D, S	T, D, S	D	T, D, S
Chromium	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Cobalt	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S		T, D, S
Copper	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Iron	T, D, S	T, D, S	T, D, S	T, D	T, D	D, S	T, D, S	T, D, S	T, D	T, D, S
Lead	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Magnesium	T, D, S	T, D, S	T, D, S	D	T, D	T, D	T, D, S	T, D, S	D	T, D, S
Manganese	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Mercury	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Molybdenum	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Nickel	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Potassium	T, D, S	T, D, S	T, D, S	D	T, D		T, D, S	T, D, S	D	T, D, S
Selenium	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Silver	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Sodium	T, D, S	T, D, S	T, D, S	T, D	T, D		T, D, S	T, D, S	D	T, D, S
Thallium	T, D, S	T, D, S	T, D, S	T, D		T, D, S	T, D, S	T, D, S		T, D, S
Vanadium	T, D, S	T, D, S	T, D, S	T, D	T, D	T, D, S	T, D, S	T, D, S	T, D	T, D, S
Zinc	T, D, S	T, D, S	T, D, S	T, D	T, D, S	T, D, S	T, D, S	T, D, S	T, D	T, D, S

A)

Photo by Utah Department of Environmental Quality.

B)

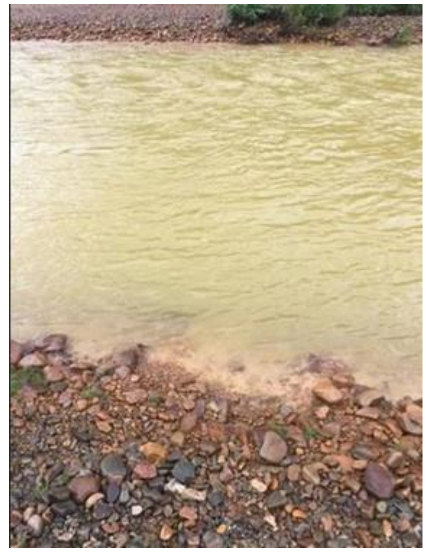


Figure 2-9. Photographs of water sampling and sediment. Data providers collected water and sediment samples that were processed for the 23 metals on the Target Analyte List (TAL). Surface waters were grab sampled except USGS samples. Sediment was sampled by digging in the top 2-5 cm of sediment. Immediately following the plume, samplers often targeted recent Gold King deposits. (A) Utah DEQ field crew collecting a grab sample. (B) Photo of example substrate at channel edge.

The USGS collected some depth-integrated samples at gage sites during passage of the Gold King Mine plume. Depth-integrated techniques provide a composited sample collected across the entire width of the channel. There can be significant variability in the concentrations of suspended materials from channel edge to center and depth integration often gives a better representation of the material in transport, unless there is little flow variation, such as in a highly turbulent stream. This technique requires specialized equipment, either safe wading conditions or over-stream access via bridge or cableway, and considerably more time to collect a sample than standard water grab sampling methods. With exception of these samples at USGS gage sites, all other water samples were collected by grab sampling.

Sediment Sampling. Sediment samples were collected by shoveling the top layer of sediment to a depth typically less than 5 cm. Protocols allowed samples to be shoveled from one location or composited from several locations at the sampling site. Because much of the initial sampling for the Gold King Mine release was performed to assess potential risk to contaminants in order to guide management actions, EPA field samplers preferentially selected obvious deposits of GKM material immediately after passage of the plume. For statistical comparisons and trend analysis, this sampling bias could influence comparisons with pre-event sediment samples. Sediment samples required no field preparation or preservation prior to analysis, other than storage at 4 °C, and there was no established holding time limitation for solid samples (U.S. EPA 2001).

Data collection focused on sampling water and sediments for the concentration of the 23 metals on the priority Metal/Cyanide Target Analyte List (TAL), plus molybdenum (Table 2-5). Most of the data providers collected and processed water samples following EPA Methods 200.7 (U.S. EPA 2001) and 200.8 (U.S. EPA 1994a), both of which have the same field sample preparation requirements. Sediment samples were generally collected and analyzed following EPA methods 6010C (U.S. EPA 2007a) or 6020A (U.S. EPA 2007b). Appendix A includes links to data sources, information about testing methods used by each provider, sampling locations and identifiers, and quality assurance documentation links.

2.3.5 Laboratory Analytes and Methods

Metals and Metalloids. Water and sediment samples were processed for elemental concentrations of the 23 TAL metals plus molybdenum using primarily inductively coupled plasma (ICP) technologies that utilize either atomic emission spectrometry (AES) or mass spectrometry (MS) instrumentation. Sample collection, preparation, and processing techniques, including sample digestion procedures, are similar for these testing technologies but vary in some details depending on the instrument. An exception was mercury, which was tested using cold vapor atomic absorption spectrometry (CVAAS), usually following EPA Methods 245.1 (U.S. EPA 1994a) and 7471A (U.S. EPA 1994c). Most samples were analyzed by contract laboratories, with the exception of the first samples from August 5, which were processed in EPA Region 8 laboratories.

Sample preparation methods described in EPA Methods 200.7 and 200.8 8 (U.S. EPA 2001, 1994a) were used for ICP-AES and ICP-MS, respectively. These methods were used for aqueous and sediment samples. Note that USGS laboratory methods for metals and metalloids include EPA Method 200.7, but USGS also applies several other protocols and technologies for these metals. Some data providers conducted laboratory analysis of a subset of the 24 metals. A general guide to the relationship between technology and methods protocols is provided in Table 2-6.

Table 2-6. Main Laboratory Tests and Technologies used for the Majority of Samples

	Matrix	Methodology	Parameter	Technology
Metals	Sediment	EPA Method 6020A	Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Mo, Ni, Se, Ag, Tl, V, Zn	ICP/MS[1]
		EPA Method 6010C	Al, Ca, Fe, Mg, K, Na	ICP-AES[2]
		EPA Method 7471A	Hg	CVAA[3]
	Surface Water (Dissolved and Total)	EPA Method 200.7	Al, Ca, Fe, Mg, K, Na	ICP-AES[2]
		EPA Method 200.8	Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Mo, Ni, Se, Ag, Tl, V, Zn	ICP/MS[2]
		EPA Method 245.1	Hg	CVAA[3]
General Analytes	Surface Water	Standard Method 2320B	Alkalinity	Titration
		Standard Method 2340B	Hardness (as $CaCO_3$)	Calculation
		EPA Method 300.0	Anions-Chloride	Ion Chromatography
			Anions-Fluoride	
			Anions-Nitrate as N	
			Anions-Sulfate	
		Standard Method 4500H+B	pH	Potentiometry
		Standard Method 2540C	Total Dissolved Solids	Gravimetry
		Standard Method 2540D	Total Suspended Solids	Gravimetry

[1] ICP/MS – Inductively Couple Plasma/Mass Spectrometry
[2] ICP-AES – Inductively Coupled Plasma-Atomic Emission Spectroscopy
[3] CVAA – Cold Vapor Atomic Absorption

Filtering. The distinction between dissolved and colloidal fractions of metals is important to many of the hydrodynamic, geochemical, and biological analyses applied in this study, including evaluation of concentrations relative to water quality criteria as an indicator of potential adverse effects. To determine the dissolved elements, the sample was filtered through a 0.45-μm pore diameter membrane filter at the time of collection or as soon thereafter as practically possible. This filtering mesh size is the standard procedure of Methods 200.7 and 200.8 and was routinely used by data providers.

Field sampled metals data were reported as total (unfiltered) and dissolved (filtered) concentrations. The dissolved concentration was subtracted from the total concentration of simultaneously-collected samples to obtain the solid phase, which is referred to as “colloidal/particulate” in this study.

Digestion. Unfiltered water samples and sediment samples must be digested prior to instrument testing. The addition of acid preserves and digests was standard across samples, while specific preparation techniques varied on the mix of acids used. Most aqueous and sediment samples were digested with solutions of nitric acid (HNO_3), with the addition of hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), or both depending on method. Samples were then heated and refluxed according to method. After extraction, the solubilized analytes were diluted to specified volumes with American Society for Testing and Materials (ASTM) Type I water, mixed, and either centrifuged or allowed to settle overnight before analysis.

Diluted samples were analyzed by the appropriate mass and/or atomic spectrometry methods as soon as possible after preparation, but after preservation sample processing can be delayed. Methods are summarized in Table 2-6. Additional details of applied metals preparation and testing methods are provided in Appendix A (Table A.10). EPA contractors reported that all water samples collected during the plume release were digested. Most sediment samples were digested following EPA method 3050B (U.S. EPA 1996.)

Digestion methods for sediments, such as EPA Method 3050B, are not a total digestion technique for most samples. It is a very strong acid digestion that dissolves almost all elements that could become “environmentally available.” By design, elements bound in silicate structures are not normally dissolved by this procedure, as they are not usually mobile in the environment.

Other Analytes. Field crews for all data providers routinely collected supporting parameters in the field, such as water pH, specific conductance, and temperature. Metals analysis was the primary analysis performed on the samples, but some data providers also analyzed samples for additional analytes (Table 2-7). Some of these analytes were added in post-event monitoring in accordance with EPA’s (2016) conceptual monitoring plan.

Geochemically-relevant parameters that could assist with equilibrium calculations related to acid mine drainage were highly desirable, but were sparse or absent in the available data. For example, measurement of acidity in the water phase, with a heated pre-oxidation step followed by titration with a base (EPA Method 305.1, U.S. EPA 1983), would allow speciation of dissolved ferrous iron (Fe^{2+}), ferric iron (Fe^{3+}), aluminum (Al^{3+}), and manganese (Mn^{2+}) and improve understanding of metal mobility and the potential for precipitation or dissolution of ferric and ferrous minerals. Sulfate (SO_4^{2-}) measurements allow calculation of ionic strength, activity coefficients, and complexation, but a limited amount of sulfate measurements were available during the plume. Selective extraction of sediments (e.g., oxalate and/or dithionite extractions) could aid interpretation of solids formed by reactions of acid mine drainage in the environment. These parameters were not generally measured during the passage of the GKM plume, but would have enhanced geochemical interpretations. Analytes and parameters other than the target metals were not commonly available.

Table 2-7. General Laboratory Analytes and Field Sampled Parameters by Data Provider

	Federal Agencies				States			Tribes		
	EPA Region 8	EPA Region 6	EPA Region 9	U.S. Geological Survey	Colorado DPHE	New Mexico ED	Utah DEQ	Southern Ute Indian Tribe	Ute Mountain Ute Tribe	Navajo Nation NNEPA
OTHER CHEMICALS AND CONSTITUENTS										
Alkalinity	X	X	X	X		X	X	X	X	X
Bicarbonate				X		X	X	X	X	X
Boron				X	X	X			X	X
Bromate					X					
Bromide					X	X				
Carbonate				X		X	X	X		X
Carbon dioxide				X			X			
Chloride	X	X	X	X		X	X		X	X
Conductivity	X	X	X	X	X	X	X	X	X	X
Cyanide						X				X
Dissolved oxygen	X	X	X	X	X	X		X	X	X
Fluoride	X	X	X	X	X	X			X	X
Hardness	X	X	X	X		X	X	X		X
Hydroxide							X	X	X	X
Nitrate/Nitrite					X	X	X			
Phosphate					X		X			
pH	X	X	X	X	X	X	X	X	X	X
Residue filterable								X		
Residue non-filterable								X		
Salinity	X	X	X			X				X
Silicon					X					
Strontium				X	X		X			
Sulfate	X	X	X	X	X	X	X		X	X
Temperature, water	X	X	X	X	X	X		X	X	X
Titanium					X					
Total dissolved solids	X	X	X	X		X	X	X	X	X
Total suspended solids	X	X	X			X	X	X	X	X
Turbidity	X	X	X	X		X	X			X
Uranium-234/235/238				X	X	X			X	X

2.3.6 Sampling Datasets

This study utilized publicly-available data gathered as of September 2016 from the data providers listed in Table 2.1. Data were obtained from publicly-accessible websites sponsored by the data providers, (as Excel or Access electronic files or occasionally, in paper format) and from EPA's STORET database, where many of the data providers submit data for public access. EPA's Gold King Mine website (https://www.epa.gov/goldkingmine) also provided a number of links to information about the release, relevant reports, and data. By October 2016, the more than 1,400 samples collected since the Gold King Mine release had been obtained and were collated into a database.

Data files varied in naming conventions, file content, and organization, but all contained key information regarding sampling and laboratory analysis, such as sampling location and time and metals concentrations, usually both dissolved and total fractions. In some instances, the files contained additional laboratory analytes and field-collected parameters. Data files contained reference to laboratory testing methods for each analyte and quality assurance documentation from the laboratory tests.

The approach was to use as much of the data as possible to provide a robust analysis of the Gold King Mine release and its transport and fate in the system. Quality assurance documentation from the data providers was compiled and reviewed. It was concluded that the critical metals data were collected and processed relatively uniformly, using the same methods (see Appendix A), which allowed data from multiple data providers to be combined.

Data were compiled, filtered for parameters of interest, and synthesized into integrated data sets. Individual files for data on dissolved and total metals in surface water and sediment were created for the Gold King Mine event, along with a separate set of files for historic data. The integrated data sets included sampling organization, sampling time stamps, and location information, including station name and identifiers and latitude and longitude. The integrated data sets can be traced to the original data through these identifiers. Analytes of interest to this study included the 23 TAL metals plus molybdenum, sulfate, and hardness (when available), and field parameters, including specific conductance, pH, turbidity, and suspended sediment concentration.

Many of the data sets had a number of sites within the watersheds, including tributaries, where monitoring was conducted for various purposes. This study only concentrated on those sites located on the Animas and San Juan Rivers and Cement Creek.

Laboratory quality assurance information was included in the data sets. The detection status of the sample was extracted. When below the detection limit, the data point was included at a value equal to the detection limit. The data file also allowed the sample to be excluded, if desired. Concentrations were adjusted to the same units of measure, generally either µg/L or mg/L for water concentrations and mg/kg for sediment concentrations.

Distance from the Gold King Mine was the main organizing and identification parameter for many analyses in the study. This important variable was added to integrate data sets. Each site was assigned an approximate distance from the plume source (i.e., the Gold King Mine entrance). Distance of each site from this starting location was established by tracing the center line of the river using the distance line tool in the interactive sampling sites map on the EPA Gold King mine website[1]. EPA mapper tool analysts had previously traced the river path placing a marker every 5 miles.

Data providers supplied the latitude and longitude of each site, presumably established with a global positioning system (GPS) device in the field. The study's geographic information system (GIS) analyst added each sampling site into the EPA-established mile marking system, measuring the distance to the nearest-established mile marker using a similar tracing technique; distances should be viewed as approximate. The term "distance from GKM source" used in this report refers to each site's distance from the Gold King Mine source (i.e., entrance). Appendix A, Table A.7 provides this distance for all sites in the compiled database. Note that the critical first leg of the Gold King Mine path from the mine entrance to the sampling site near the Cement Creek gage is 12.5 km using the EPA tool. This gage appears to actually be 11.7 km according to the National Hydrography Dataset (NHD) high-resolution data (USGS 2013), but for consistency with other measurements, the distance assigned to the gage is 12.5 km. This discrepancy is important in later estimates of travel time of the plume in this river segment, but not for general organization of study results.

We acknowledge that establishing the distance of the locations along the river course in GIS required subjective decisions by the analysts. No two analysts are likely to produce exactly the same distance, and basemaps with different resolution can lead to different distance measurements. This study used the distances established on the EPA website to maintain consistency with EPA data, as EPA was the largest provider. NHD high-resolution (USGS 2013) provides river segment measures that can be used to perform river distancing. In a test segment 12 km in length, the EPA tool distance was within 5.8% of the NHD high-resolution length for the segment. The cumulative distance from Gold King Mine to Mexican Hat, Utah determined from NHD high-resolution data was 426.4 km, and the EPA tool-based distance was 421.3 km (-1.2%).

[1] The measuring tool used in the study is part of the interactive sampling sites map available from EPA's "Emergency Response to August 2015 Release from Gold King Mine" webpage (https://www.epa.gov/goldkingmine/emergency-response-monitoring-data-gold-king-mine-incident). To use the tool, expand the Measurement menu on the left side of the map, and select the ruler icon.

Data Quality and Uncertainties. When merging data from multiple data sources, there is potential for unexplained and/or undocumented sources of variation due to differences in sampling protocols and testing methods. Data documentation suggests that the data collected in response to the Gold King Mine release were obtained and processed using similar protocols (primarily EPA Methods 200.7 and 200.8). Nevertheless, specific decisions regarding field and laboratory procedures employed by each of the data providers, including biases in sampling during the event, variations in detection limits, and so on, likely introduced unexplained variations in the merged datasets. There is generally more variability, however, in methods, analytes, and media within the historic data sets. For example, historic USGS data were collected with many different methods due to the myriad of project objectives that have guided data collection in this area over the decades.

Statistical comparisons of data collected over many years by different organizations for various purposes are subject to biases that may exist due to sampling or laboratory procedures. Establishing comparability of samples collected by multiple agencies was challenging. The timing of sampling by different data providers at the same or nearby locations was occasionally close enough during plume passage for reasonable comparison. These samples generally matched well and were within the same level of variability as duplicate samples. Generally, it appeared that the combined datasets provided the consistent data needed for robust analysis of plume movement and characteristics and post-event trend analysis. The variability among samples was generally small compared to the high concentrations of metals that passed during the Gold King Mine plume. Occasionally, there were marked differences in data between data providers during the plume; this will be discussed in the presentation of results where appropriate. Data uncertainties manifested to a greater degree in post-event analysis of water quality trends, when metals concentrations were lower, closer to background, and often at or below method detection limits for many of the metals.

The distinction between dissolved and solid phases of metals is an important basis for interpretation of Gold King Mine release effects. Metal colloids are likely to span a range of particle sizes from nearly nanoparticle-size (0.010 µm) to silt-size (as large as 40 µm). The filtering of samples using a 0.45-µm mesh is not a natural, nor necessarily effective, break for distinguishing dissolved metals from particulate metal fractions in acid mine drainage (Church *et al*. 1997), but it is standard practice called for in the laboratory procedures. Earlier USGS studies used ultrafiltration techniques to improve isolation of truly small dissolved metals (Church *et al*. 1997). It should be noted that data reported as dissolved may include a portion of colloidal particles that were able to pass through the filter.

2.4 Overview of Approach to Simulate the Gold King Plume

The Gold King Mine plume was quantified at each location by estimating the trace of metals concentrations and flow during the time period, as the plume passed. Characterization of metals concentrations (expressed in mg/L or µg/L) at a location required estimates of the time of arrival, peak, and end of plume to determine the rise and fall of metal concentrations as the plume passed (i.e., the plume shape; Figure 2-1). The concentrations of metals in the water established the potential for exposure to adverse levels of the metals carried in the Gold King Mine plume (usually characterized by water quality criteria as concentration thresholds). Potential health and ecosystem effects can result from exposure for some length of time to various concentrations of a contaminant.

Streamflow was essential for determining the velocity of the plume and the volume of flow at a location. Metals concentrations during the plume were translated to cumulative plume mass, with streamflow enabling tracking of deposition and fate of the Gold King Mine metals within the system.

Several approaches were used to simulate the plume concentrations and movement. A stationary model of the plume was built at a limited number of locations, making full use of the water samples collected by the data providers and flow records at USGS gages; this is referred to as the “empirical model.” A mechanistic fate and transport model, the Water Quality Analysis Simulation Program (WASP version. 7.5.2; U.S. EPA 2013) was also utilized to provide a dynamic simulation of plume movement. WASP applied hydrodynamics principles to move the plume through the river system at a fine scale of spatial resolution, while it adjusted velocities and volume of flow, computed metals concentrations, and tracked geochemical transformations and loss of mass. The dynamic and empirical models worked synergistically and in parallel to quantify metals as the plume moved through the system and to ensure that the dynamic representation of the plume was well-grounded in field observations and that the empirical model appropriately characterized movement and timing between widely-spaced locations.

Interpreting measured concentrations from the samples collected during the plume required understanding what part of the plume they actually sampled. Although many samples were collected as the plume moved through 550 km of river, only a handful actually sampled at or near the peak of the plume. The hydrodynamic model helped locate samples relative to plume timing.

A variety of data and observations collected in the Animas and San Juan Rivers allowed plume characteristics, such as travel time, peak concentrations, and plume "shape" to be quantified at locations where there was sufficient data. However, none of these data were sufficient, in and of themselves, to establish all three plume characteristics at a location, nor could they be extrapolated to the rest of the river length without some means of adjusting for the physical makeup of the plume and the river along the way. These aspects of plume dynamics were supported by process-based analysis enabled by software-based analytical models. Water quality modeling of transit and concentrations of entrained metals enabled estimates of metals concentrations incrementally throughout the rivers, while accounting for transformation in chemistry, concentrations, and mass.

An overview of the empirical and dynamic modeling approaches used to characterize the plume are provided in the following sections. Specific details of model application and development for determining travel, concentration, and deposition will be further described in the chapters characterizing those aspects of the Gold King Mine plume.

2.4.1 Empirical Gold King Plume Model

The Gold King Mine plume concentrations were empirically characterized at select locations in the Animas and San Juan Rivers using water samples and flow data. Modeling locations were chosen for their proximity to the USGS gages and sampling sites. Establishing the plume at a location required determining the arrival time of the plume, its duration, and peak concentration, and obtaining streamflow from the USGS gages during the interval. Concentration is expressed as the mass of contaminant per unit volume of water (mg/L or µg/L). An example of a replicated plume at a location with the Empirical reconstruction from samples and the WASP model location are plotted in Figure 2-10.

Once the peak was estimated (or measured), the trace of plume concentration was then established between consecutive samples. Measured data always determined the concentration when it was available. A plume trace was created for the total and dissolved concentrations of each individual metal. The load or mass transported during the duration of the plume was calculated by multiplying flow by concentration and summing for the time of plume passage to yield a time-integrated weight (kg).

$$\sum_{1}^{n} Concentration\ \left(\frac{mg}{L}\right) x\ \frac{Q\ (liters)}{1{,}000{,}000} = Load\ (kg) \qquad \text{Equation 2.1}$$

Ideally, locations were repeatedly sampled by one or more organizations during the hours when the plume passed, so that there were multiple samples well distributed in time on the rising and falling limb of the plume (e.g., Figure 2-10B). However, only one location had frequent sampling that covered much of the plume. Most sites had 2–3 widely-distributed samples that could be used to reproduce a plume that passed over 48 hours or more (e.g., Figure 2-10C).

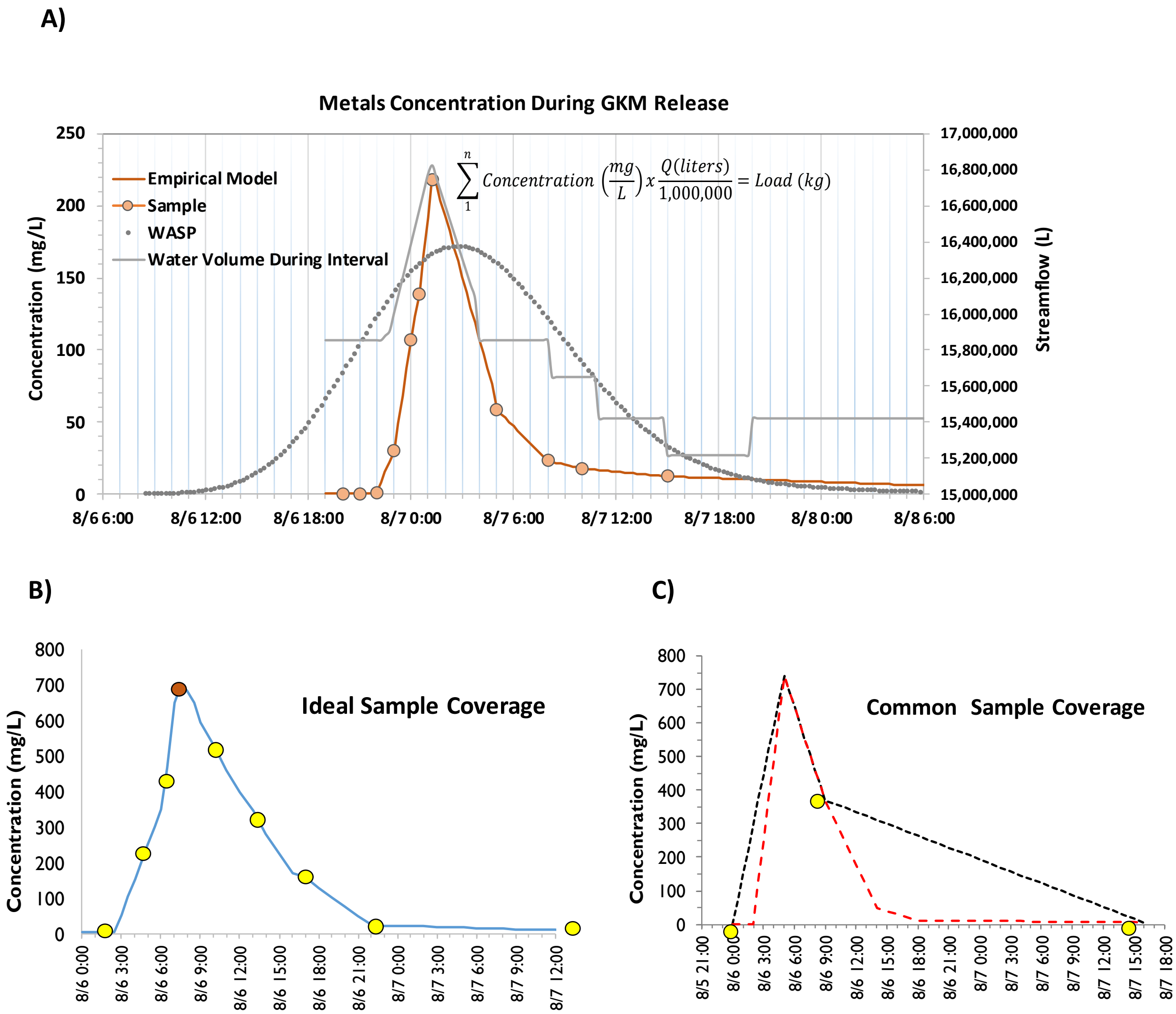


Figure 2-10. Schematic of simulated plume metal concentrations by the empirical model at a location to quantify the Gold King release metals concentration and mass. To construct an empirical model at a location, concentrations from water samples collected during the period when the plume passed are plotted. The peak was estimated and the plume was traced by interpolating between samples, providing concentrations in 15-minute time steps. Flow for the period was taken from a nearby USGS gage. A) Simulated plume from the Animas River at Durango where multiple samples were collected during passage of the plume showing concentration and streamflow. B) Ideally, multiple samples were available to define the rising and falling limbs and the peak. C) Commonly few samples were available. Various techniques were used to replicate the likely shape of the plume based on available data.

Each empirically-modeled location required various techniques to estimate the plume peak and to help replicate the likely shape of the plume at 15-minute intervals between samples, depending on what corroborating data was available, such as flow hydrographs or sondes. The empirical model built a plume uniquely at each modeling location, making maximum use of the available observations from multiple lines of evidence. The Empirical Model replicated the Gold King plume at 12 locations spaced, on average, approximately 40 km apart. Plume simulations and the associated data are discussed in more detail in subsequent chapters. Data and observations are synthesized into the empirical estimate of the Gold King Mine release at the mine in Chapter 3 and for the plume as it moved through the Animas and San Juan

Rivers in Chapter 4. Metals mass was computed at each location to track the GKM release, as changes in mass between sequential locations was assumed to represent deposition of metals (Chapter 6).

A strength of the empirical modeling is that it always fits the observed data at a location and maximizes the use of field-collected samples and other observed information. The empirically-modeled plumes provide perspective for water quality samples collected at or near each location. Without some way of knowing the timing of the plume, the relevance of each sample during the rapidly-changing plume movement could not be fully recognized. However, the number of representative sites that could be empirically modeled was limited by proximity to USGS gages and sufficient samples.

2.4.2 Dynamic Gold King Mine Fate and Transport Model (WASP Model)

A software-based water quality model was also used to dynamically simulate the Gold King Mine plume through the Animas and San Juan River system. The Water Analysis Simulation Program (WASP, version 7.52; U.S. EPA 2013) is a water quality modeling framework that allows the user to develop a dynamic and spatially-resolved mechanistic fate and transport model for metal contaminants in surface waters and sediments that can be parameterized for a system of interest in 1, 2, and 3 dimensions.

WASP was parameterized to simulate the hydrodynamics of the river (including flow, velocity, depth, and width) and metal concentrations (dissolved and particulate) from segment to segment through the Animas and San Juan Rivers. Unlike the empirical modeling, where a plume is built at a few locations from available data, the WASP model was initialized at the start of the Gold King Mine release at its source in the Animas River headwaters and then the plume mass moved through the length of the Animas River between its confluence with Cement Creek and its confluence with the San Juan River and finally, through the San Juan River, from its junction with the Animas River to Lake Powell. The plume was carried downstream with numerically-simulated flow, making adjustments to account for changes in flow and hydrodynamic conditions, the chemical and physical properties of the plume, and deposition of material as it moved, applying hydrodynamic principles that control water movement in rivers (Figure 2-11). The processes captured in this application of WASP included: kinematic wave hydrodynamics, diffusion between the water column and sediment pore water, boundary conditions for concentrations and flow, kinetic sorption, and settling, resuspension, and burial.

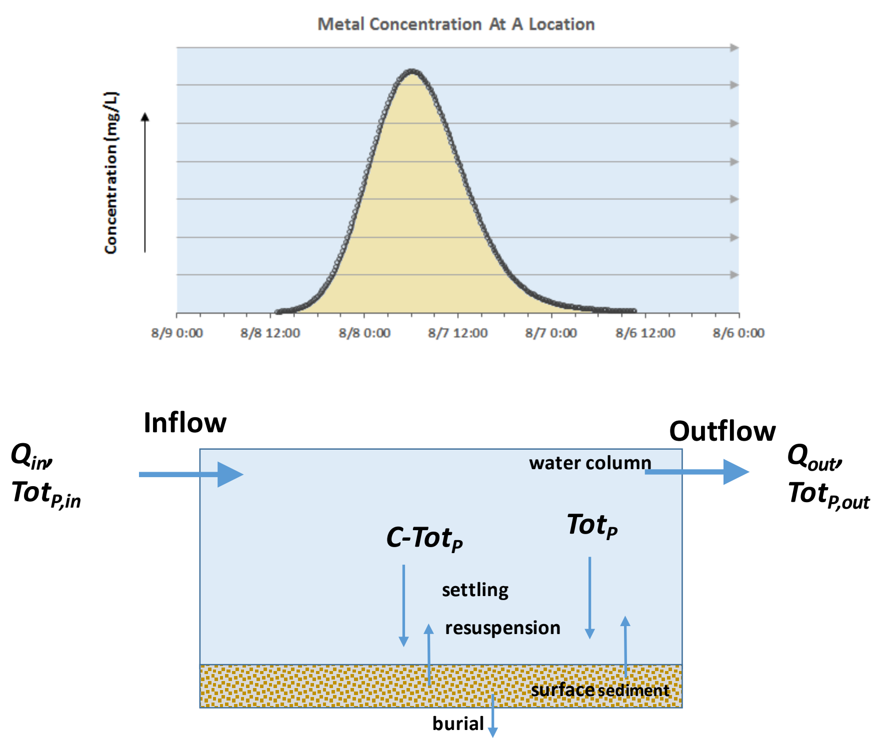
Developing the model for this application required a balance between complexity to capture the appropriate governing processes and simplicity to minimize the parameters necessary to describe the governing processes, the time and effort to implement the model, and the potential uncertainty that comes with increasing complexity. The specific model parameterized to simulate the Gold King Mine plume in the Animas and San Juan Rivers using WASP version 7.52 (Table 2-8) is hereafter referred to as the “WASP” model for simplicity. Critical elements of the model setup are briefly described here; complete details on model setup and calibration are available in Appendix B.

Table 2-8. Water Quality Assessment Simulation Program (WASP) Parameterization, Calibration, and Data Sources

Parameter	Source
Stream Description (segment length, width, depth, volume, slope)	BASINS, NHDPlus
Hydraulic Geometry (velocity and depth exponent)	USGS gage cross-section, regression, calibration
Bottom Roughness (Mannings roughness)	Calibrated
Stream Flow	USGS Gages
GKM Release Load	Estimated from empirical data
Settling Velocity	Estimated from empirical data
Partition Coefficients	Estimated from empirical data

A)

B)



Q: flow into and out of each segment (m^3/s)

Tot_P: Sum total of all particulate metals in the system (mg/L)

Figure 2-11. Gold King Mine plume transport conceptual model. WASP (Water Analysis Simulation Program (v. 7.52) was used to simulate the fate and transport of metals in the Animas and San Juan Rivers. A) Example of plume metal concentration through time at a location as it passes. B) WASP modeled the downstream movement of the plume with hydrodynamic forces, changing velocity in response to local channel and flow conditions. As the plume moved, total particulate metals Tot_P could settle and resuspend during transport. Particles may transport from the upstream segment and flow out to the downstream segment depending on an empirically determined settling rate that was calibrated from the mass estimated at empirically modeled locations. Each segment was simulated as a continuously stirred tank reactor.

Model Domain and Setup. The WASP model domain (Figure 2-12) was bounded by inflow at 3 USGS gages: the Animas River upstream of Cement Creek (USGS 09358000); the San Juan upstream of the Animas River (USGS 09355500); and Cement Creek immediately upstream of the convergence with the Animas River (USGS 09358550), about 12.5 km downstream from the Gold King Mine release site. The empirical model was used to simulate the plume between the mine and the Cement Creek gage, as described in Chapter 3. WASP utilized the metals concentrations from the empirical model as the boundary condition for the duration of the Gold King Mine release; boundary conditions were zero at all other times and boundaries. The flow at the boundary was given by the USGS gage at Cement Creek.

The Better Assessment Science Integrating Point and Nonpoint Sources Modeling Framework (BASINS 4.1; U.S. EPA 2015) was used to delineate the WASP segmentation, which resulted in 229 segments based on the NHDPlus dataset. WASP Builder, part of BASINS, determined the length of each segment, varying them to maintain approximately equal travel times based on mean stream velocities, in order to minimize numerical dispersion and numerical instabilities in the computations. Segments ranged from 0.9–4.7 km in length; the average length was 2.45 km. The variation indicates the spatial variability in flow velocity induced by varying river conditions.

Each spatially-defined segment had two individual layers – the water column and the sediment. Total metals in the water segment were transported with the unidirectional flow of water (i.e., advection) and sequentially passed to the next downstream segment. Particulate metals, which were suspended in the water

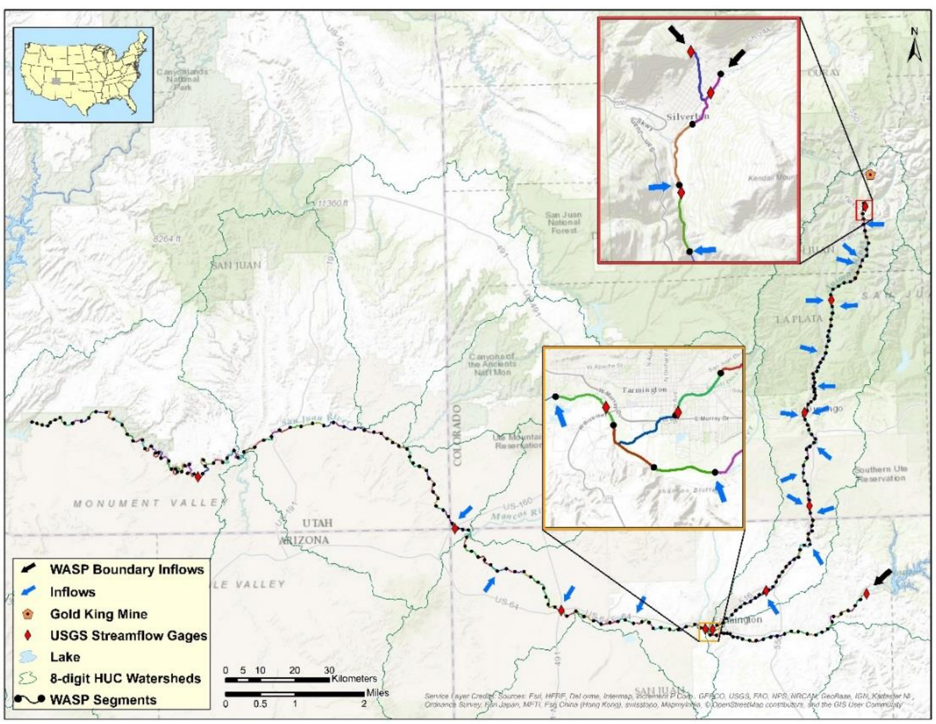


Figure 2-12. Model domain and setup for the Gold King WASP Model. The model domain for the WASP Model was constructed using BASINS to download NHDPlus and associated files to create the WASP segmentation. The dots represent the division between the WASP segments. Each segment has a length, width, depth, and volume. Black arrows represent the 3 major domain boundaries with inflow concentrations including the Upper Animas above Cement Creek, the portion of Cement Creek above the release site, and the San Juan River upstream of its confluence with the Animas. Streamflow at the start of the Gold King plume are provided from USGS gages at these locations. The blue arrows represent the inflows based on partitioning of USGS gages (red diamonds). There were 229 surface water and 229 sediment segments. Mean length was 2447 m, ranging from 922 to 4655 m. (See Appendix B for more details on segment parameterization.)

column, were carried via advection downstream and could be transferred between the water and streambed segments via settling. Dissolved metals could diffuse perpendicularly to the flow of the river between the water column and pore water in the sediments, while particulate metals in the sediments could resuspend back into the water column.

Metals Composition. WASP was applied to simulate total metal concentrations and the dissolved and total fractions of the individual metals arsenic (As), lead (Pb), copper (Cu), and zinc (Zn). To meet study objectives, it was important for the WASP model to account for the geochemical transformations that occurred during plume movement, at some level of resolution. Metals changed from dissolved to particulate form as the plume traveled through complex geochemical reactions including sorption, oxidation, and precipitation. Some fate and transport models can account for these processes, but the data needed to perform sophisticated equilibrium and speciation transformations were not collected during Gold King Mine plume movement. Therefore, rather than explicitly modeling these processes, a more general approach was adopted that used the WASP Toxicant (TOXI) module to account for the partitioning of metals between dissolved and colloidal/particulate phases. This approach applied a lumped parameter treatment of the partitioning coefficient (K_d). This partitioning coefficient was determined using total particulate metal concentrations and the unfiltered and dissolved concentrations of the individual metals of interest estimated from the empirical model at the plume peak. A regression was used to estimate K_d as a function of river distance, so that K_d changed as the chemistry of the plume changed traveling downstream. There was a specific K_d established, as a function of distance, for each of the four metals simulated (i.e., As, Cu, Pb, and Zn). The WASP TOXI module also addressed diffusion between the water column and the sediment pore water. Appendix B provides a detailed explanation of model parameterization and methods.

Deposition and Entrainment. Once initialized with flow conditions at the time of the Gold King Mine plume release, the WASP model moved material and water through each segment. Flow was increased to reflect incoming flow, and plume material was deposited depending on water velocities, based on the available USGS gage flow data. WASP used a constant settling velocity, based on Stokes' law, to partition materials to the bed or entrain them during higher flows. To determine the settling particle size, the deposited mass determined at select locations by the empirical model was used to calculate the effective particle size and determine the settling velocity that would result in the loss of mass within that reach. Resuspension of settled metals was incorporated using a default, constant resuspension rate. Additional information on particle mobility and methods is provided in Appendix B.

2.4.3 Plume Modeling Synergies

The empirical and WASP models were used together to simulate the metals composition of the Gold King Mine plume, including the dissolved and total fractions of metals and other plume simulation elements. There are a number of synergies and differences between the two modeling approaches used to characterize the GKM release. These are summarized in Table 2-9.

The empirical model simulated all 23 of the TAL metals, plus molybdenum, while WASP focused on simulating total metals and arsenic, copper, lead, and zinc. The empirical model produced the plume at just 12 locations, but a strength of the empirical model is that it was built entirely with observed water sampling data at those locations. WASP, in comparison, significantly increased the temporal and spatial characterization of the plume as it traveled through the river system, as it simulated the plume within shorter segments of the system providing greater spatial resolution. WASP provided objective estimates of travel time based on hydrodynamic principles and estimated and adjusted metals concentrations to reflect physical and geochemical processes encountered in the river as the plume moved through the system.

WASP was not calibrated (or validated) against sample concentrations directly, but instead used key empirical model results to calibrate critical processes, thus linking WASP calibration firmly to observed data. These processes included partitioning of metals to dissolved and solid phases and particle settling velocities. WASP informed the empirical model regarding plume arrival times; the empirical model takes no other information from WASP simulations.

There were many uncertainties in estimating plume composition and travel. The two models did not produce the same metals concentrations or estimates of mass where they met, but rather were largely, independent methods for determining plume metals concentrations. The two modeling approaches provided a range of estimates, which reflects the strengths of using observed data and using process-based tools, when data is limiting. Both situations existed within the long length of river affected by the Gold King Mine release. The two models together were the basis for the quantitative analysis of the transport and fate of Gold King Mine metals in the Animas and San Juan Rivers, as presented in the following chapters.

Table 2-9. Synergy of Plume Modeling Approaches Used in this Study to Characterize the Gold King Plume

Plume Simulation Component	Empirical Model	WASP Model
Location	12 locations selected based on nearby USGS gages and availability of sampling data	229 segments; average length 2.45 km
Streamflow	USGS gage records	Simulates streamflow initialized at flow boundaries at start of plume. Moves water from segment to segment adding water between gages
Plume travel (duration at a location, timing between locations)	Estimated from field evidence (recorded observations, hydrology, continuous records at sonde locations) and assisted by WASP	Simulates movement of plume based on hydrodynamic principles informed by channel and flow characteristics
Metal Concentration	Creates plume concentrations by interpolating between observed concentrations from water samples collected as the plume passes the site and known or estimated peak concentration Partitions between dissolved and colloidal based on sample data	Simulates concentrations of dissolved and total metals for arsenic, copper, lead, and zinc, accounting for dilution and particle settling Models partitioning between dissolved and colloidal particles
Metals Mass	Computes mass of dissolved and colloidal particulate solids as plume passes the site from concentration and flow	Computes mass of dissolved and colloidal particulate solids as plume passes the site from concentration and flow
Deposition	Infers deposition as difference in mass between sequentially modeled locations	Suspends and deposits particles during transit through each segment according to velocities relative to particle size Particle settling parameterized using metal mass developed by empirical model
Relationship to Observed Data	Uses all available observed data as input for reconstructing the plume	Does not use observed data for any component. Synergizes with key empirical model output for calibration of particle mobility and historic USGS gage records to calibrate for flow

2.4.4 Other Supporting Modeling

There were several additional analyses conducted that were of importance to the Gold King Mine plume simulations, which were supported by other software-based process models (Table 2-10). These analyses and models are introduced briefly here, as part of the overall plume modeling approach, but will be described in greater detail in the following chapters, in the context of the analyses performed. Development and application of these software-based models are described in detail in Appendices B, C and D.

Geochemical Reactions. Geochemical reactions and transformations are important processes controlling the characteristics and fate of metals released from Gold King Mine as the plume traveled through the river system. Geochemical analyses addressed neutralization of acidity and the subsequent transformation of dissolved metals to colloidal precipitates. Geochemical calculations were informed by observed water chemistry and assisted by the Geochemist's Workbench® software (Bethke 1998), an integrated set of tools for solving the stoichiometry of equilibrium chemistry and other elements of aqueous chemistry. Geochemical analyses helped inform reconstruction of the plume, although the scope of these analyses was limited by the lack of geochemically-relevant data. Geochemical analyses are further described in Appendix C.

Potential Groundwater Impacts. Questions arose as to whether wells drilled into the alluvium adjacent to the Animas and San Juan Rivers could have drawn in Gold King Mine contaminants if water moved from the river into adjacent alluvial sediments. Potential groundwater exchange between the river and wells was examined using groundwater modeling in several locations in the Animas River to explore floodplain-scale and local-level interactions between wells and the Animas River. We applied several groundwater models to address various aspects of river interaction with alluvial aquifers. The analytic element computer program GFLOW (v.2.2.2; www.haitjema.com) was used to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). The USGS MODFLOW-NWT and MODPATH (particle tracking) solvers within the Groundwater Modeling System (www.aquaveo.com, GMS v.10.1) were used to investigate the influences of fully three-dimensional flow, and transient pumping. The AnAqSim model (v.3, release 29 Sept 2016; www.fittsgeosolutions.com) was used for local scale modeling under the influence of aquifer heterogeneity and anisotropy of hydraulic conductivity. Groundwater analyses are presented in Chapter 8, with model development described further in Appendix D.

Table 2-10. Software-based Process Models Used to Support Various Analyses of the Gold King Mine Release in the Animas and San Juan Rivers

Software Model	Supports	Website
AnAqSim v.3, release 29 Sept 2016	Groundwater assessment	www.fittsgeosolutions.com
GFLOW (v.2.2.2)	Groundwater assessment	http://www.haitjema.com/
GMS-MODFLOW v 10.1	Groundwater assessment	http://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction
The Geochemist's Workbench®	Geochemical analysis of plume and deposits	https://www.gwb.com/
Water Quality Analysis Simulation Program (WASP) Version 7.52	Gold King plume movement, deposition and resuspension	https://www.epa.gov/exposure-assessment-models/water-quality-analysis-simulation-program-wasp
WhAEM	Groundwater assessment	https://www.epa.gov/exposure-assessment-models/whaem2000

2.5 Post-Event Water and Sediment Quality Trends

Temporal and spatial trends in water and sediment quality were explored with empirical analysis of data collected before, during, and after the Gold King Mine plume. Metals concentration data was collected at numerous locations in the Animas and San Juan Rivers post-release, allowing comparisons of water chemistry in the river and sediments after passage of the GKM plume relative to pre-event water chemistry to assess if and when the system returned to its baseline condition. Potential impacts on water users were assessed by comparing the plume water concentrations and post-event sediment concentrations to relevant federal, state, and tribal water quality criteria.

2.6 EPA Conceptual Monitoring Plan

In March 2016, EPA released the Post-Gold King Mine Release Incident: Conceptual Monitoring Plan for Surface Water, Sediments, and Biology. This monitoring plan is designed to gather scientific data to evaluate river conditions over the course of the year and to identify any potential impacts to public health and the environment from the release. The Conceptual Monitoring Plan (CMP) is an effort by EPA to assess physiochemical and biological parameters downstream of the GKM Release Incident.

The specific study objective of the plan is to identify changes in surface water quality, sediment quality, biological tissue contaminants, and biological community metrics since the GKM Release Incident at 30 locations in the Animas and San Juan Rivers, comparing post-release data against pre-release or historic trends, where available. The 30 longer-term monitoring sites include a number of the locations listed in Table 2-2.

There are two primary study questions:

- Have water and sediment quality trends in Cement Creek, the Animas River, and the San Juan River changed since the GKM Release Incident?
    - What are the water column and sediment metals concentrations/loadings and how do they compare to pre-release or historic trends?
    - What are the conditions of the biological communities, macroinvertebrates and fish, and how do the indices used to assess them compare to pre-release or historic conditions?
- If post-release conditions are of lower quality than pre-release/historic trends, are water quality standards or screening levels exceeded for human health (including recreation and fish consumption), agricultural, and aquatic life uses in the watershed?
    - If metals concentrations in sampled media are higher than pre-release/historic trends, are they meeting screening levels identified as acceptable for recreation, agriculture, and aquatic life? Screening levels that may be used by EPA include those benchmarks identified as part of the GKM Release Incident emergency response and other applicable water quality standards or benchmarks.

Water and sediment quality will be addressed in multiple chapters of this report and a separate CMP report will address the condition of biological communities. This report provides scientific analysis of the chemical characteristics of river water and sediments in the year following the release.

CHAPTER 3 . GOLD KING MINE RELEASE VOLUME AND CONSTITUENTS

On August 5, 2015, a breach occurred at the entrance of the abandoned and sealed Gold King Mine entrance located in the headwaters of the Animas River within the Cement Creek subwatershed. Behind the earthen and rock barrier at the mine entrance was a large volume of low pH water with high concentrations of metals that was suddenly released into the North Fork of Cement Creek. The mine drained sufficient amounts of water to raise streamflow at a USGS gage located 12.5 km downstream for a period of about 8 hours.

This chapter describes the events at the Gold King Mine release. The analysis focuses on quantifying the amount of water and metals in dissolved and colloidal/particulate form that were released from the mine and generated by erosion, as the spilled volume moved from the mine through Cement Creek. Additional metals were entrained into the plume of metals outside of the mine due to the erosive force of the flood. Analyses determined the mass of metals delivered to the Animas River at its junction with Cement Creek. These results were then used as the initial Gold King Mine plume composition that then flowed through the remainder of the river system.

3.1 The Release Event

The Gold King Mine is located in the northern portion of the Silverton caldera within the Cement Creek watershed. Economic production from the Gold King Mine began in 1886 and ended in 1923 (BOR 2015). The mine has a complex series of vertical and horizontal shafts that extend approximately 2.4 km (1.5 mi) horizontally and about 210 m (689 ft) vertically within the mountain. The release was from the mine entrance (adit) at level 7, at an elevation 3,475 m (11,401 ft) above sea level. The Gold King Mine portal is situated on a steep slope, composed primarily of mine waste about 70 m (300 ft) upslope from a small tributary of Cement Creek near the watershed divide (Figure 3-1).

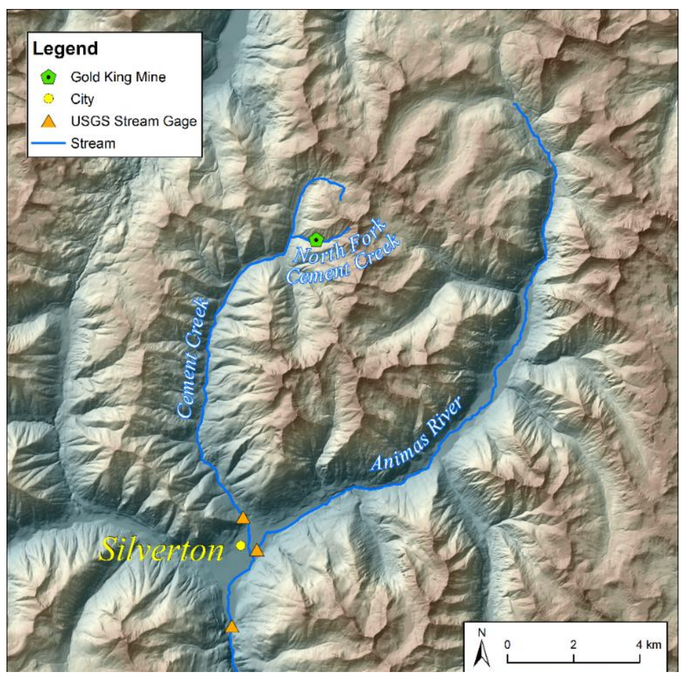


Figure 3-1. General location map of the Gold King Mine within the upper Animas River watershed in the North Fork of Cement Creek. The mine is located approximately 13.9 km upstream from the confluence of Cement Creek and the Animas River. The mine portal is located at 11,400 ft above sea level.

Gold King Mine delivers acid mine drainage to Cement Creek via subsurface and overland drainage at a rate of flow that has varied over time from 285 gpm to more recent estimates of 480 gpm before the spill (BOR 2015). A number of other mines in this area also leak significant volumes of acid mine drainage to Cement Creek on an ongoing basis. The creek has historically been recognized as highly contaminated (Church *et al*. 2007).

The mine setting and release from the Gold King Mine was described in a report by the Bureau of Reclamation (BOR) after the release. According to BOR (2015), the groundwater regime in the Gold King Mine area, upper Cement Creek, and Sunnyside Basin area is influenced by extensive underground mine workings, such as those shown in Figure 3-2, and a very complex system of fractures related to the various volcanic flows, tuffs, breccias, and faults in the area (BOR 2015). Gold King Mine shafts and voids interconnect within the

San Juan Mountains with other nearby mines, including the Sunnyside, Red Bonita, Mogul, and Grand Mogul Mines located at both higher and lower elevations. All of these mines are connected to and partially drained by the American Tunnel, an adit located at the lowest elevation on the mountain that opens to the surface. Changes to drainage in any one of these other mines could have contributed to the conditions that facilitated the breach at Gold King Mine.

The process of remediating Gold King Mine and other mines in the area has been ongoing for several years by the Colorado Division of Reclamation Mining and Safety (DRMS) and EPA, in consultation with BOR and others. Preliminary excavations at the Gold King Mine were conducted in 2014 to determine mine conditions within the sealed mine and assess the ongoing adverse water quality impacts caused by mine discharges.

Remediation work was completed on the nearby Red and Bonita Mines in early August 2015. The contractor crews and equipment moved from there to Gold King Mine to conduct preliminary investigations in preparation for a multi-agency on-site planning meeting scheduled for August 14, 2015. The heavy equipment operator was conducting exploratory excavations around the main Gold King Mine adit (i.e., the entrance), which had become plugged with emplaced material and debris that had fallen from the slope above, when the lower portion of the bedrock crumbled and pressurized water began leaking from the adit (EPA 2016c; Figure 3-3).

The mine pool behind the plug contained mine water and drainage from other higher-elevation mines at a higher hydraulic head. The small leak quickly turned into a full breach that rapidly drained the mine pool behind the plugged entrance and rushed directly downslope to the North Fork of Cement Creek. Adding to the severity of the release, the initial flood of water eroded soil and rock debris from the mine portal, as well as a significant volume from the large waste pile outside the mine entrance, where mining waste-rock was dumped during almost 40 years of mining operations. The rushing water also swept away the fill of several unpaved road stream crossings in its path (BOR 2015) and could have entrained sediments and associated metals from the Cement Creek channel.

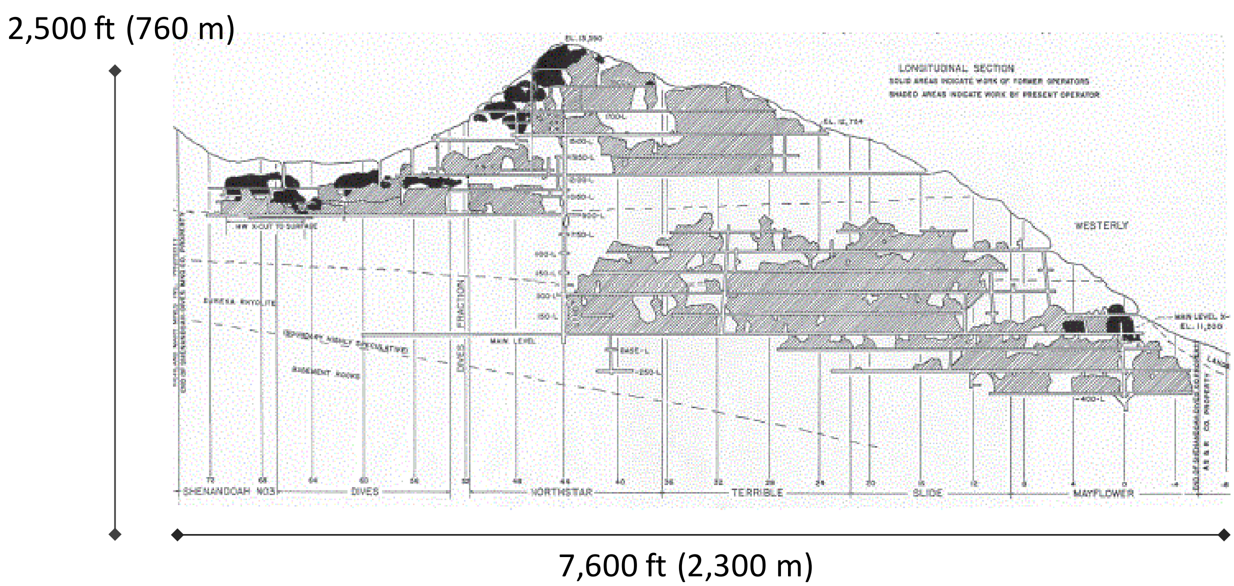


Figure 3-2. Illustration of the internal structure of vertical and horizontal mine shafts in this mining area. This illustration is of the Shenandoah-Dives mine taken from Jones (2007). It shows the subsurface interconnection of mine voids at a mountain scale. Gray areas are mined out areas. Mine shafts alter internal plumbing and alter flow pathways. Interconnected mine shafts in the Gold King, Red Bonita and Sunshine mines contributed to the pressurization of the closed Gold King mine (BOR 2015).

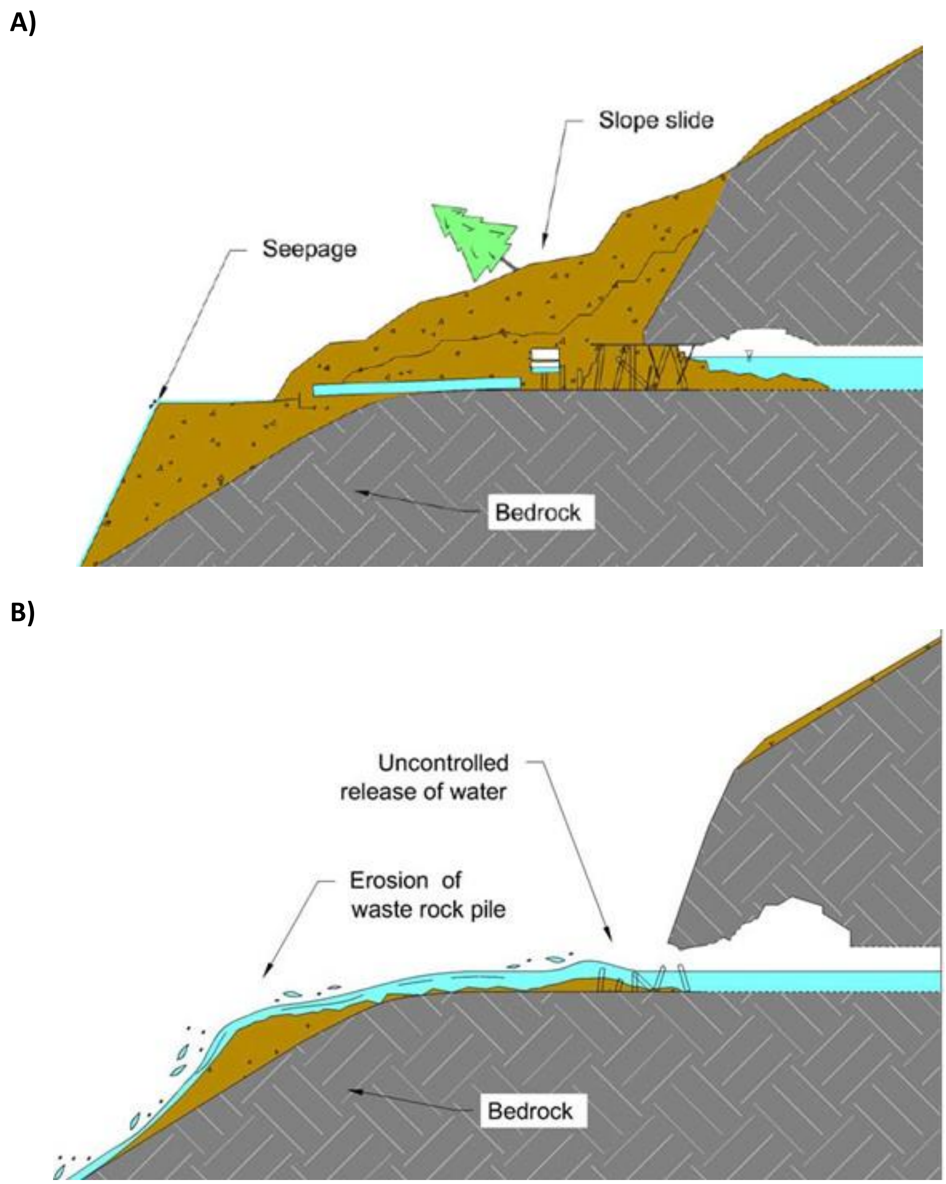


Figure 3-3. Schematics of the Gold King Mine before and after the breach at the mine entrance (reproduced from Bureau of Reclamation report 2015). A) Before the breach the entrance was plugged with emplaced material and debris that had fallen from the slope above. The mine pool behind the plug contained mine water at higher hydraulic head with buildup of drainage from other higher elevation mines, B) Equipment disturbance at the entrance triggered a sudden breach of the plug releasing the mine pool. The acidic water rushed from the mine and eroded the plugged material and part of the large mine waste pile outside the entrance.

This study considered the Gold King Mine release to include both what came from within the mine and what was eroded from the mine waste pile and carried through Cement Creek and delivered to the Animas River. The first step in assessing the Gold King Mine release was to quantify the volume and content of the acid water spilled from the mine. The second step was to determine the volume and content of additional materials entrained outside the mine as it traveled through Cement Creek, before entering the Animas

River. The erosion was significant, and analysis shows that the mass of metals released from the mine was small compared to what was entrained outside the mine.

3.2 Hydrology in Cement Creek During the Gold King Mine Release

There are three USGS stream gages located in the upper reaches of the Animas River that allowed the volume of water released from the Gold King Mine to be quantified. USGS gage 09358550 located in Cement Creek, 12.5 km downstream from the mine near the confluence with the Animas River, directly measured the additional water released from the mine as it flowed past the gage.

Two gages in the Animas River, which bracket the town of Silverton, monitor flow immediately above the Cement Creek confluence, which was unaffected by the release (USGS gage 09358000) and 3.8 km downstream from Cement Creek (Animas below Silverton, USGS gage 09359020). Both Cement Creek and Mineral Creek enter the Animas River within this segment. These gages provided a reference for flow conditions during the release, recording water and streamflow in 15-minute intervals.

Immediately prior to the release, streamflow in the Animas River and its tributaries was receding from rains several days earlier, and Cement Creek was contributing 20% additional flow to the Animas River at their confluence (Figure 3-4).

The mine breached at approximately 10:45 on the morning of August 5, 2015 and was in full drainage mode by 10:55, based on a time-stamped video recorded by the on-site crew. The release first arrived at the Cement Creek gage at 12:45, with a nearly five-fold increase in flow from 0.736 to 3.40 m^3/s (26 to 120 cfs) within the first 15-minute period (Figure 3-5).

The arrival of the plume at the gage was readily apparent. Determining the end of the release was less clear, as flow tapered off slowly after 14:00 and appeared to have returned to background by 18:30. To investigate whether the release extended further, the unit area discharge ($m^3/s/km^2$) for the Cement Creek gages was compared to the upper Animas River gage as a reference. The unit area discharge accounts for differences in flow at the two locations. The relative relationship indicated by the ratio of unit area discharge had been steady prior to the release, as evident by the line fit to the pre-release data in Figure 3-6. Return to that relationship after the Gold King plume passed may not have occurred until near 24:00 or possibly as late as 06:00 the next day. However, close examination of the flow records at each site suggests other factors, such as normal diurnal fluctuation, may also have influenced the hydrographs at each gage individually.

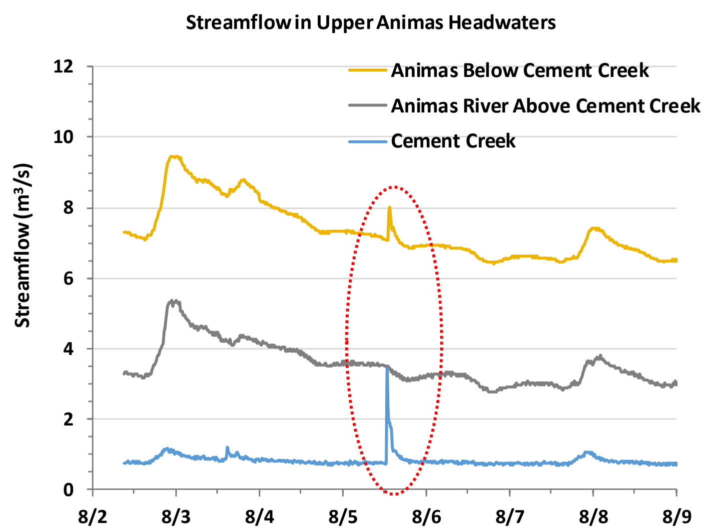


Figure 3-4. Hydrology at the time of the Gold King release. Three USGS gages monitor streamflow in Cement Creek and in the Animas River up and downstream from where Cement Creek joins the Animas River in Silverton. At the time of the release streamflow was receding from earlier rains. The release created a moderate flood wave in Cement Creek and a small peak in the Animas River below Silverton. Flood peaks are circled in red. Flow in the Animas River was about five times greater than Cement Creek prior to the arrival of the release. During the first 15-minute period the flow was equal to that arriving from Cement Creek.

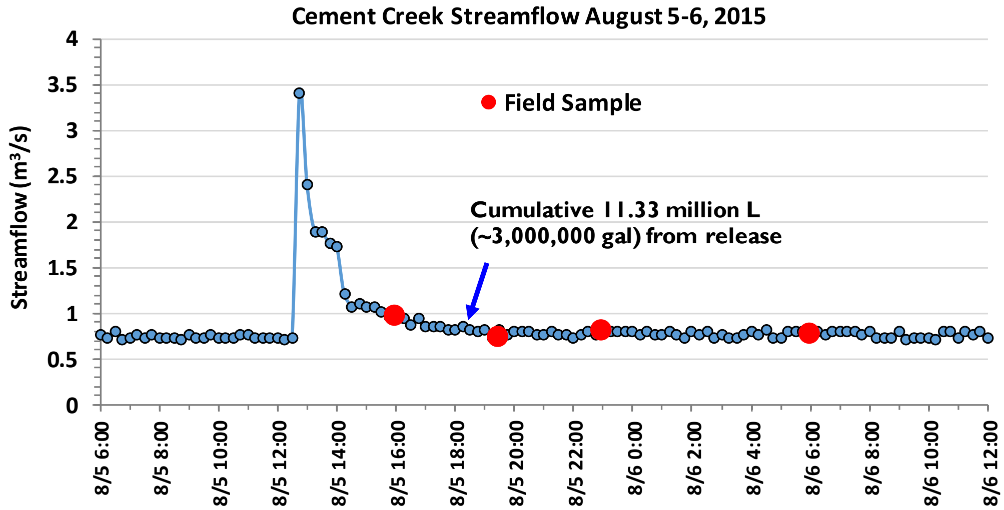


Figure 3-5. Cement Creek streamflow during passage of the Gold King release. Flow recorded at the USGS gage in Cement Creek in the period prior to the release and for 24 hours after the slug of mine water first arrived at the gage at 12:45, after traveling approximately 11.6 km from the mine. Return to background flow occurred at approximately 18:30 hours. The red dots indicate times when water samples were collected from Cement Creek near the gage.

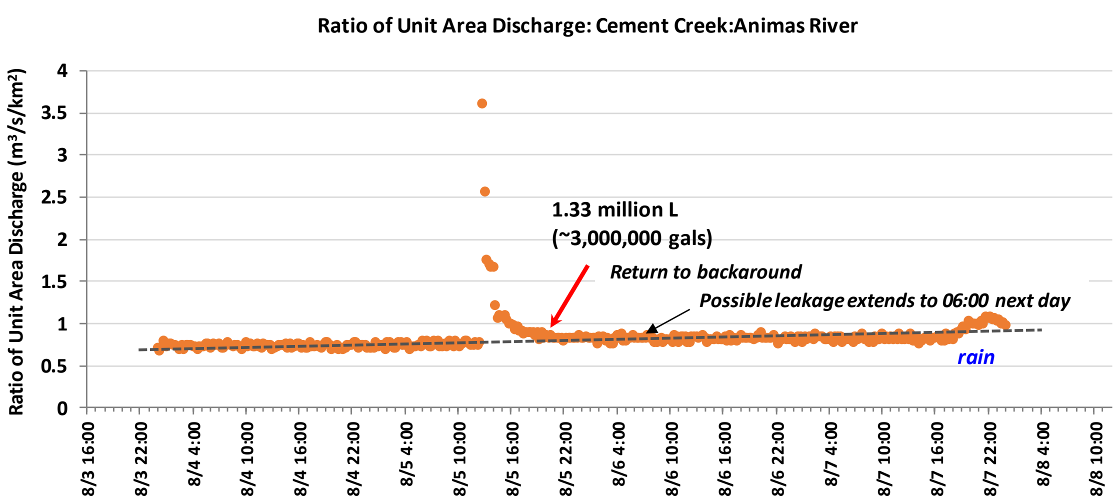


Figure 3-6. Comparison of streamflow (discharge) in Cement Creek with the Animas River gage above Cement Creek. The unit area discharge was calculated for each gage by dividing streamflow by watershed area to normalize for differences in flow. The ratio of Cement to the upper Animas gage is shown. A steady relationship between the two gages was observed prior to the release and flow settled back into that pattern within 24 hours.

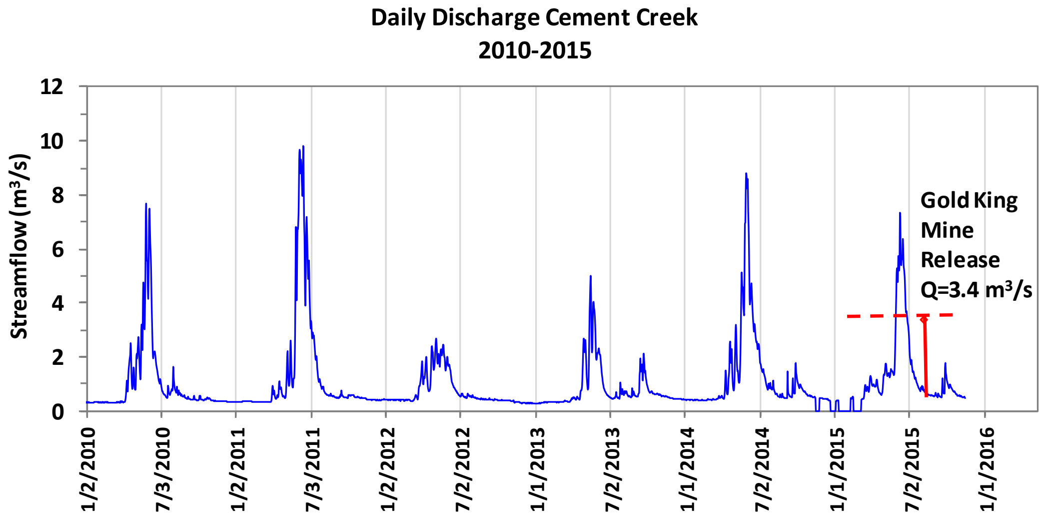


Figure 3-7. Five years of flow record in Cement Creek from 2010-2015 are shown. The Gold King Mine release generated a moderate flood of 3.2 m^3/s (120 cfs) in Cement Creek. The peak flow that occurred in the Gold King release was equivalent to a moderate day on the rising or falling limbs of the spring snowmelt hydrograph.

The peak flow observed as the slug of water passed the gage was similar to that observed on a moderate day of snowmelt runoff in Cement Creek (Figure 3-7). The flow duration statistic of the peak was P≤0.92. Based on the cross-section and velocity characteristics relative to gage height measured at each USGS gage, water level increased from a low flow height of approximately 0.3 m to about 0.5 m. This moderate stage suggests that the flood probably remained within the banks of the active channel. Based on gage statistics, the velocity of the peak ranged from 1.40 m/s to a maximum of 1.71 m/s, which is consistent with the maximum observations in the gage records.

The upper peak velocity value is in good agreement with the observed travel time of the plume. The first photograph and video at the mine adit where water is visibly flowing from the mine was time stamped 10:55 (BOR 2015; U.S. EPA 2016c). The first pulse of water traveled 12.5 km to the gage, arriving within the 15-minute window between 12:45 and 12:59. The time it took the plume to travel this distance (i.e., 110–124 min) suggests a velocity between 1.68 and 1.89 m/s. This is close to, but higher than suggested by the gage statistics. Uncertainty in the calculations arose from inaccuracies in the distance measurements and the range of variability in the gage velocity measurements.

3.3 Metals Mass Released from Within Gold King Mine

The mass of metals released from Gold King Mine was determined from the volume of water released and the concentration of metals in the mine pool, pictured in Figure 3-8.

3.3.1 Volume of Water

The Gold King Mine release volume was assumed to equal the volume of flow in excess of baseflow at the USGS gage from 12:45 to 18:30. Baseflow was taken as the flow at 12:30 and was receded slightly during the time period, following the baseflow pattern observed at the Animas River gage upstream of Cement Creek. The GKM volume was computed as the observed flow (expressed in m^3/s) multiplied by 900 for each 15-minute period (i.e., 15 min = 900 s), then summed from 12:45 to 18:30. The estimated baseflow in each 15-minute period was subtracted from the observed streamflow in each 15-minute period.

Figure 3-8. Photograph of the mine pool inside the Gold King Mine. Note that water is clear and not yellow colored as observed throughout Animas River as release plume moved through.

From 12:45 to 18:30, close to 11.33 million L (approximately 3 million gal) of flow volume in excess of baseflow flowed past the Cement Creek gage. This computation concurs with the USGS estimate of 3,000,000 gallons made at the time of the release. This volume indicates that the effective end of the mine pool release occurred at 18:30 at this gage. The gage records show that the slug of water drained from the Gold King Mine passed within about 6 hours, but the bulk of the water passed within an initial 2-hour time period (Figure 3-5).

3.3.2 Metals Concentrations in the Gold King Mine

There were only four water samples collected from within the Gold King Mine over a six-week period after the release that could be used to estimate metals concentrations within the mine at the time of the release. However, mine pool chemistry immediately after the release likely varied from pre-release conditions, as the influx of water re-established an equilibrium for the new mine pool that had a different water level.

The Colorado Department of Public Health and Environment (CDPHE) sampled the mine pool at the GKM adit on August 7 and August 11, 2015, reporting concentrations of 19 and 11 of the 24 metals of interest (23 TAL metals, plus molybdenum), respectively. EPA sampled the mine pool at the adit for the complete panel of dissolved and total metals on August 15, 2015, and an EPA contractor sampled total metals only on September 21, 2015.

Total Metals Concentrations. Total metals concentrations in the mine pool water sampled from the adit following the release are provided in Table 3-1, along with the concentrations selected to represent the GKM effluent at the time of the release; these selected values were later used to calculate the mass of metals delivered from the mine in the release. Concentrations of total metals changed in the 6-week period after the release, as represented in the sampling, so a value had to be selected to represent those at the time of the release.

Table 3-1. Total Metal Concentrations in Samples Collected from the Mine Adit. Four samples were collected from the effluent in the Gold King Mine over a period of six weeks after the release. Sample total metal concentrations are reported. 100% of each metal was in the dissolved fraction in the Aug 15 sample except arsenic that was 75% dissolved (see Figure 3-10). The average of the adit samples and the value selected to represent the effluent in calculations of mass delivered from the release are also listed. The selected value primarily used the August 15 sample for reasons described in the text. The main difference between the August 15 and September 21 samples was an increase in calcium. NR indicates no value was reported.

	Total Metals Concentrations (mg/L)					
	CDPHE	CDPHE	EPA	EPA		
Metal	7-Aug	11-Aug	15-Aug	21-Sep	Average	Selected[1]
Aluminum	32	31	34	32	32	34
Antimony	NR	NR	0.0037	0.0063	0.0050	0.0037
Arsenic	0.086	0.067	0.060	0.044	0.064	0.060
Barium	0.021	NR	0.009	0.002	0.010	0.009
Beryllium	0.003	0.006	0.011	0.013	0.008	0.011
Cadmium	0.100	0.084	0.082	0.084	0.088	0.082
Calcium	330	330	370	460	373	370
Chromium	0.015	NR	0.006	0.016	0.012	0.014
Cobalt	0.13	0.12	0.11	0.12	0.12	0.11
Copper	6.0	7.2	4.6	7.8	6.4	7.0
Iron	185	NR	150	120	152	150
Lead	0.160	0.048	0.042	0.042	0.073	0.042
Magnesium	30	30	27	31	30	27
Manganese	34	33	36	42	36	36
Mercury	0.00000	0.00000	0.00000	0.00000	0.00000	0.00004
Molybdenum	NR	NR	0.004	0.005	0.005	0.004
Nickel	0.070	0.066	0.069	0.064	0.067	0.069
Potassium	2.8	NR	2.4	3.0	2.7	2.4
Selenium	0.002	0.001	0.005	0.010	0.004	0.005
Silver	NR	NR	0.0001	0.0006	0.0004	0.0001
Sodium	92	NR	5.3	4.8	34.0	5.3
Thallium	NR	NR	0.0003	0.0600	0.0301	0.0003
Vanadium	NR	NR	0.038	0.033	0.036	0.038
Zinc	28	28	20	26	26	27
Sum of Metals	*Incomplete*		650	727	691	659
Sum of Metals Less Cations	*Incomplete*		245	228	253	254

[1] **Selected to represent the total metals concentration in the GKM effluent at the time of the release**

Trends in metals concentrations of the mine waters were analyzed and centered around commonly measured analytes. There were trends observed in the total metals concentrations in the mine pool during the six weeks after the release. Many of the metals declined rapidly from the initially-high concentrations observed two days after the release (Figure 3-9 and Table 3-1), with the exception of beryllium (Be) and calcium (Ca; not shown), which continued to increase through the entire time period.

Metals Concentrations Selected to Represent Gold King Mine Effluent at the Time of Release. The metals concentrations that were selected to represent the GKM mine effluent at the time of the release were based on the four mine pool samples taken post-release. (There were four samples for total metals including Sep 21, but just three samples with dissolved.) The averages of the samples collected after the release and the selected concentrations are shown in Table 3-1 for total metals and dissolved metals, respectively. The August 15 sample was selected as the primary basis for assigning total and dissolved metals concentrations to the GKM effluent at the time of release, with three exceptions. The August 15 sample was low relative to other samples for copper, zinc and chromium, so an average of the other samples was used. Calcium increased from August 15 to September 21, accounting for the difference in the summed total concentrations of metals, but the August 15 calcium value was used.

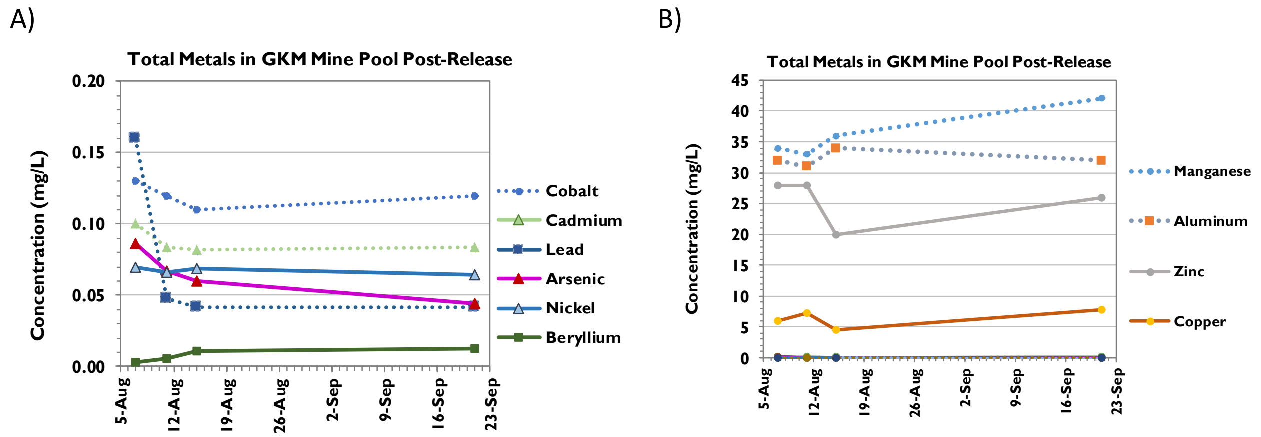


Figure 3-9. Trends in effluent concentration in the Gold King Mine after the release. Colorado Department of Public Health and Environment collected samples August 7 and 11. EPA collected samples August 15 and September 21.

The summed total concentration of metals is provided in Table 3-1 with and without the major cations (calcium, magnesium, potassium, and sodium). The summed metals load minus the major cations are very close among the individual samples, differing from the low to high estimates by 10%. The end result of the "selected" set of concentrations results in the highest concentration, and therefore mass, of the metals of most interest.

Dissolved Metals Concentrations. While total metal concentrations generally decreased in the mine pool the first ten days after the release, the proportion that was dissolved increased. The ratio of dissolved to total concentrations of samples is shown in Figure 3-10. Dissolved concentrations in the samples and average and selected values are shown in Figure 3- 11.

Metals were generally colloidal soon after the release, but most trended towards dissolved by August 15, when the pH of the mine water was 2.93 (Figure 3-10). Earlier samples did not report pH, but the trend in the dissolved to total metals fraction suggests that pH decreased during the 10-day period following the release. Johnson and Hallberg (2005) suggest that dissolved metals concentrations in emptied mines tend to be higher initially, as new water dissolves any acidic salts. Trends in the ratio of dissolved to total fractions and stabilizing of concentrations suggest that the mine pool reached an equilibrium condition by August 15 that may or may not have been the same equilibrium as existed prior to the release.

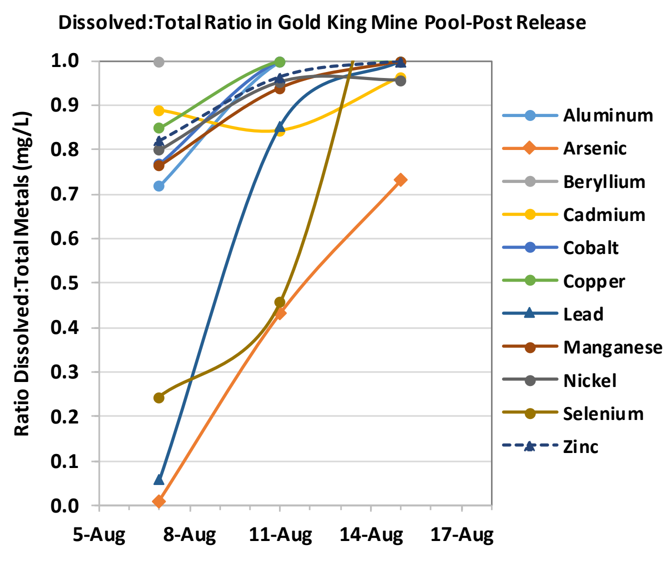
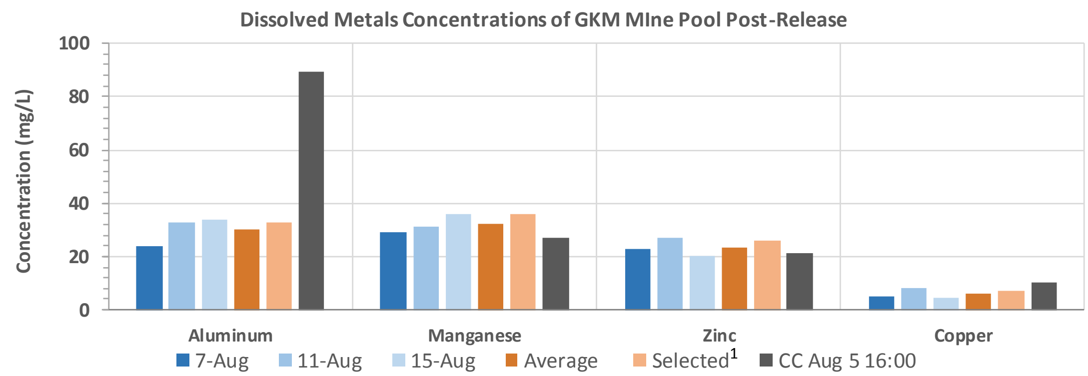


Figure 3-10. Ratio of dissolved to total fraction of metals in the Gold King Mine after the release in three samples collected August 7, 11, and 15. The figure includes the subset of metals that reported dissolved and total metals for the 3 sampling events.

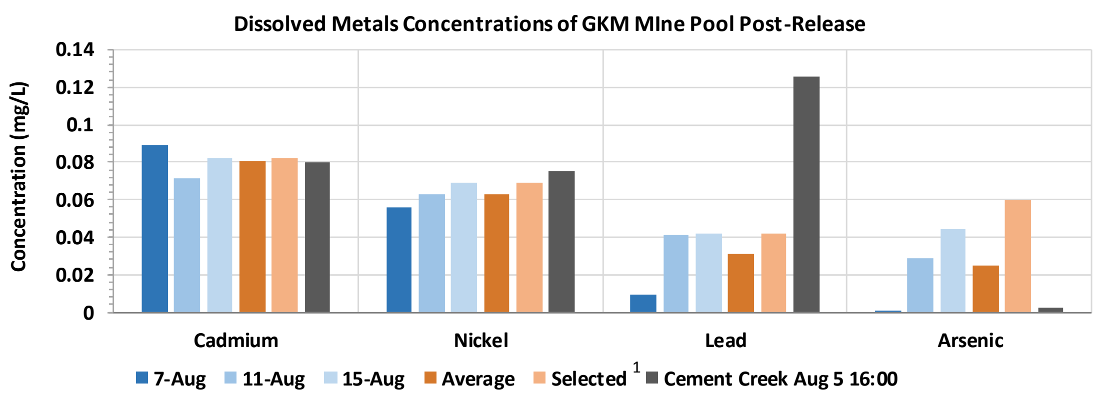
It is possible that none of the post-event samples represents the mine pool before the release when it was sealed. The only sample that may have represented the mine effluent at the time of the release was collected from Cement Creek far downstream at 16:00 hours, well after most of the plume had passed. The dissolved constituents in that sample minus estimated background stream concentrations are shown with the other estimates in Figure 3-11. Dissolved concentrations observed in Cement Creek were generally similar to the post event mine samples with several exceptions. Some dissolved metal concentrations in Cement Creek during the release plume were notably higher (aluminum, lead, and copper) and several were lower (arsenic, iron, manganese). Once the effluent left the mine, reactions within the stream could have altered the chemical makeup of the plume. Therefore, since the sample was collected from the mine the chemical concentrations appeared stable by August 15, that sample was the primary data used to represent each metal in the effluent. This choice does not influence mass calculations much since all possible choices vary relatively little from one another.

A)



[1]Selected to represent the dissolved metals concentrations in the GKM effluent at the time of the relase

B)



[1]Selected to represent the dissolved metals concentrations in the GKM effluent at the time of the relase

Figure 3-11. Comparison of dissolved metals concentrations measured in the Gold King adit. Dissolved concentration of metals in the August 15 sample were selected to represent most of the metals in the pre-event mine pool in calculating the release mass. Also shown are the average of the August 7, 11, and 15 samples, and the selected value. (Dissolved metals were not reported for the Sep 21 sample.) The dissolved concentration of the sample collected in the Gold King plume in lower Cement Creek August 5 16:00 is also shown for comparison.

3.3.3 Mass of Metals Released from GKM

Metals mass in the mine pool was calculated by multiplying the volume of effluent (11.33 million liters) by the concentrations of the metals and other constituents. A total of 2,900 kg of dissolved TAL metals, excluding the major cations, were released from the Gold King Mine, most of which was iron and aluminum (72% of the total). The higher loadings for trace elements included Zn (306 kg) and Cu (79 kg). The remainder of the trace metals totaled 5 kg; the mass of lead and arsenic were each approximately 0.5 kg. There were no measurable quantities of mercury released from the Gold King Mine. The mine effluent also contained sulfate SO_4^{2-} (18,000 kg), and the major cations (Ca, K, Mg, Na; 4,600 kg). Acidity load was calculated to be 7,600 to 8,100 kg $CaCO_3$, with this uncertainty reflecting the unknown valence state of Fe (Figure 3-12).

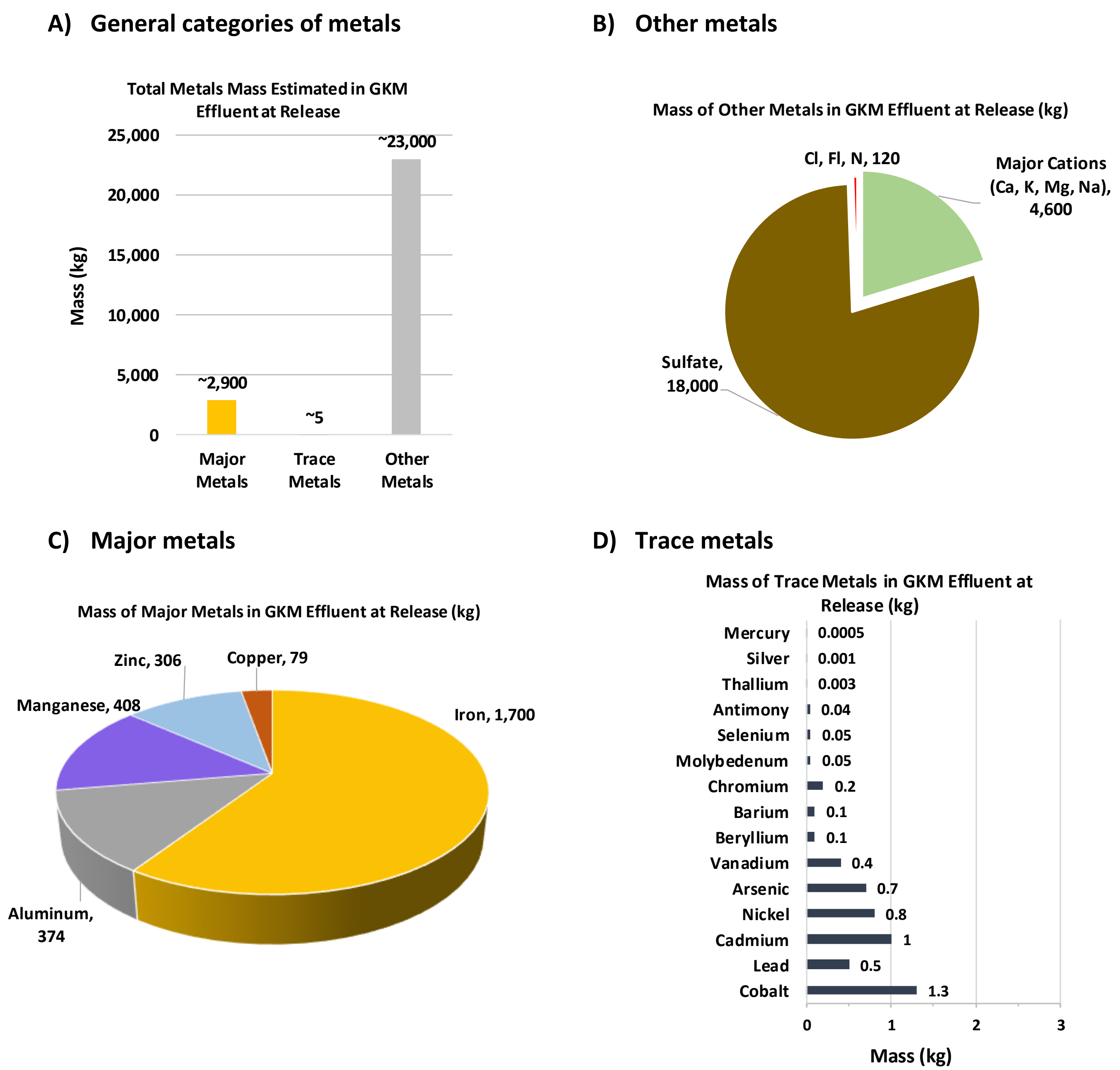


Figure 3-12. Mass of total metals in effluent released from the Gold King Mine. A) General categories of summed constituents. B) Metals including sulfates and the major cations calcium, magnesium, potassium, and sodium are included in "Other". C) Major metals including iron and aluminum that made up most of the load. D) Trace elements present in small quantities (< 1.3 kg).

3.4 Reconstruction of the Plume Created by the Gold King Mine Release in Cement Creek

The sudden release of pressurized water from within Gold King Mine sent an erosive flood of water to the North Fork and mainstem of Cement Creek. Crews captured the event on video (see https://www.epa.gov/goldkingmine); some stills extracted from the video are shown in Figure 3-13.

Outside the mine entrance, there was considerable opportunity for the acidic spill to entrain additional metals, most prominent of which was a large waste pile outside the mine entrance. A historical photograph of the level 7 entrance to the operating Gold King Mine prior to its full closure shows the significant size of the pile that had amassed over 40 years of operation (Figure 3-14). Mine waste piles are often very concentrated in metals, because they are the residual of ore processing. The release cascaded downslope to Cement Creek, excavating a portion of the waste pile (Figure 3-14). The void left after the release was determined, by EPA contractors cleaning up the site, to be approximately 7,645 m^3 (10,000 yd^3). Substantial amounts of mining waste and soluble salt minerals were eroded and likely carried downstream by the flood as part of the particulate load. Eroded material was vigorously washed in the acidic water for two hours as it traveled downstream before joining the Animas River. Depending on the mineralogy and pH, desorption of metals from the ores and dissolution of salts also likely increased the dissolved metals in the release depending on pH (Smith 1999, Nordstrom 2011). Since the release, contractors have recovered the eroded material from the stream and stabilized it.

Figure 3-13. Photographs of the Gold King release as it was occurring. Stills taken from a video shot by personnel on site (video can be viewed at https://www.epa.gov/goldkingmine.) The water rapidly flowed over the slope towards the North Fork of Cement Creek.

3.4.1 Characteristics of the Plume as it Traveled Through Cement Creek

Material that was eroded by the GKM effluent and transported with the plume through Cement Creek and delivered to the Animas River had to be accounted for in order to determine the full measure of metals mass generated from the Gold King Mine release. The sediment load was likely a mix of (1) clays eroded from the mine waste pile during GKM release, (2) clays (mostly Fe and Al oxyhydroxides) formed during oxidation and mixing with downstream transport, and (3) clays eroded from Cement Creek during turbulent mixing of the GKM plume.

A)

B)

Figure 3-14. Mine waste sediments were eroded with the Gold King release. A) Historic photograph of the mine waste pile outside the mine entrance where the breach occurred (Photo from BOR 2015); B) The released water that rushed from the mine eroded a portion of the mine waste pile outside the entrance (center of photo). The void left after the release was determined to be 10,000 cubic yards (7,645 m^3) by site contractors. Most of the eroded material was later retrieved from the North Fork of Cement Creek and stabilized.

The plume of metals generated from the release was reconstructed at the Cement Creek gage, located 12.5 km from the mine entrance. Reconstruction of plume metals composition accounted for metals delivered from within the mine (i.e., metals in GKM effluent) and those eroded by the flood of water outside the mine. The mass and concentrations of metals determined at this gage location was considered the mass and concentration of metals generated from the Gold King Mine release.

Plume reconstruction required estimates of concentration, including at the peak of the plume; duration of elevated metals; and streamflow. Duration of the plume and streamflow velocity and volume of the release were already determined in Sections 3.1 and 3.2 (see Figure 3-5).

The flow peak arrived at the Cement Creek gage (RK 12.5) at 12:45. The first water sample was collected from Cement Creek at 16:00, well past the peak and probably after the bulk of the mass had passed. Even this late in the plume, the summed concentrations of the 24 metals of focus was 12,225 mg/L (Figure 3-15), most of which was total recoverable iron and aluminum. This was a large increase in metals concentrations relative to what was observed in the mine effluent (656 mg/L). Most of the increase was in the colloidal/particulate fraction.

Based on the hydrograph, it is assumed that metals concentrations were much higher at the peak than when they were measured at 16:00. Different techniques were used to reconstruct the plume and estimate the peak colloidal/particulate and dissolved concentrations. Colloidal/particulate metals were initially entrained by physical erosion processes and probably behaved similarly to suspended sediment. The dissolved fraction would reflect mixing of the very low pH mine effluent in streamwater of somewhat higher pH. Dissolved metals could have also been augmented through chemical dissolution or desorption from ore and soil particles during transit through Cement Creek, in the turbulent flow of the highly-acidic water. As the plume flowed through Cement Creek, the chemical reactions leading to the formation of iron and aluminum (hydr)oxides probably began as well, albeit at a slow rate due to the low pH. In the absence of other information, a simple approach was used to increase concentrations based on the relative change in flow from the water sample collected at 16:00 for the duration of the plume in 15-minute intervals.

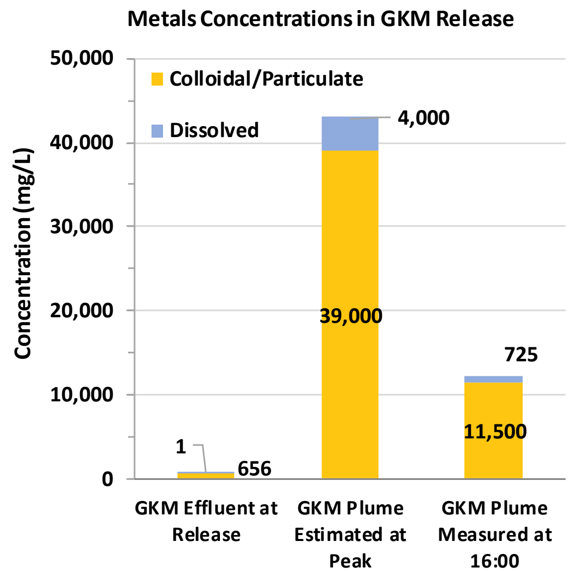


Figure 3-15. Comparison of summed metals concentrations in dissolved and colloidal/particulate fractions in the mine effluent; the measured concentration in the GKM plume in Cement Creek at RK 12.5 at 16:00 hours and the estimated concentration at RK 12.5 at the flood peak at 12:45.

Colloidal/Particulate Metals Concentration. The Gold King plume began abruptly at the Cement Creek gage at 12:45. Peak colloidal/particulate metals concentrations were assumed to have occurred at the same time as the peak flow. At the peak, flow was 3.52 times greater than that at 16:00, when the metals concentrations were initially measured at USGS gage 09358550 (Figure 3-5). The concentration of each metal at the peak was reconstructed by multiplying its concentration measured at 16:00 by this 3.52 flow factor. The measured colloidal/particulate metals concentrations, estimated metals concentrations at the plume's peak, and the metals concentrations measured in the Gold King Mine effluent post-event are shown in Figure 3-15.

This flow comparison was repeated for each 15-minute time step and the metals concentration calculation repeated. Therefore, the total mass of the plume directly traced with the flow. After 16:00, the effect of flow was small, but metal concentrations remained elevated. From 16:00 to the end of the plume, metals concentrations in the water were linearly interpolated between the measured samples. The concentration trace is shown in Figure 3-18.

The impact of the waste pile erosion on peak concentrations was evident. Both dissolved and colloidal concentrations measured at 16:00 were significantly higher than in the Gold King Mine effluent at the time of the release, and metals concentrations at flow peak were estimated to be roughly 3.52 times greater than those measured at 16:00 using the techniques and assumptions that were applied.

Dissolved Metals Concentration. Dissolved metals concentrations in the Gold King plume were reconstructed using a mixing model approach. The GKM effluent concentrations and volume were mixed in proportion to the background concentrations and flow volume in Cement Creek, taking into account the pH of Cement Creek as the plume passed through (Figure 3-16). Background metals concentrations were determined from water samples collected by CDPHE in Cement Creek upstream of the Gold King Mine and downstream to the confluence with the Animas River two weeks after the release. Flow was apportioned between the Gold King Mine effluent and natural streamflow during the plume; background flow was the baseflow at 12:30, prior to the arrival of the plume. Initially, the plume made up almost 80% of the flow at Cement Creek (Figure 3-16A).

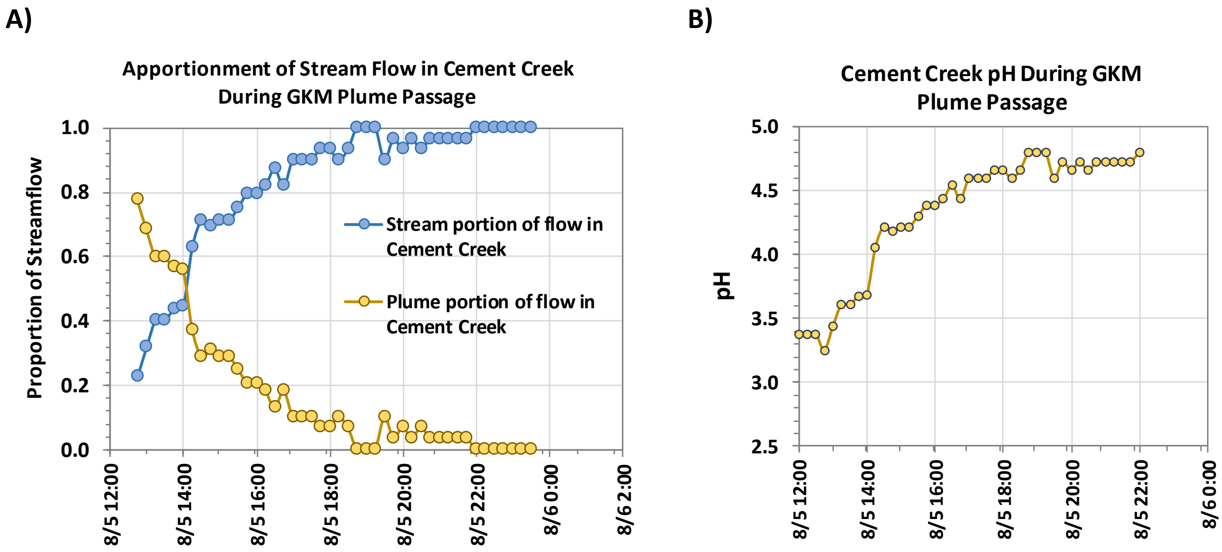


Figure 3-16. Relative mixing of Gold King Mine effluent with Cement Creek waters during the 8 hours of elevated flow. A) Initially the effluent made up 80% of the flow in Cement Creek, returning to normal flow by approximately 18:30. The effluent was 20% of flow when the first water sample was collected at 16:00. B) Estimated pH as a result of mixing was close to 3 on the leading edge of the plume.

This analysis assumes that the effluent emptying from the mine was uniform in composition during the entire release. No pH measurements were taken in Cement Creek during passage of the Gold King plume. Background pH was estimated at 4.8, based on a series of measurements through Cement Creek two weeks after the release, and as described earlier, the pH of the mine water taken from Gold Creek Mine during the August 15 sampling event was 2.93. Using these values, the pH of Cement Creek was estimated during passage of the GKM plume and ranged from approximately 3.5 to 4.8 (Figure 3-16B), varying as the slug moved through the creek.

The low pH typical of Cement Creek was enhanced as the highly-acidic "front" passed early in the plume. The suspension of soluble mineral salts in the suspended load of the spill probably resulted in the dissolution of metals as the plume passed through Cement Creek. When studying the quality of mining-degraded watersheds, Nordstrom (2011) noted that initial flushes of water leaving watersheds after precipitation events are highly enhanced in mining-related solutes as evaporated salts are solubilized. The plume was different from rainfall, but may have had similar effects as evidenced by the sample collected from Cement Creek at 16:00. After partitioning the flow and separating background metals from those in the effluent, the dissolved concentrations of most metals were higher than would be predicted from the mixing of stream water and effluent alone. The dissolved concentrations of Cu, Zn, Al, and Mg, in particular, increased substantially from sources other than the effluent (Figure 3-17). This particular group of metals is soluble in the pH range of 4 to 5 (Smith 1999; Nordstrom 2011), indicating solution of solids to dissolved fractions could have occurred in the pH environment in the stream during the event. Concentrations of arsenic (As) and lead (Pb) were consistent with concentrations in the mine effluent (as the pH of Cement Creek was too high for these metals to desorb), as were concentrations of nickel (Ni) and cadmium (Cd), because the pH of Cement Creek was too low and these metals had already desorbed.

Under these pH conditions, concentrations of Al, Ca, and perhaps Fe, likely were buffered in Cement Creek at near equilibrium with mineral phases, including alunite [$KAl_3(SO_4)(OH)_6$], gypsum ($CaSO^4 \bullet 2H_20$), and perhaps jarosite [$Fe^{3+}{}_3(OH)_6(SO_4)_2$], or other similar minerals. Other than dissolution/precipitation of these soluble mineral phases, however, few other chemical changes likely occurred in the spill waters during the short residence time in Cement Creek (i.e., 2–8.5 hrs).

Time-dependent total and dissolved metals concentrations in Cement Creek (C_{obs}) during plume passage were estimated using a general mixing model (Equation 3.1) that assumed a time-invariant concentration in the mine discharge (C_{GKM}), a time-invariant background concentration in Cement Creek (C_{bkg}), and the time-dependent flow ratios shown in Figure 3-16. First, C_{GKM} was estimated using observed concentrations in Cement Creek at 16:00 (Equation 3.2):

$$C_{\mathrm{obs}}(t) = C_{\mathrm{GKM}}\left(\frac{Q_{\mathrm{GKM}}(t)}{Q_{\mathrm{GKM}}(t)+Q_{\mathrm{bkg}}(t)}\right) + C_{\mathrm{bkg}}\left(\frac{Q_{\mathrm{bkg}}(t)}{Q_{\mathrm{GKM}}(t)+Q_{\mathrm{bkg}}(t)}\right) \qquad \text{Equation 3.1}$$

$$C_{\mathrm{GKM}} = \left[C_{\mathrm{obs}}(16:00) - C_{\mathrm{bkg}}\left(\frac{Q_{\mathrm{bkg}}(16:00)}{Q_{\mathrm{GKM}}(16:00)+Q_{\mathrm{bkg}}(16:00)}\right)\right] \Bigg/ \left(\frac{Q_{\mathrm{GKM}}(16:00)}{Q_{\mathrm{GKM}}(16:00)+Q_{\mathrm{bkg}}(16:00)}\right) \qquad \text{Equation 3.2}$$

To account for the "first flush" effect (Nordstrom 2011), the concentrations of metals in the first two 15-min time steps were doubled after solving the mixing computations. The total and dissolved metals concentrations estimated in the Gold King plume (minus cations) as it traveled through Cement Creek are shown in Figure 3-18. Both total and dissolved metals calculations are strongly dependent on streamflow and trace the flow hydrograph. Similar concentration traces were prepared for each metal The estimates of peak dissolved concentrations in Cement Creek were evaluated using Geochemists' Workbench® (see Appendix C for additional discussion of this geochemistry analysis). The mixture produced at the estimated concentrations shown in Figure 3-18B would be supersaturated with gypsum ($CaSO^4 \bullet 2H_2 0$) and other minerals. This suggests that the metals concentrations at the peak of the plume are most likely overestimated for at least some solutes (See Appendix C).

3.4.2 Metals Mass Delivered to the Animas River

The metals mass delivered to the Animas River from the Gold King Mine release was calculated by multiplying flow volume by the metals concentrations estimated in Cement Creek (Section 3.4.1) and summing for the period from 12:45 on August 5, 2015 to 6:00 on August 6, 2015. The period of flow was extended past the end of the flow-defined period because concentrations of metals remained elevated until the following day even though flow levels did not.

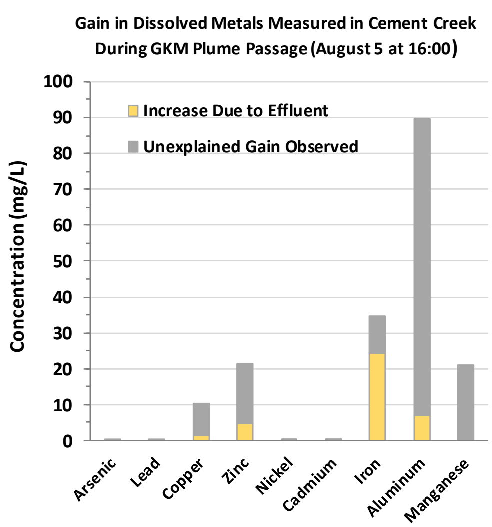
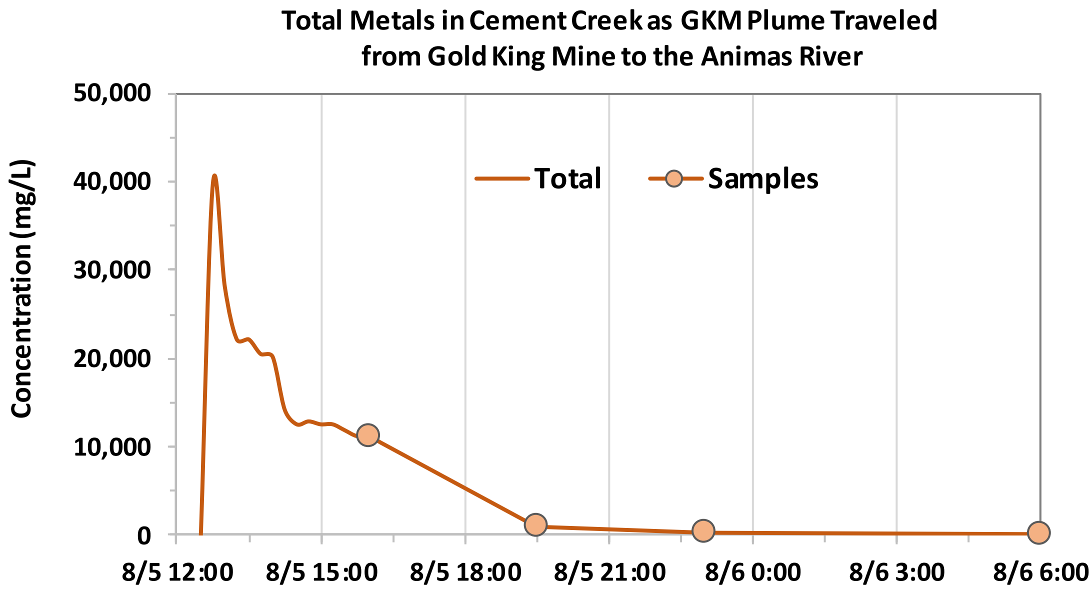


Figure 3-17. Dissolved concentrations of metals observed in Cement Creek at 16:00 relative to the mine effluent. After mixing the effluent with Cement Creek (e.g., Figure 3-16), a portion of the increase was explained by concentrations from the mine effluent.

A)



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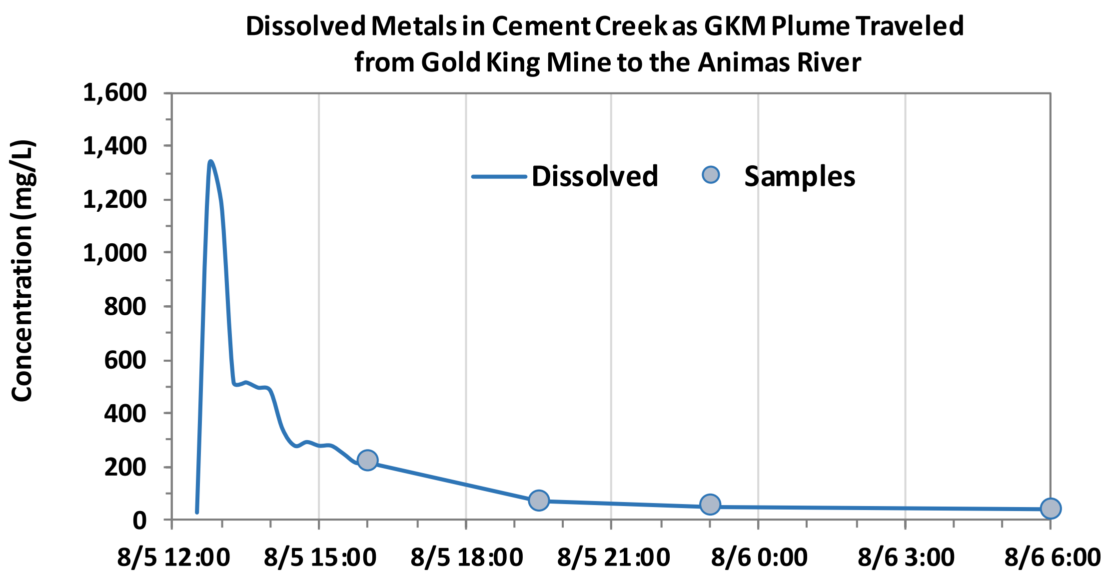


Figure 3-18. Estimated metals concentrations in Cement Creek near the confluence with the Animas River during the Gold King plume. Shown is summed metals, with sample times indicated. The peak of the plume was estimated and the remainder of the concentration trace was guided by flow and the measured sample. A concentration trace was needed for each metal fraction; A) Total metals, B) Dissolved metals.

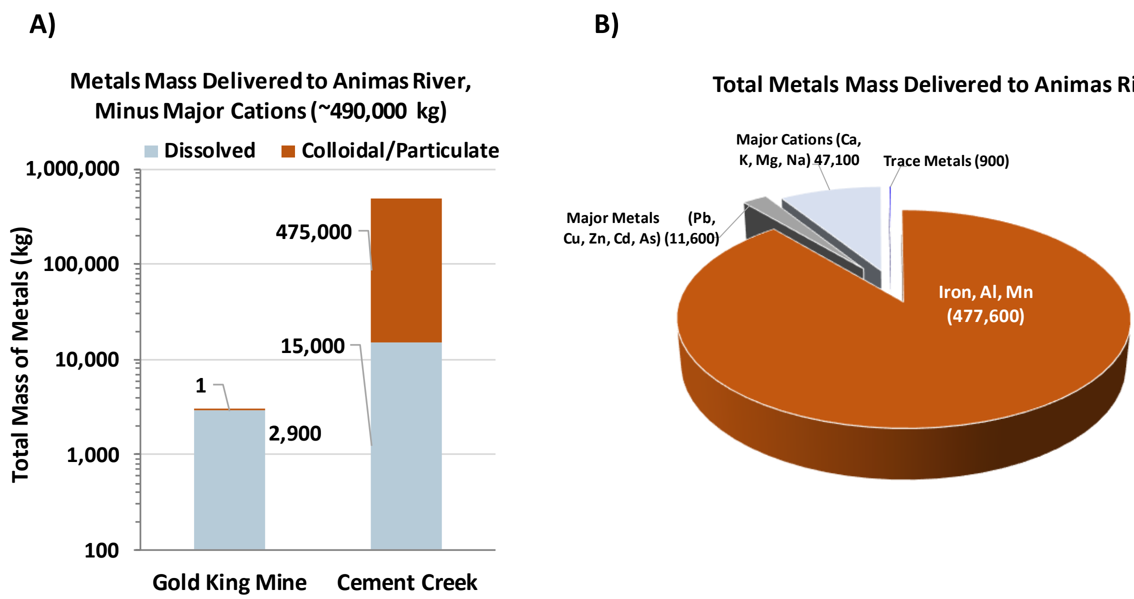


Figure 3-19. Estimated mass of metals delivered to the Animas River from the Gold King release. A) Comparison of dissolved and total metals mass from inside the mine and estimated at Cement Creek. Note data are presented on a log scale. B) Composition of the summed total metals mass released to Cement Creek.

Erosion of waste material outside the mine significantly increased the metals mass relative to what came from inside the mine (Figure 3-19). The total estimated mass input of metals, minus cations, to the Animas River from Cement Creek was approximately 490,000 kg; of this total, approximately 475,000 kg were colloidal/particulate metals and approximately 15,000 kg were dissolved metals (Figure 3-19; Table 3-2). By far, the biggest constituents were Fe, making up 433,086 kg of the total metals mass, and Al at 41,132 kg. Together, these metals accounted for over 96% of the metals, minus cations, in the Gold King Mine release. The plume carried approximately 47,100 kg of major cations (Ca, K, Mg, and Na), and approximately 11,600 kg of Pb, Cu, Zn, Cd, and As (Figure 3-19). Particulate lead was a significant component, having increased to 7,658 kg in Cement Creek from just 0.5 kg in the mine effluent. The trace metals increased from approximately 5 kg in the mine effluent to 900 kg in the GKM plume. The mass of dissolved and colloidal/particulate fractions of individual metals delivered to the Animas River from the Gold King Mine release are shown in Figure 3-20.

There is significant uncertainty in the estimates of concentration and mass of dissolved and total metals for the release given the assumptions required to estimate peak concentrations. In the absence of other supporting information, both reconstructions applied arbitrary methods for estimating the peak from one sample collected very late in the plume. There was no real way to validate either the metals concentrations or mass loads estimated in Cement Creek from the Gold King Mine release.

The volume of material eroded from the waste pile outside Gold King Mine during the release was approximately 7,645 m^3 (10,000 yd^3). This mass is much more than needed to account for the increased metals concentrations and mass estimated in the Gold King plume as it traveled through Cement Creek. However, the question remained as to whether the estimates of material carried downstream to the Animas River during the Gold King Mine release were high enough.

Table 3-2. Estimated Mass of Metals Delivered to the Animas River from the Gold King Mine Release

Metal	Total (kg)	Dissolved (kg)	Colloidal/Particulate (kg)
Aluminum	41,132	6,376	34,755
Antimony	14.2	0.173	14.0
Arsenic	358.4	2.9	355.4
Barium	417.6	2.2	415.4
Beryllium	6.0	2.4	3.6
Cadmium	7.7	7.0	0.7
Calcium	30,484	30,345	139
Chromium	30.6	0.38	30.2
Cobalt	17.7	14	3.7
Copper	1,615	731	884
Iron	433,086	3,750	429,335
Lead	7,658	11.2	7,647
Magnesium	15,891	2,490	13,401
Manganese	3,599	2,581	1,018
Mercury	0.8	0.0001	0.8
Molybedenum	86.8	0.4	86.4
Nickel	12.5	6	6.2
Potassium	11,854	426	11,428
Selenium	11.2	0.4	10.8
Silver	47.4	0.2	47.3
Sodium	1,427.4	290	1,137.1
Thallium	5.6	0.2	5.4
Vanadium	237.8	0.8	237.0
Zinc	2,059	1,904	155
Total Metals	**550,060**	**48,942**	**501,118**
Major Cations	**59,656**	**33,551**	**26,106**
Total Minus Cations	**490,404**	**15,391**	**475,012**
Sulfate	18,170		
Chloride	13.63		
Fluoride	114.0		
Nitrate as N	0.28		
Total All Constituents	**568,358**		

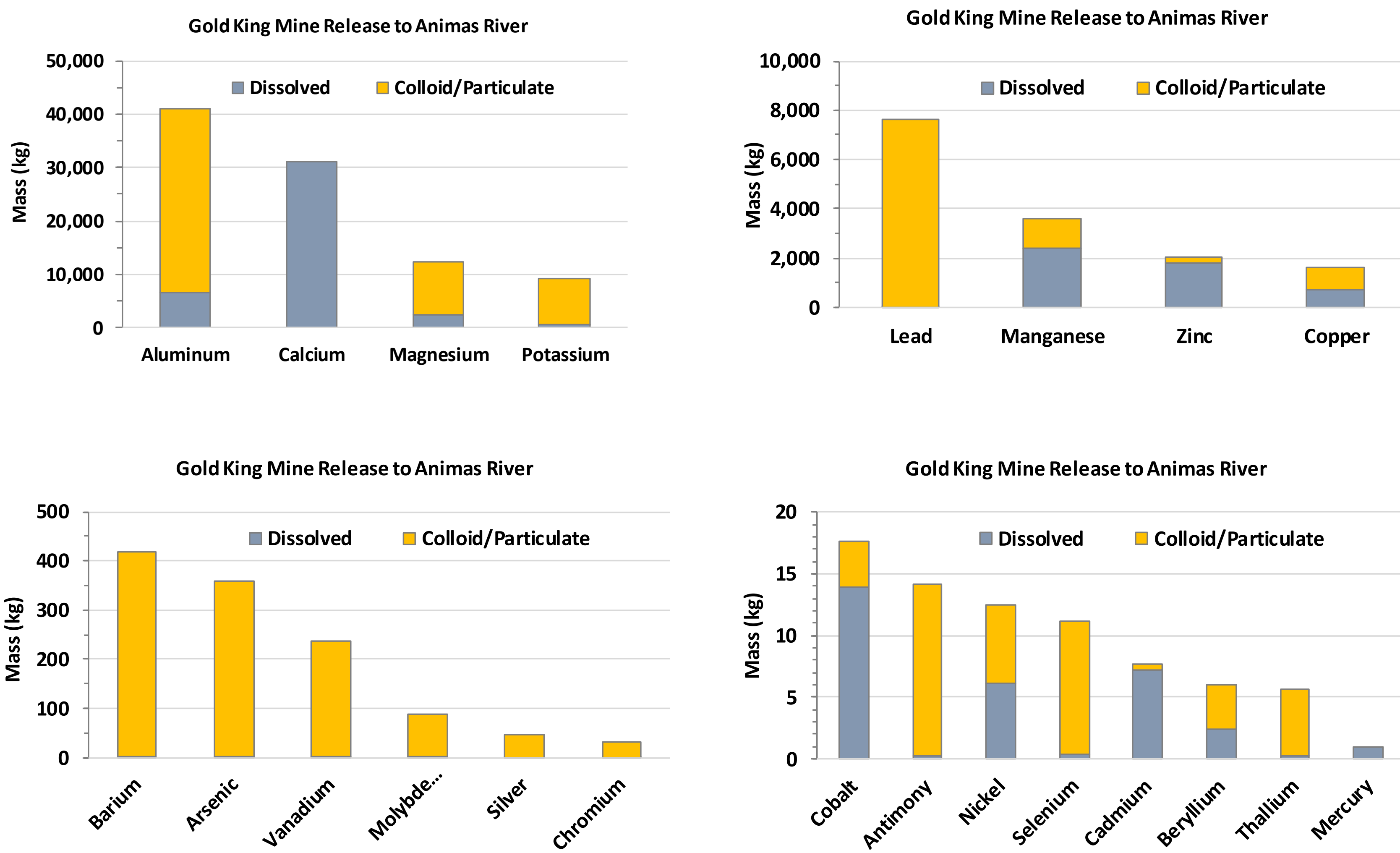


Figure 3-20. Colloidal/particulate and dissolved metals load, by metal, delivered to the Animas River from the Gold King Mine release. Iron, not shown, was the largest constituent making up 88% of load.

CHAPTER 4 CHARACTERISTICS OF THE GOLD KING PLUME AS IT TRAVELED

The Gold King Mine release generated a volume of acidic water and metals that mixed into the Animas River near Silverton, Colorado and traveled with the ambient flow for 9 days until it eventually reached Lake Powell in Utah, a distance of 550 km (Figure 4-1). The plume initially arrived from Cement Creek (RK 12.5) as a highly-concentrated slurry carried in a slug of acidic water (pH close to 3 initially) and contained approximately 490,000 kg of dissolved and colloidal/particulate metals. Plume composition was dynamic and changes occurred rapidly as the river moved at a pace of almost 2 mph over a distance equivalent to a trip between Boston and Washington or San Francisco and Los Angeles.

Quantifying the water quality characteristics and chemical transformations that occurred during migration of the Gold King plume required consideration of the hydrodynamic and geochemical processes that transformed it as it moved. For those analyses to be realistic, it was critical to accurately quantify plume characteristics at multiple locations along the rivers. The characteristics that had to be understood in order to replicate release concentrations and mass were the concentration peaks and "shape," which defined the rise and fall of concentration, and the streamflow velocity and volume, which determined the travel time and metals mass. No two places along the river system experienced exactly the same plume (Figure 2-1).

A)

B)

Figure 4-1. Gold King plume as it moved through A) the Animas River at Silverton and B) the Animas canyon between RK 30 and RK 63.

This chapter establishes the movement and general characteristics of the Gold King plume as it passed through the Animas and San Juan Rivers, using field observations assisted by modeling. A variety of data and observations were available that allowed the plume to be quantified. The hydrographic records from USGS gages, water quality parameters from six continuously-recording sondes, and more than 250 water samples collected by field crews were synthesized to characterize the overall behavior of the Gold King Mine release during plume movement. The WASP model was also initiated at Cement Creek with the metals concentrations and flow conditions quantified in Chapter 3. WASP provided an independent estimate of the travel time and concentrations.

The synthesized observations were used to complete parameterization of an empirical model of plume metals concentrations and mass at select locations along the river. The WASP model and the empirical model provided both dynamic and location-specific quantification of the GKM plume movement and characteristics throughout its course; this provided the basis for quantifying metals concentrations and transport and deposition of mass in the rivers in subsequent chapters.

4.1 Observations of the Gold King Plume

Streamflow originated high in the San Juan Mountains and was low to moderate in the Animas River when the Gold King plume entered. Streamflow in the Animas River was receding from a summer storm several days earlier when the release occurred. The water of the Animas River was clear and its constituents were mostly the dissolved cations Ca, K, Mg, and Na (referred to in this report as major cations).

The slurry of metals and acidic water dramatically altered the metals content and coloring of the Animas River; coloring of the river, as seen in Figure 4-1, intensified as the plume traveled further. The Gold King Mine plume was readily observed through the 192-km length of the Animas River, where it traveled over three days before joining the San Juan River in Farmington, New Mexico. The turbidity of the water in the San Juan River obscured visibility and measurement of the plume through the next 360 km of travel. Most of what we learned about plume movement is understood from observations of the Gold King plume in the Animas River.

4.1.1 Hydrology and Plume Volume

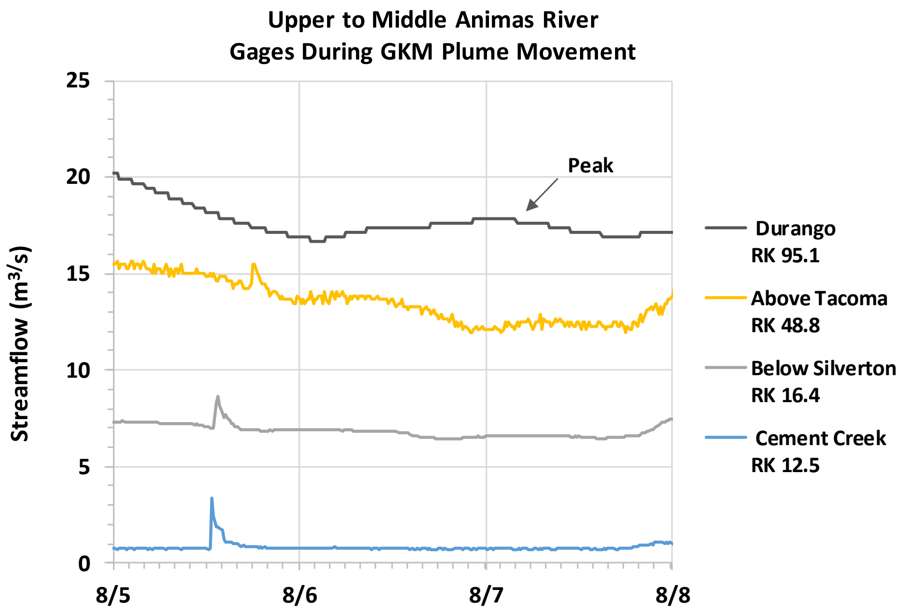
The Gold King Mine release surged into the Animas River at Silverton, Colorado as both a plume of metal mass and a wave of water. Late summer (monsoonal) storms are characteristic of this region, and flow was receding from one when the GKM release occurred. On a normal summer day, Cement Creek contributes about 20% of the combined flow of the Upper Animas River and Cement Creek at their confluence. That percentage rose to 50% in the first 15 minutes of the plume (see Figure 3-4).

Plume movement through the upper Animas River was documented at the USGS gages below Silverton (RK 16.4) and above Tacoma (RK 48.8). The same rapid rise and fall of the hydrographs seen at the Cement Creek gage (see Figure 3-5) was also observed at these gages (Figure 4-2).

Gage hydrographs normalized to baseflow illustrate the relative increase in flow in the upper Animas River as the GKM plume passed (Figure 4-3A). The relative rise in flow less at each of the gages in the upper watershed in the downstream direction, as the river gained substantial volumes of flow (Figure 4-3A). The relatively small volume of released water was more difficult to reliably separate from river flow in the middle and lower segments of the Animas River and the San Juan River.

Gage hydrographs normalized to the peak highlight the relative duration and shape of the plume mass (Figure 4-3B). The three upper gages were very similar in duration and relative change as the plume passed, although the peak lagged in time of arrival at successive gages. Most of the rise and fall of the hydrographs for the three upper gages occurred within three hours (i.e., twelve 15-min time steps) of plume arrival at these locations (Figure 4-3B). The normalized hydrographs suggest that the duration of detectable flow was probably as short as five hours in length (i.e., twenty 15-min time steps) at downstream locations.

A)



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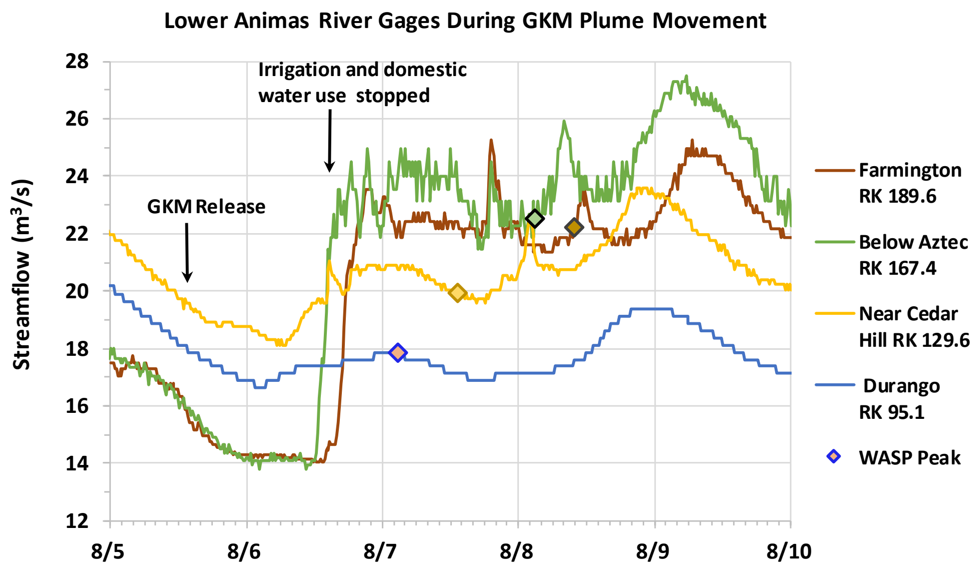


Figure 4-2. Hydrographs at USGS gages in the Animas River during passage of the Gold King plume. A) Flow from August 5 to August 8, 2015 at upper Animas gages at Cement Creek, Animas below Silverton at RK 16.4, Tacoma/Tall Timbers at RK 48.8 and Durango at RK 95.1). B) Flow from August 5 to August 10, 2015 at USGS gages in the lower Animas River at Cedar Hill at RK 129.6, Aztec at RK 167.4, and Farmington at RK 190.2). WASP estimated time of plume peak time is plotted on the lower Animas gage traces.

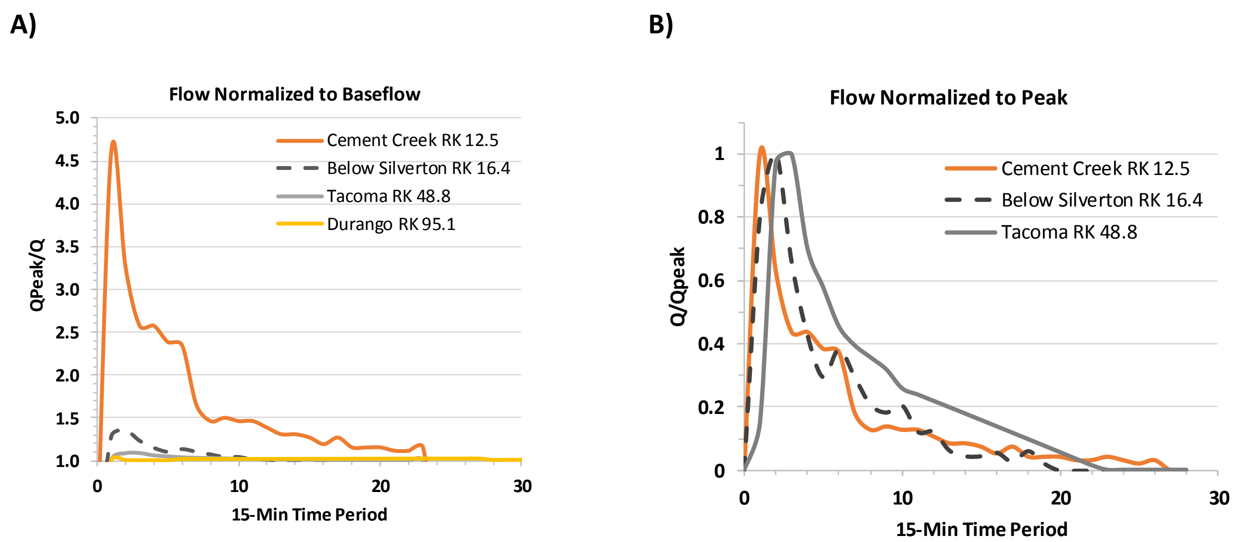


Figure 4-3. Normalized hydrographs of streamflow (Q) at 3 upper Animas River gages. A) Peak streamflow normalized to baseflow (Q at peak/Q for time period) showing relative rise in flow at each gage. B) Flow normalized to the peak (Q for time period/Q at peak), illustrating the relative duration and change in water volume in the gage record.

Hydrology in the lower Animas River from Durango, Colorado south to the San Juan River was notably disrupted from what is normally observed as the plume traveled through the area from August 6 to August 10, 2015 (Figure 4-2B). In downstream segments of the Animas River, water withdrawals for public water supply, irrigation, and agriculture were halted as an emergency spill response measure. This shutdown occurred on August 6, immediately increasing flow by 70%.

Ideally, the volume of water and the mass of metals could be tracked in the river system as the plume flowed through the Animas and San Juan Rivers. We began by analyzing the water, as the flow records were also important for establishing plume movement.

Gold King Plume Volume. The plume volume was calculated as the cumulative excess flow above baseflow at USGS gages during passage of the GKM plume (Figure 4-4). The plume was located directly from the USGS flow record if it could be clearly identified (e.g., Figure 4-2A). Where the flow records did not indisputably identify the plume water volume, the timing was confirmed by sondes and/or WASP modeling predications.

If baseflow was receding or increasing, the baseflow at the start of the plume was adjusted to match flow at the end of the plume period by simple interpolation. Plume flow was assumed to be 5 hours in length (see Figure 4-3B), so cumulative volume was summed for a period limited to 5 hours. To account for the 11.33 million L volume of the GKM plume delivered to the Animas River, a rise in flow of 0.63 m^3/s (22 cfs) would be required over the five-hour period.

Cumulative excess flow above baseflow was calculated using published flow records for the gage in the Animas River below Silverton, Colorado (USGS gage 09359020; RK 16.4); this calculation identified a plume volume of only 5 million L (1.3 million gal) or about 44% of the plume volume delivered to the Animas River from Cement Creek. A check of the gage record suggested inconsistencies between the approved flow and what would be estimated using the adjusted rating curve provided by USGS with the station data. Recalculating flow with the adjusted rating curve and gage height record for the short plume interval, the plume volume at this gage was calculated to be 7.5 million L (2.0 million gal). This revision was an improvement, but still failed to account for one third of the initial plume volume delivered to the Animas River (Figure 4-4).

Approximately 80 km downstream, at the gage at Durango, Colorado (USGS gage 09361500; RK 95.1), there was almost no flow signal when the Gold King plume was known to have arrived (Figure 4-2). The recorded rise in flow at this gage was just 0.25 m^3/s (8.8 cfs) relative to a baseflow of 17.6 m^3/s (622 cfs). At this observed flow, a volume of water equivalent to the plume volume (11.33 million L) would pass the gage in less than 10 minutes suggesting detection of the plume volume could be difficult.

Detecting the volume of plume water in the lower Animas River was hampered by generally-unusual hydrographs (e.g., Figure 4-2B) and rather poor-quality hydrology records published for several of the USGS gages during this period; data at one gage below Aztec, New Mexico (USGS gage 09364010; RK 167.4 still remains provisional. The flow records at the lower Animas River gages were choppy, fluctuating as much as 0.5–1.5 m^3/s (17.7–53.0 cfs) from one 15-min period to the next. For example, at three gages in the lower Animas River from Cedar Hill to Farmington, New Mexico (RK 129.6 to 189.6), several small to moderate flow peaks occurred within a reasonable arrival window for the Gold King plume (Figure 4-2B), although only one of those could have been associated with the GKM plume peak, itself.

The variable gage records contributed to uncertainty in reliably tracking the plume volume in the lower Animas River. Where uncertainty existed, the timing was confirmed by sondes and/or WASP modeling predications, as described later in this chapter. Despite the flow record uncertainties, a plume volume ranging from 6.3 to 12.8 million L was identified at the gages (Figure 4-4). As soon as the plume entered the Animas River, there was an accounting loss of 1/3 of the volume that was measured reliably in Cement Creek. Downstream estimates were increasingly uncertain due to the small volume in the plume relative to large volume of river flow and the quality of the flow records.

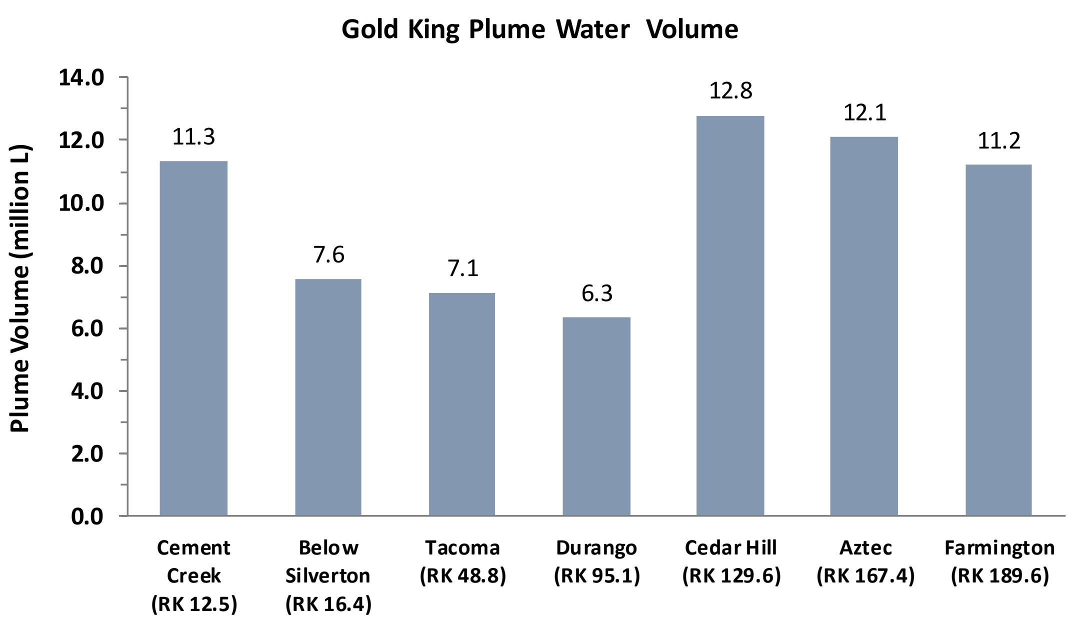


Figure 4-4. Excess water volume above baseflow at USGS gages during passage of the Gold King plume. The time of plume passage was determined by USGS observed peaks, WASP model predictions and sondes. Baseflow was estimated as flow at the time of arrival and was adjusted to the baseflow at the end of the flow to account for changing flow during the interval. The hydrograph was limited to 6 hours.

4.1.2 Water Quality Observed at Continuously Recording Sondes

Plume travel through the lower Animas River was recorded by five continuously-recording sondes that documented its passage through 85 km of the river (Figure 4-5). Three sondes were operated by the Southern Ute Indian Tribe (SUIT) between RK 104.1 and 131.5, as the river flowed through tribal lands (i.e., at RK 104, 109, and 132), and two were operated by the New Mexico Environment Department (NMED) at RK 164.1 near Aztec and RK 189.4 in Farmington. All five sondes measured specific conductance (SC), pH, and dissolved oxygen; in addition, the NMED sondes also measured turbidity and the SUIT sondes measured dissolved oxygen concentration and saturation. Although the sondes did not measure metals directly, the instruments established travel time through the lower Animas River with parameters that correlated with the chemistry of the plume. SC, in particular, was used, as it is an indicator of the presence or absence of conducting ions in solution and is often related to total dissolved solids. The traces of SC measured by the five Animas River sondes are plotted in Figure 4-5.

The continuously-recording sensors on board the sondes traced the rise and fall of the plume's dissolved and colloidal solids as it passed. The minimums and maximums provided an observation of both travel time and concentration shape of the plume. Figure 4-6 shows the arrival times for the GKM peak at three locations in the lower Animas River (as estimated by WASP) superimposed on the USGS gage hydrograph and the sonde-measured specific conductance. The timing of the WASP peak agreed well with the SC peak at these locations, but not with the flow peak recorded by the USGS gages; only the gage in Farmington, New Mexico was close to the WASP- and sonde-defined peaks.

The hydrograph peak trailed behind the plume defined by the sonde parameters and WASP modeling at each of the three sites (Figure 4-6). The hydrology peak ranged from 10.5 hours later at Cedar Hill, New Mexico to 3.5 hours later at Farmington, New Mexico. The hydrograph of the GKM plume at these lower Animas River sites was short (~4 hours) and the volume above baseflow was similar to what was produced by the plume in Cement Creek, but several factors suggested that the peaks shown in the hydrographs were not the Gold King plume.

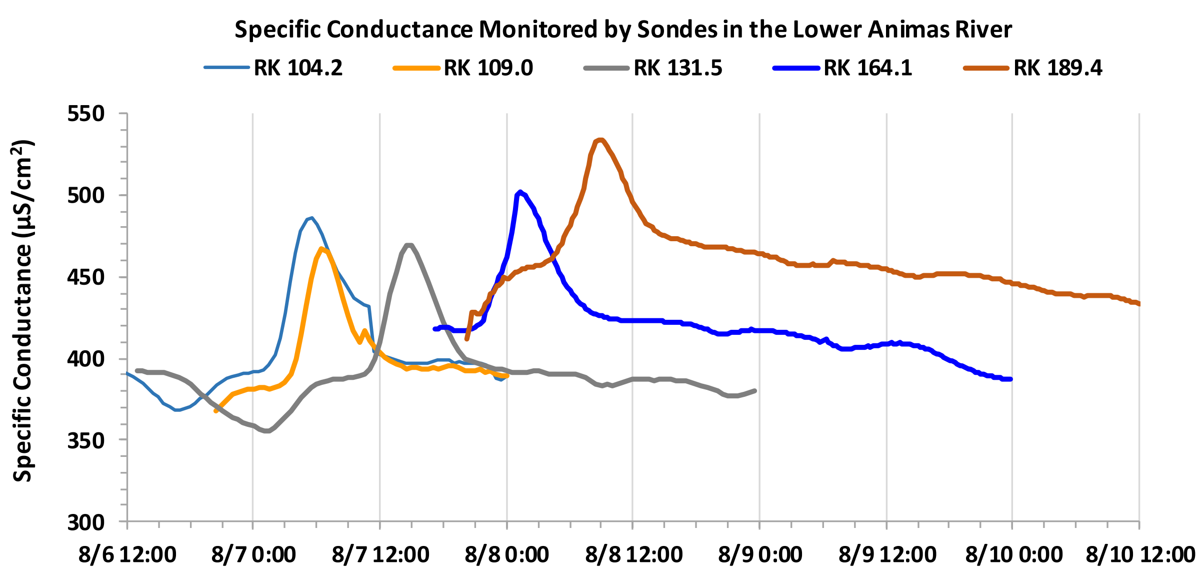


Figure 4-5. Plume movement was measured by continuously recording sondes measuring specific conductance at five locations in the lower Animas. Sites are identified by distance from source. Sites at RK 104.2, 109.0 and 131.5 were operated by the Southern Ute Indian Tribe. Sites at 164.1 at Aztec NM and 189.4 at Farmington NM were operated by the New Mexico Environment Department.

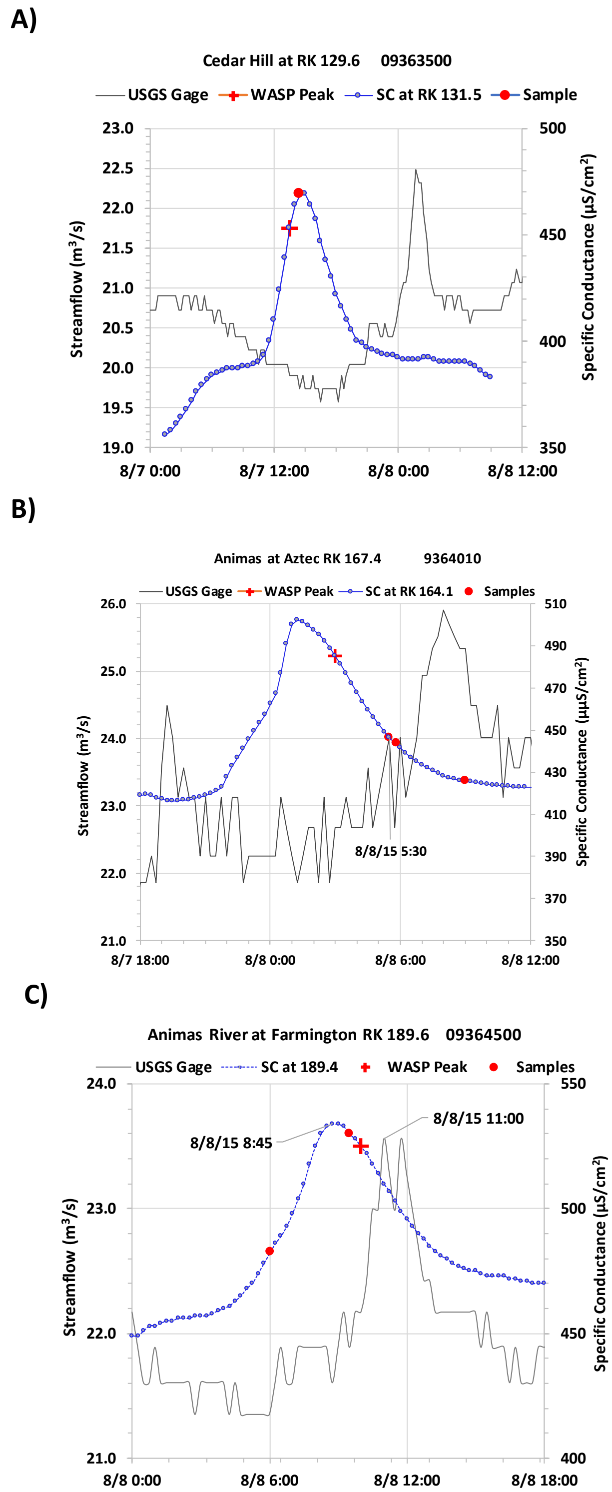


Figure 4-6. Flow and specific conductance (SC) at three locations in the lower Animas River during plume passage A) SC at RK 131.5 near the gage at RK 129.6, B) SC at RK 167.1 near the gage at RK 167.4, and C) SC at RK 189.4 near the gage at RK 189.6. SC recorded by sondes is shown in blue dots. The hydrograph is shown in gray. WASP predicted time of plume peak and the timing of samples collected near peak is plotted on the SC trace.

Peak flow rates in the lower Animas River increased more than they did in the upper Animas River, including in Durango, Colorado where there was no sharp increase in flow observed at the time the plume was known to pass. Similarly, the direction and magnitude of changes in metals concentrations between samples (discussed more in Chapter 5) was better explained by the sonde trace than the hydrograph trace. This suggested that the trailing hydrograph observed at the three gages in the lower Animas River may have been an event unrelated to the GKM release. Given the uncertainties in the hydrographic record, it was determined that the water mass of the plume could not be reliably established from Durango, Colorado southward.

4.1.3 Passage of the Plume at Sondes

The sonde parameters followed similar patterns in rise and fall as the plume passed, but they did not peak at the same time. Specific conductance and turbidity are shown as the Gold King plume passed through the Animas River at RK 189.4 (Farmington) in Figure 4-7. This same pattern was illustrated at each of the sondes in the Animas and San Juan Rivers. Peak arrival statistics are provided in Table 4-1. SC was always the first parameter to peak upon arrival of the GKM plume, followed by a pH trough within 30–60 min. A peak in turbidity trailed a peak in pH by 15 to 75 minutes and SC by up to 120 min. These sonde observations suggested that there was no single arrival time of the GKM plume peak, as measured by individual parameters, possibly including water mass.

The consistency of this pattern at each of the sondes suggested that the plume was stratified in "fronts" or zones, with dissolved ions leading, followed by a low-pH acidic band, and trailed by colloidal precipitates and particulates (Figure 4-8.). It appeared that the dissolved metals within the initial Gold King plume were pushed in front, and as chemical reactions occurred in the low-pH center, a trail of colloidal/particulate material was left, elongating the tailing edge of the plume. At the velocities suggested by peak times, these reaction fronts were likely 1–2 km in length.

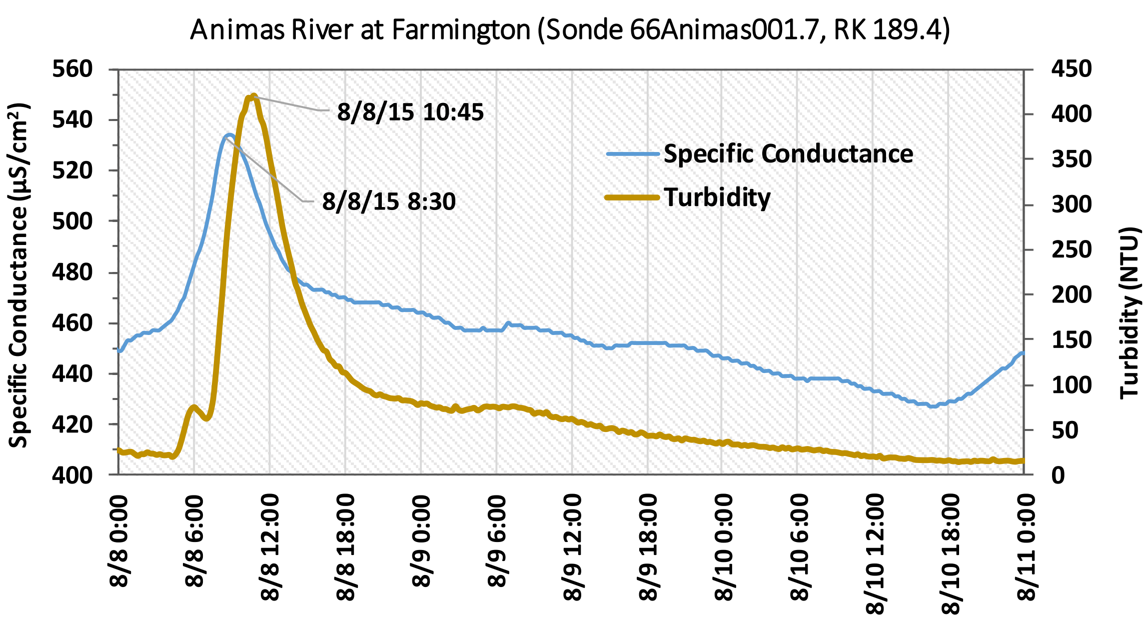


Figure 4-7. Continuous record of specific conductance and turbidity at the sonde measuring the Animas River at RK 189.4 in Farmington NM. The turbidity peak trailed the specific conductance peak by 2 hours. Other locations showed similar offset peaks in individual parameters. (See Table 4-1).

Table 4-1. Statistics of time of peak in sonde parameters at five sonde locations in the Animas River and one in the San Juan River at Farmington. The time for SC identifies the arrival time of the peak as this parameter always peaked first. The additional time to arrive for pH and turbidity are added to the SC arrival time.

		Sonde Measured Peak Arrival		
Sonde Name	**Distance from GKM Source (km)**	**SC**	**pH**	**Turbidity**
AR 19-3	104.0	8/7/15 5:30	+ 30 minutes	
AR 16-0	109.0	8/7/15 6:30	+ 60 minutes	
NAR 06	132.0	8/7/15 14:30	+ 60 minutes	
66Animas028.1	164.1	8/8/15 1:15	+ 60 minutes	+ 75 minutes
66Animas001.7	189.4	8/8/15 8:45	+ 45 minutes	+ 120 minutes
67SanJua088.1	204.5	8/8/15 13:45[a]	+ 45 minutes	+ 45 minutes

[a] Uncertainty in arrival time of SC with instrument malfunction

4.1.4 Plume Concentration Shape

To assess plume “shape” from sonde data, the SC plume traces shown in Figure 4-5 were normalized by dividing each 15-min observation into the peak value (maximum value = 1); results are shown in Figure 4-9. Measured values differed at each location, reflecting the differences in background and plume metals and cation concentrations. However, the normalized plumes in Figure 4-9 show that specific conductance maintained a consistent general shape as the plume traveled through 85 km of the Animas River, and even after having traveled almost 200 km from the Gold King Mine. The other parameters behaved similarly, as shown for turbidity in Figure 4-7. The sonde observations suggest that the overall plume of the GKM release traveled as three different front or zones. The large volume release of low pH waters and a large metals mass seemed to effectively create a large chemical reactor moving downstream. The observations suggested that the core of the plume maintained a sharp advective front, with relatively-low lateral dispersion. The sharp front was maintained as it moved downstream, with the tail elongating behind the core of the plume as it traveled. Each front or zone seemed to maintain its integrity as it continued to move downstream. It is unclear if the processes governing the effective chemical reactor worked in some way to minimize overall lateral dispersion. In a river system such as this, more lateral dispersion would be expected than was observed (Schnoor, 1996).

Upon arrival of the GKM plume, indicator parameters such as SC and turbidity rose quickly, peaked sharply, and then fell back towards normally-observed conditions within 12 hours. However, the trailing limb of the plume abated more slowly and elevated SC elevated levels persisted for several days after the plume passed.

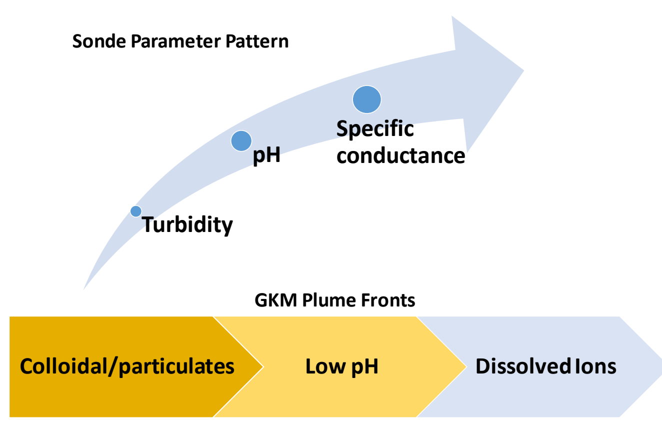


Figure 4-8. Schematic of the pattern in which the peak values arrived at sonde locations, suggesting a stratification of chemistry within the plume.

The question remained as to whether metals concentrations followed the same pattern observed for surrogate parameters at the sondes. Only one location was sampled with sufficient intensity during passage of the plume to establish the “shape” of the metal concentrations. Several organizations collected samples at locations at or near Rotary Park in Durango, Colorado (RK 93–96). Collectively, they provided the most detailed sampling of the GKM plume peak and both the rising and falling limbs of the plume. Figure 4-10 shows summed total metals concentrations at this location integrating numerous samples from nearby locations accounting for travel time.

With the arrival of the Gold King plume, metals concentrations rose and fell quickly, with a rapid and large increase near the peak. Metals concentrations increased by 55% in the 45 min between two samples near the peak. Return to background levels was slower, as dispersion elongated the tailing end. The metals concentrations measure at the Durango location, normalized to the peak, are plotted in Figure 4-9. Metals followed the same pattern as the average of the normalized sonde shape factor shown in Figure 4-9. This suggests that the sonde-measured specific conductance factor closely represented the rise and fall patterns in metals within the plume. The sonde shape factor was used to assist the empirical model's simulation of metals concentration, as described later in this chapter.

The rapid change in metals concentration at the plume peak increased the difficulty of sampling the Gold King release. Although many samples were collected over several days during the plume and throughout the river length, only a small subset coincided with passage of the inner core of the plume, and few, if any, caught the peak. This was especially true at sites where the plume passed during the night or in remote locations.

The intensity of sampling in Durango, Colorado allowed the general pattern of metals concentrations before, during, and immediately following the passage of the Gold King Mine plume to be elucidated. Total metals concentrations at this location declined towards pre-event conditions within 24 hours, but would continue to slowly decline for a number of days following the plume.

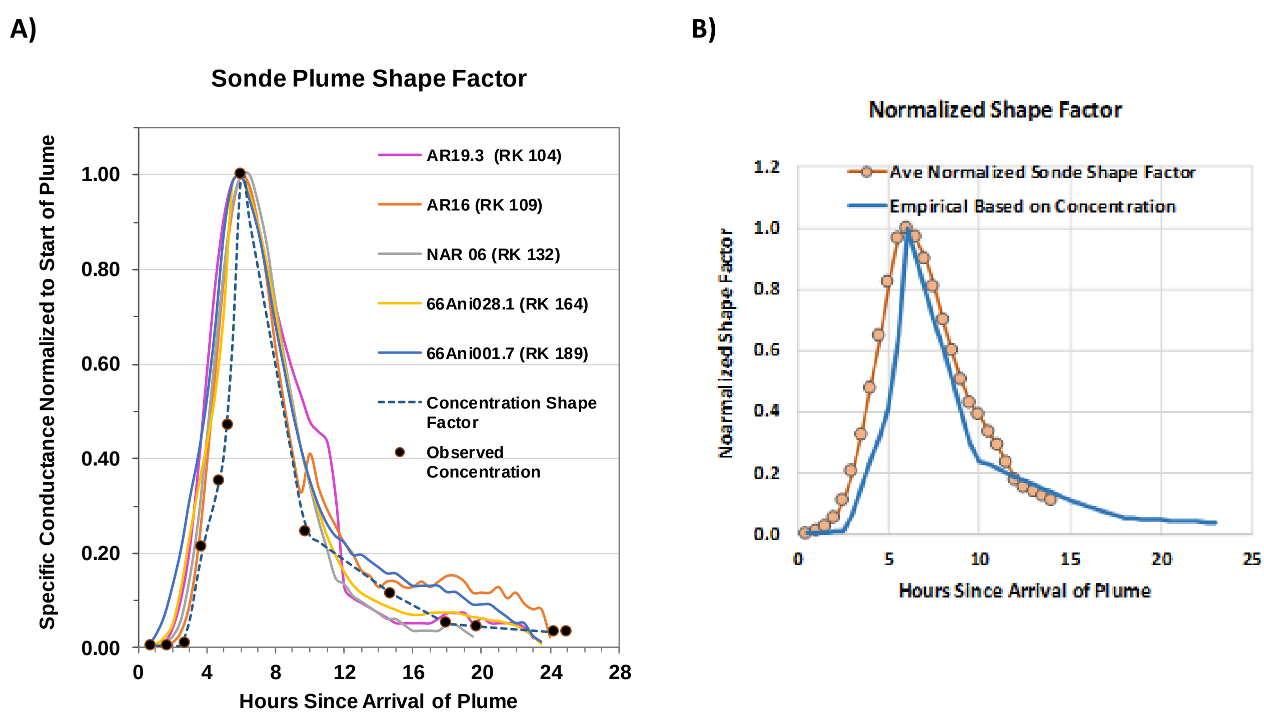


Figure 4-9. A) Sonde measured specific conductance normalized to the peak value at five sonde locations in the Animas River identified by site name and distance from Gold King Mine. B) The metals concentrations measured at Durango (RK 93 to 95) were also normalized to peak and shown as the line fit between the black dots. The normalized traces are referred to as the "shape factors".

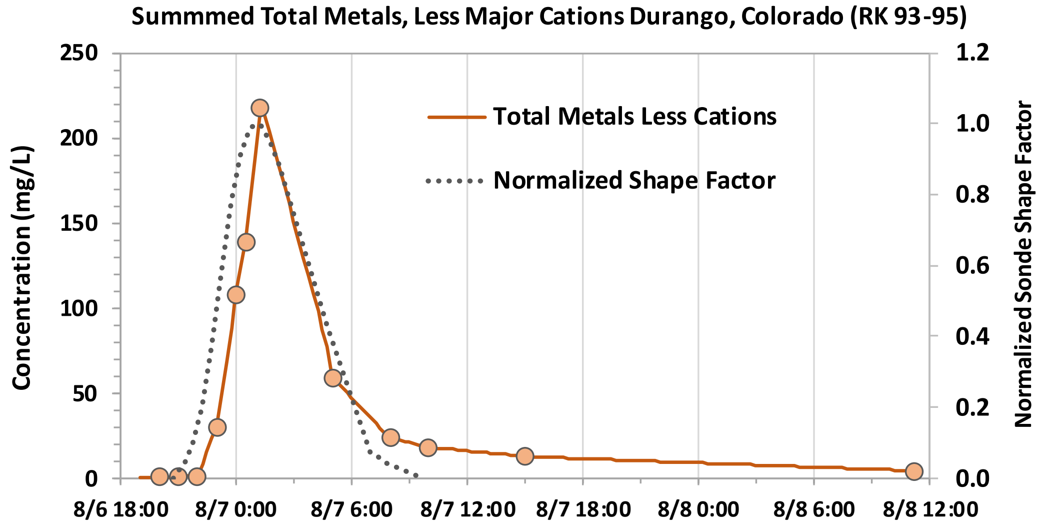


Figure 4-10. Sampled metals concentrations measured during passage of the Gold King plume through Durango, CO at two nearby locations between RK 93 and RK 95. Multiple samples were collected by the Mountain Studies Institute and Rivers of Colorado Water Watch Network from August 6 20:00 to August 7 9:30. Samples were consolidated to one location accounting for travel time. The normalized sonde shape factor from Figure 4-9 is superimposed on the samples centering at the peak of the plume.

4.1.5 Plume Timing

Plume time of travel was well established in the Animas River based on observed peaks in flow in the first 100 km of travel, where the plume was clearly visible (Figure 4-2) and in water quality parameters measured by sondes in the lower 100 km (Figure 4-5). Specific conductance was used as the travel time indicator because it was measured at all the sondes. The WASP model was then used to independently predict the time of travel between sonde and USGS gage locations. A comparison of peak arrival time predicted by WASP and observed times, as established at flow gaging stations and sondes is shown in Figure 4-11).

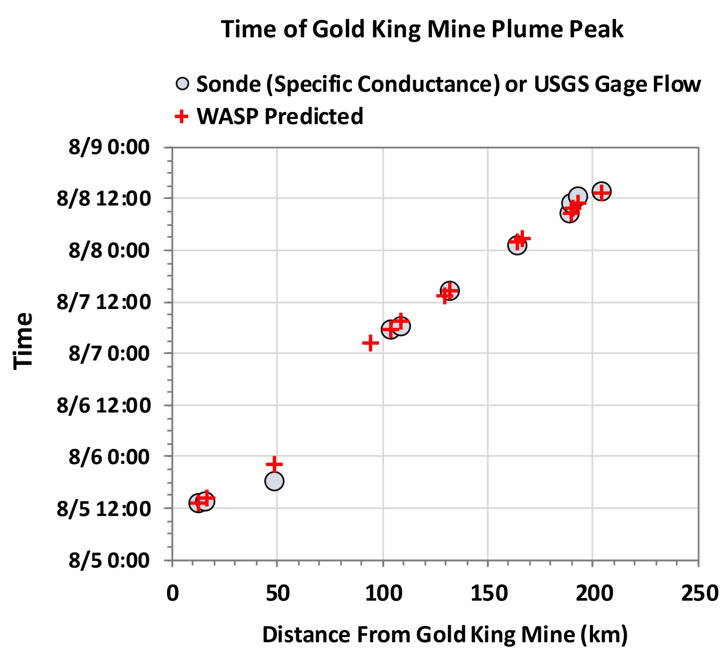


Figure 4-11. Comparison of peak arrival time predicted by WASP compared to arrival time established at flow gaging stations or using specific conductance at sonde locations.

The time of peak arrival predicted by WASP averaged within 58 min of the peak established by independent measures, ignoring whether early or late, and within 34+ minutes on average. The largest difference in peak arrival was observed at the USGS gage above Tacoma (RK 48.8), where the gage records indicated a much earlier arrival time. Without this uncharacteristic site, WASP averaged within +11 minutes of reference sites. WASP timing could be even closer considering that the plume arrival fell within a 2-hour window, depending on correlating parameter.

4.1.6 Visual Reports of the Plume

The Gold King Mine plume movement through the Animas River was a major media event that riveted public attention. Early reports of the Gold King plume's progress through the river were illustrated in the Denver Post, marking sightings by location along the upper Animas (Figure 4-12). A photograph taken from overhead of the plume's leading edge in the meandering reach of the Animas River north of Durango, dramatically illustrates the plume's sharp front (Figure 4-13). Within a distance of less than 2 km (less than 1 hr travel time), the intensity of the coloring deepened significantly, indicating the presence of higher metals concentrations. The leading edge of the plume was short, with the central core containing the highest metal concentrations (Figure 4-9), arriving within 2–4 hours after the initial plume arrival; the arrival of the core was visually signaled by an increase in color, such as seen in Figures 4-12 and 4-13.

WASP-simulated plumes were plotted at the five locations with reported observation times. According to WASP model simulations, the observed plume arrival times were close to actual; however, WASP simulations showed that metals concentrations began to rise sooner than some visual accounts of the plume arrival. Clearly, the time of arrival based on visual observations is coarse, and it is unclear at what concentrations the plume would be visually obvious.

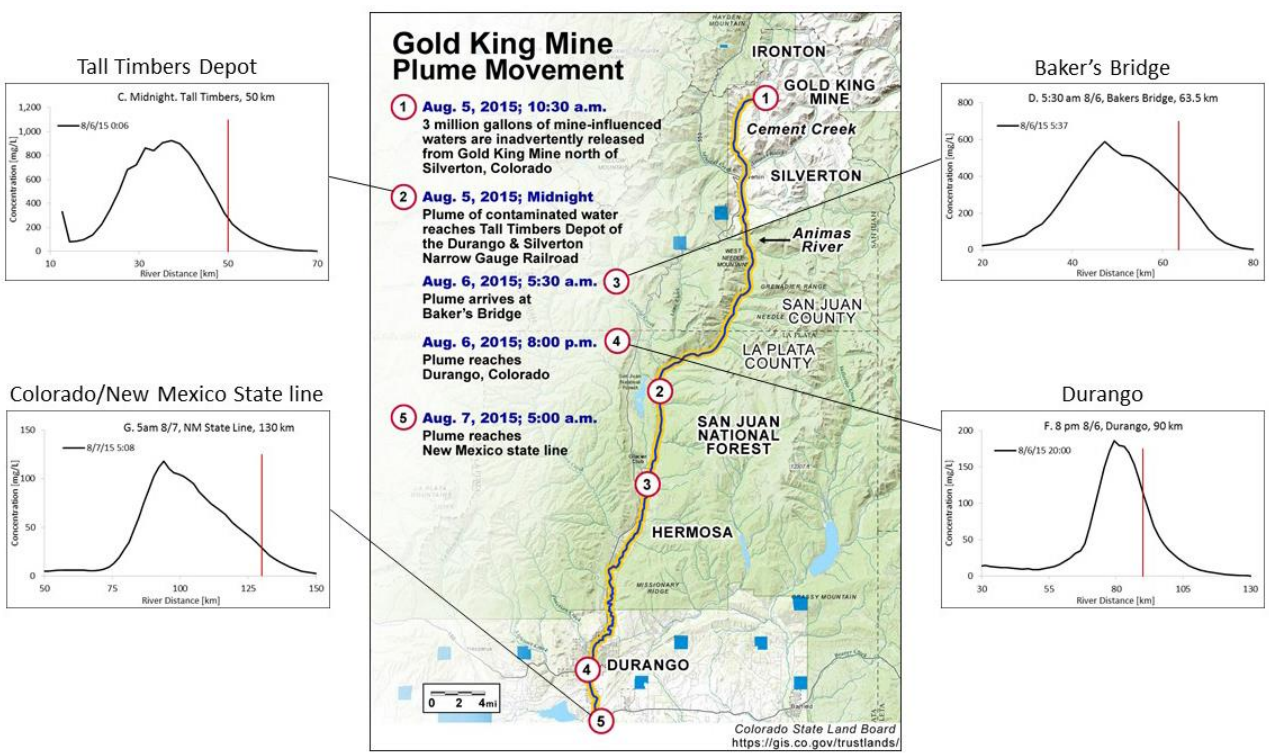


Figure 4-12. Orientation of model plume to visual observations. Simulated concentrations at a series of locations are compared to reported visual observations as an indication of what observers saw relative to what WASP modeled at that location. At each location, the concentration for a given reported time is plotted against river distance. The red line on each figure represents the location where there was a report of the plume or that the plume was approaching as chronicled in newspapers. (See map for the report at that time for a given location.)

A)

B)

Photo: Bruce Gordon EcoFlight

C)

Photo: Southern Ute Indian Tribe

Figure 4-13. Photographs of the GKM plume illustrating A) travel through upper Animas canyon reach B) arrival of leading edge to the meandering river reach north of Durango (approximately RK 80), and C) passage through Southern Ute Indian Tribe Reservation.

It is also possible that WASP predicted earlier arrival of the plume because of numerical dispersion. Typically, observation and modeling of contaminant transport in rivers expects longitudinal dispersion, as suspended materials move away from the source due to drag forces within the flow and with the streambed. The WASP model introduced numerical dispersion on the order of what would be expected from the literature for a gravel/sand-bedded river like the Animas River. The singular nature of the Gold King Mine plume, defined by what seemed like an unusually sharp, advective front, suggests that processes were at play that effectively minimized longitudinal dispersion. Further discussion on numerical dispersion and WASP analysis for the Gold King plume are presented in Appendix B.

Elevated metals and related water quality characteristics declined towards background conditions more slowly than how quickly they increased at the plume's arrival. A sequential set of photographs taken in Durango, Colorado over the 12 days during and following passage of the GKM plume (CDPHE 2016) shows water clarity and quality was impacted at this location for at least one week (Figure 4-14).

4.1.7 Correlating Water Quality Parameters During the Gold King Plume

The continuously-monitoring sondes in the Animas River documented water quality effects during and after passage of the Gold King plume. Water quality parameters, including specific conductance, pH, and dissolved oxygen are shown as the plume passed and for a number of days afterward at three locations in Figures 4-15 to 4-17. Turbidity sampled at RK 189.4 is shown in Fig. 4-17. Dissolved oxygen and specific conductance are temperature-dependent and fluctuated widely during the day. These characteristics also vary over time, reflecting ambient river conditions, temperature, and flow.

The Gold King plume affected specific conductance and pH at each of the sonde locations deployed from RK 104.1 near Durango to RK 189.4 in Farmington. The plume sharply increased specific conductance and reduced pH as it flowed past each location. SC increased within the normally-observed diurnal range of values. High values observed during the plume declined quickly, but the normal diurnal cycle was disrupted for several days following. Water pH dropped by 0.2 to 0.6 pH units during the plume, to levels below what is typically observed, and returned to normal ranges within 1 day. Changes to dissolved oxygen concentrations were not as apparent as other parameters, but concentrations appear to have been depressed below the normal afternoon highs on the day the GKM plume passed.

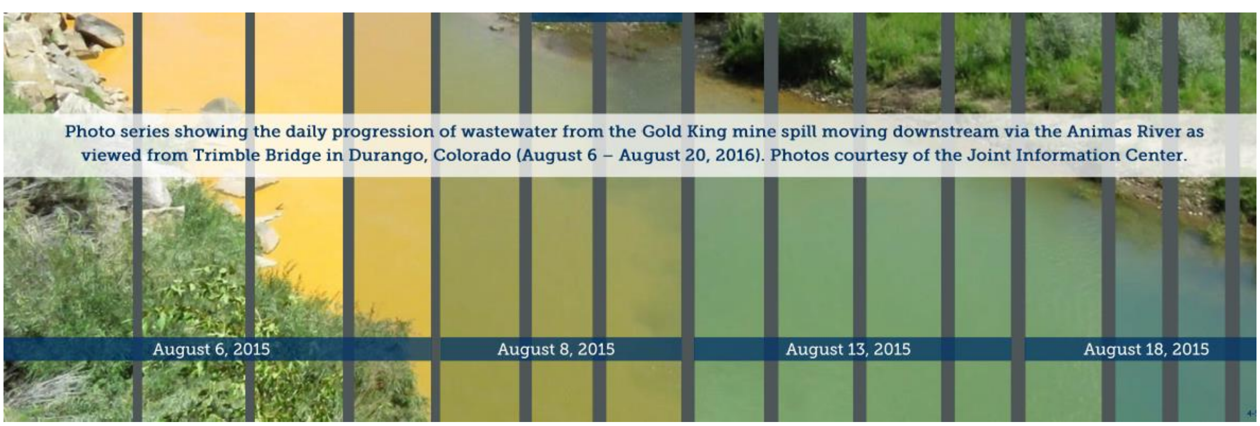


Figure 4-14. Photo collage of the Animas River photographed at the Trimble Bridge in Durango CO for 12 days following passage of the Gold King Plume. Photo from the Colorado Department of Public Health and Environment Spill report released January 2016 (https://www.colorado.gov/pacific/sites/default/files/Gold-King-Mine-Spill-Report-01-22-16-Digital.pdf).

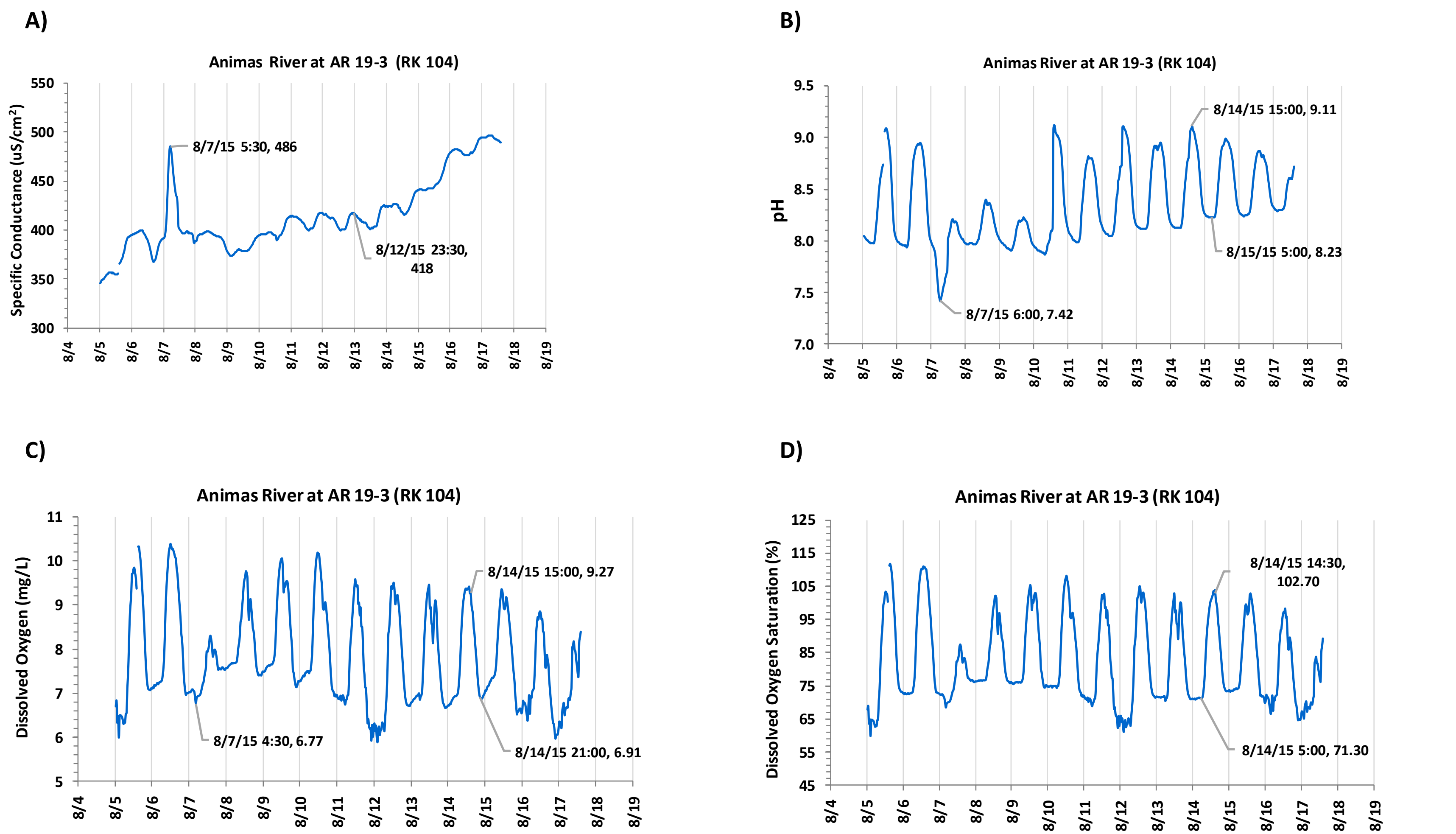


Figure 4-15. Continuous measurement of A) specific conductance, B) pH, C) dissolved oxygen concentration, and D) oxygen saturation by the sonde located at site AR 19-3 at RK 104 from August 5 to August 18 (Southern Ute Indian Tribe). Time of peak during the Gold King plume is indicated on each trace. There is a strong diurnal fluctuation in these parameters. A time at the trough and peak is labeled to help establish the diurnal pattern.

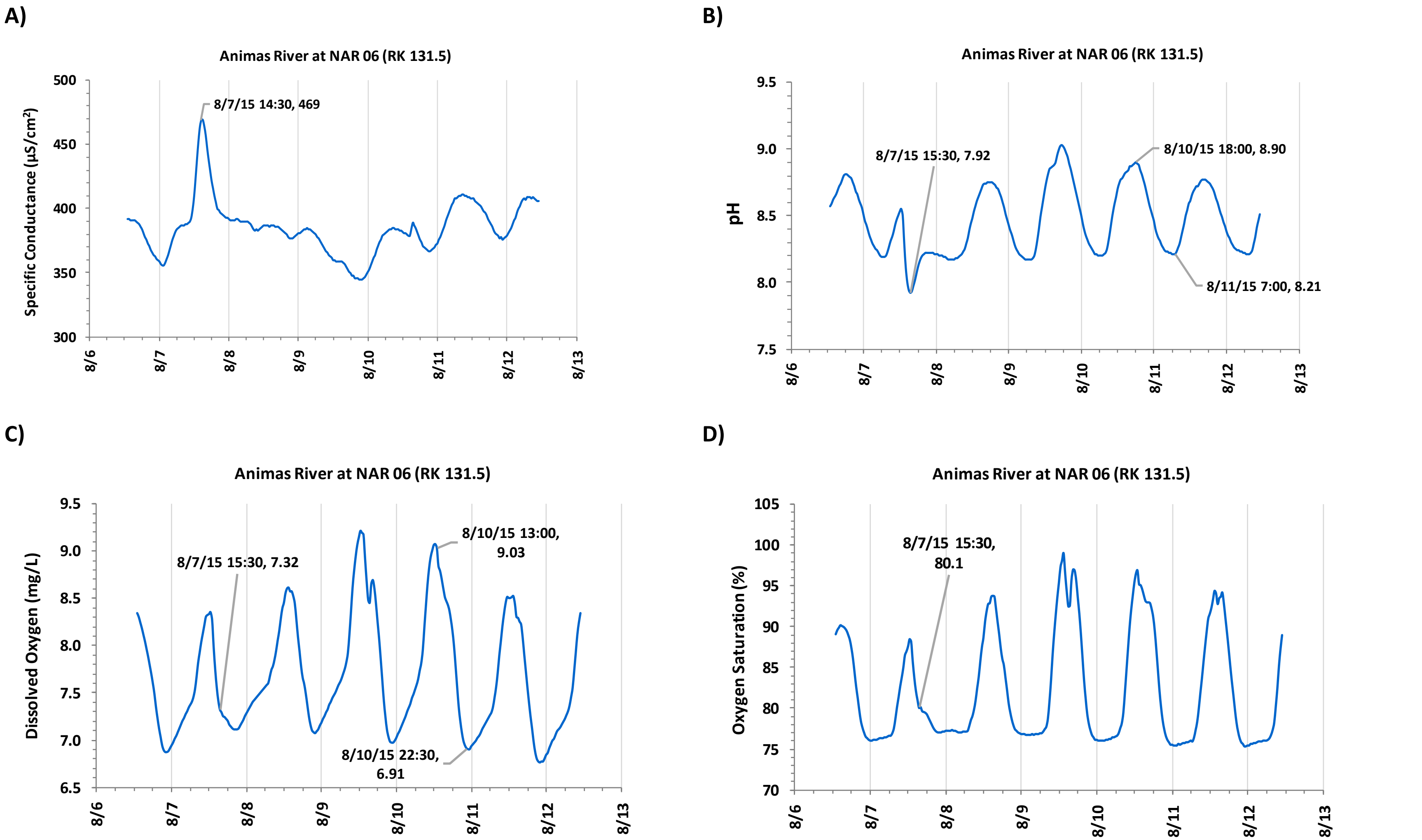


Figure 4-16. Continuous measurement of A) specific conductance, B) pH, C) dissolved oxygen concentration, and D) oxygen saturation by the sonde located at site NAR06 at RK 132 from August 5 to August 13 (Southern Ute Indian Tribe). Time of peak during the Gold King plume is indicated on each trace. There is a strong diurnal fluctuation in these parameters. A time at the trough and peak is labeled to help establish the diurnal timing.

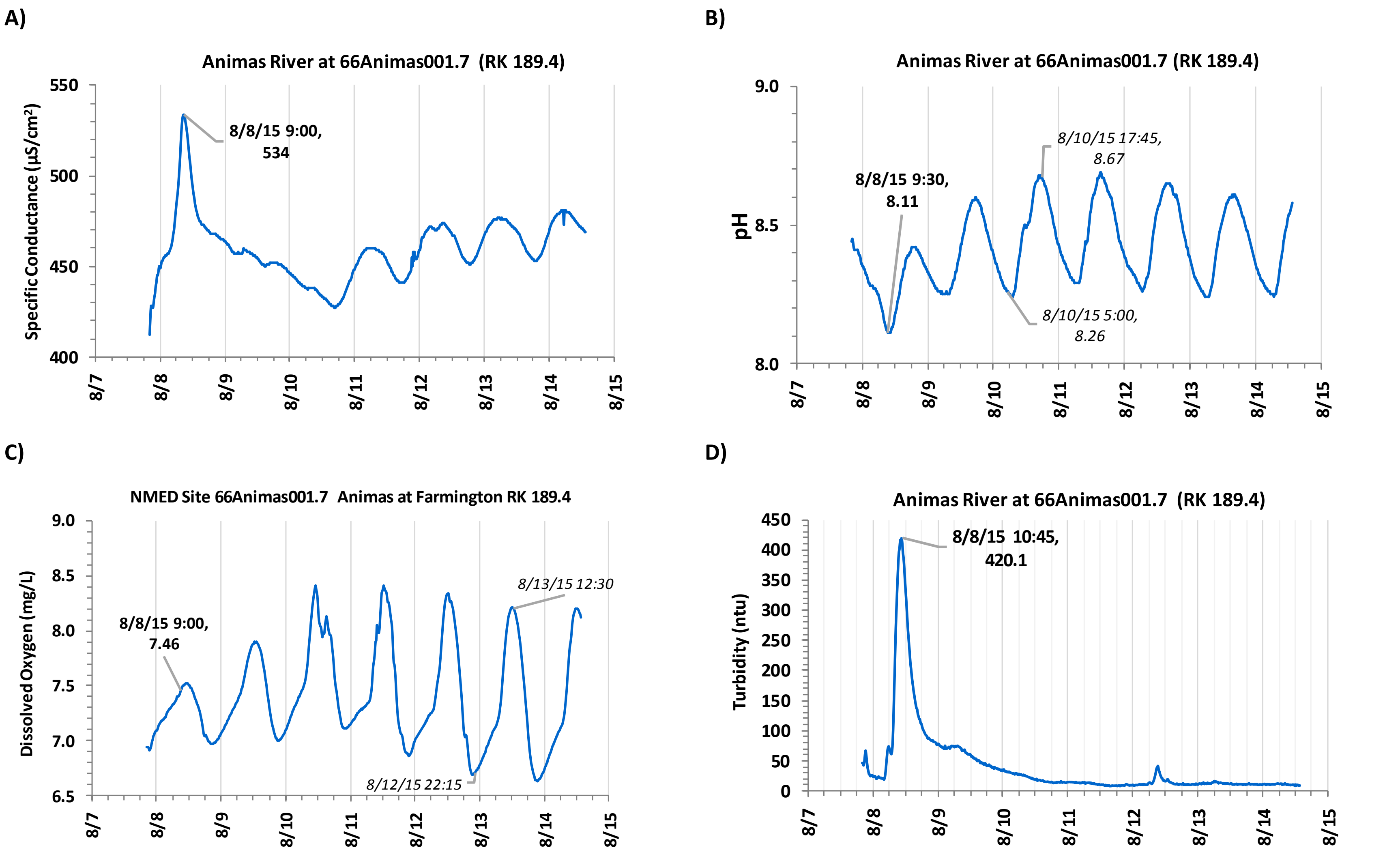


Figure 4-17. Continuous measurement of A) specific conductance, B) pH, C) dissolved oxygen concentration, and D) turbidity by the sonde located at site 66Animas001.7 at RK 189.4 from August 5 to August 15. Time of peak during the Gold King plume is indicated on each trace. There is a strong diurnal fluctuation in the parameters with the exception of turbidity. A time at the trough and peak is labeled to help establish the diurnal pattern.

Turbidity, evident in the photograph in Figure 4-13C was likely near the 400 NTU peak recorded by the sondes some 50 km down river (Figure 4-17). Individual field sampled measurements of turbidity at sites confirmed this general turbidity level of the plume in the lower Animas.

4.1.8 Peak Metal Concentrations

The Gold King plume moved as a coherent mass with metals concentrations that rose and fell quickly as the central core of the plume moved through, and then tapered back towards pre-event concentrations over a period that lasted for several days (e.g., Fig. 4-10). Analyses of various data established travel times and the general shape of the plume concentrations. Critical to empirical modeling of the metals concentrations in the plume and their movement through the river were good estimates of the peak metals concentrations.

There were 250 water samples collected during the nine days that the Gold King plume flowed through the Animas and San Juan Rivers that could be considered to have been taken within the plume. The value of a sample for representing the plume peak could not be known however without an understanding of where the plume was when the sample was taken. Figure 4-18 shows the aluminum concentrations of samples collected from August 5–14, 2015. The variation in metals concentrations within samples collected at the same location over the 9-day period was large. Those samples with higher concentrations at each location were more likely to represent the plume peak; however, the steep rise and fall in concentrations near the metals peak, such as shown in Figure 4-10, limited the likelihood of optimal sampling. Only a small subset of samples was collected within the core of the plume, where most of the metals mass was carried.

A total of 27 samples from the Animas River were identified and isolated for their proximity to the peaks; WASP was then used to corroborate their proximity to peak (Figure 4-19). Included as one of the samples was the estimated concentration at Cement Creek, as developed in Chapter 3. The estimated peak plume concentration at Cement Creek was moved into the Animas River, where it was reduced to 50% to account for the increased volume of flow from the Upper Animas River and Mineral Creek in the vicinity of Silverton. Just 3 or 4 of the samples (highlighted in red in Figure 4-19) were thought to be very close to peak. Critical to this analysis were samples collected at the sonde locations on the SUIT reservation from RK 104 to 132, located approximately midway through the Animas River. One sample in Farmington also appeared to be close to peak. Few samples were collected near the plume peak in the upper Animas River that could be used to confirm the starting concentration of the plume in the Animas River or lock in the metals concentrations of the plume in key section of the river between RK 16.4 (below Silverton, Colorado) and Baker's Bridge (RK 63.8), where no sampling was conducted due to its remote location.

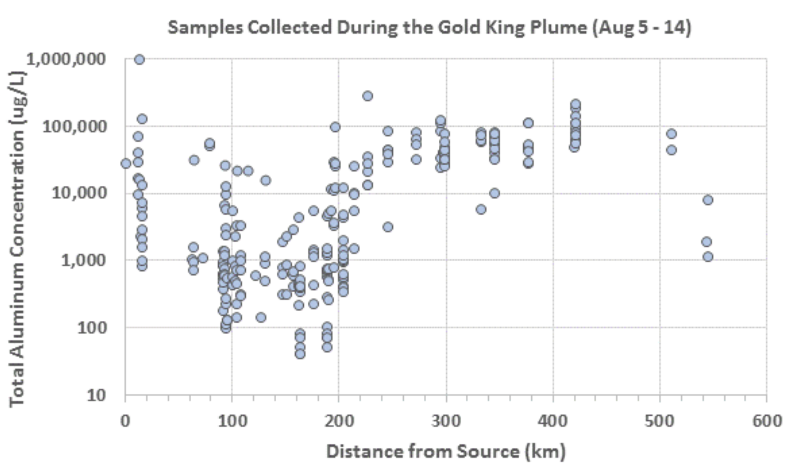


Figure 4-18. Total aluminum concentration of water samples collected during the Gold King plume from August 5 to August 14, 2015.

The difference in metals concentration between the regression line and the observed metals concentrations indicated how close the samples were taken relative to the peak. Sites less than peak were adjusted upward to meet the line as the estimate of the peak plume concentrations. Many of the middle Animas River samples were very close to the regression, consistent with interpretation of the sonde plume timing, and required very little adjustment to observed concentrations. These samples were close enough to peak that they could have been included in the regression with little impact on results. The fitting choice maximized estimated concentrations, allowing for an early or late sampling by adjusting the sites upward slightly.

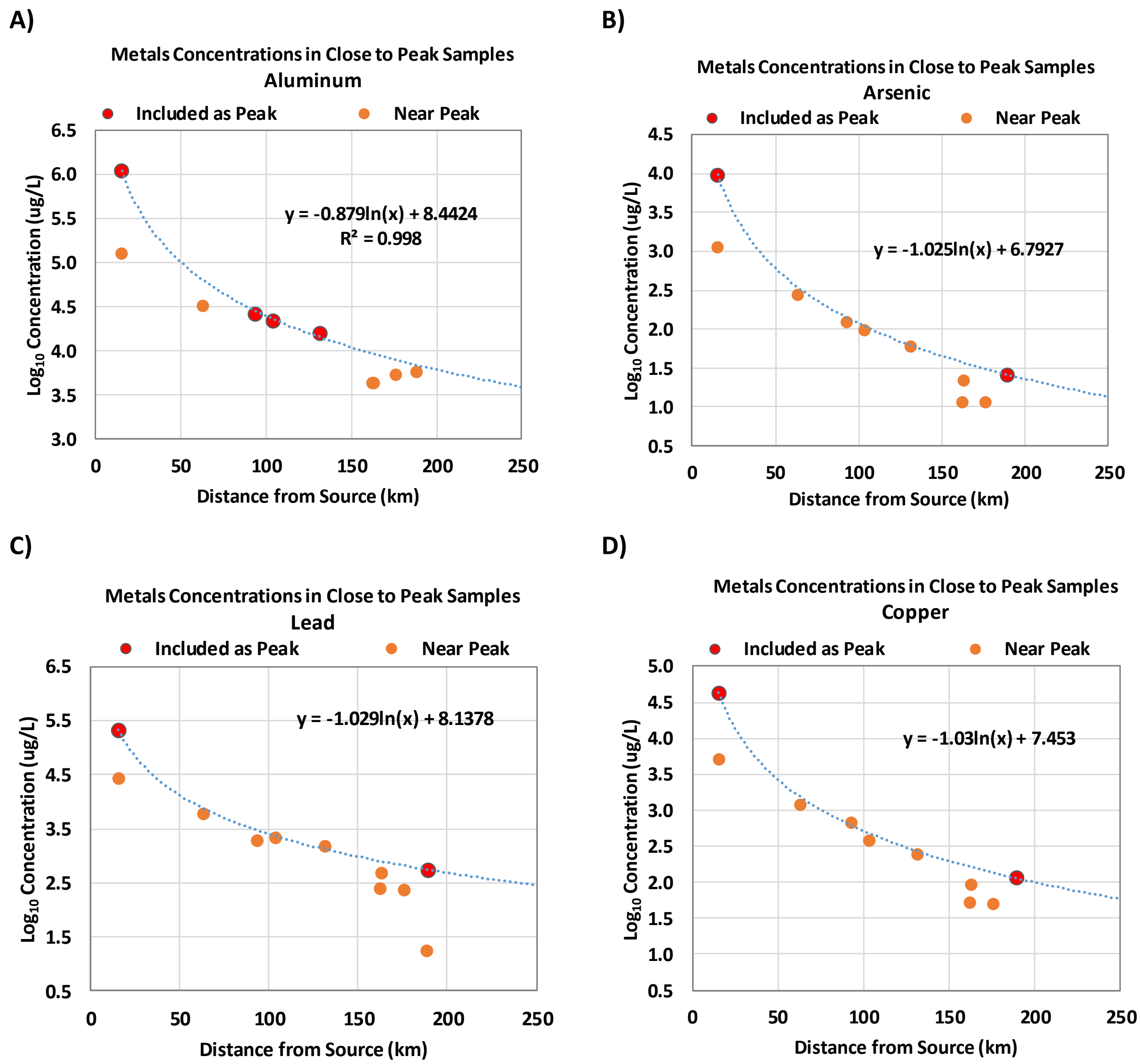


Figure 4-19. Determining peak concentration. The Gold King plume and its short duration peak passed by sampling locations quickly. Relatively few samples were collected at the peak of the plume. To reproduce the peak accurately at each site, it is essential to estimate the peak. Samples collected during plume movement are shown for four metals. Using a variety of techniques to determine the time of peak, samples near the peak were identified (red dots). A power regression was fit to these points beginning at an estimated sample at the Animas River junction with Cement Creek that mixes the Cement Creek estimated peak 50% with the Animas River. Examples are shown for A) aluminum, B) arsenic, C) lead, and D) copper.

The sensitivity of the regression to assumptions of peak concentrations was evaluated by applying alternative scenarios, which reflected possible errors in assigning initial estimates at Cement Creek and error in assuming that various locations were sampled near to or at peak. Because plume timing was known at sonde sites, metals concentrations at these sites were assumed to have occurred within 1 hr of the peak, as observed by the sampling effort at Durango, and allowed to change no more than 50%. Scenarios included raising the initial concentrations at Cement Creek, assuming some of the peak samples were at peak and then removing them and adding others, and assuming that none of the samples were actually at peak and raising them all within the timing constraints.

Because the timing of the samples from RK 93–132 were better authenticated as close to peak and were allowed less change, the peak concentration regressions were rather insensitive to varying the starting concentrations at Cement Creek or changing the concentrations by small amounts. The concentrations in the river between RK 16.4 and 63.8 were more sensitive to curve fitting. It appears that the main error potential with the peak fitting technique used was that metals concentrations and mass could be improperly distributed within the upper reaches of the Animas River between Cement Creek at RK 12.5 and Durango at RK 95.6 any errors there would correct themselves between RK 64 and RK 95, as peaks were established by sampling.

4.2 Empirical Simulation of Metals During the Gold King Plume

4.2.1 Development of the Empirical Model

After analysis of multiples sources of data there was sufficient information to complete the empirical model, which was used to simulate the Gold King Mine plume at 12 sites distributed throughout the Animas and San Juan Rivers (Figure 4-20; Table 4-2). Modeling methods were described in more detail in Section 2.5. Sites were selected near USGS gages and preferably at locations that were repeatedly measured by one or more organizations during the hours and days as the plume passed. A flow record was synthesized for the Animas River at Bakers Bridge (RK 63.8) from the Tacoma gage at RK 48.8 to enable empirical modeling of the plume at this important location. The hydrograph was simulated by adjusting the gage record by the increase in basin area between the two gages and adjusting time to the WASP-estimated peak arrival time.

The empirical model made maximum use of the available observations from a variety of data. Each site was handled independently to assess the best approach based on the available data. The process of determining the time of peak was iterative using all available information, including sondes, the flow record, and WASP travel time.

The empirical model used the flow taken from the nearest USGS gage and the observed or estimated metals concentrations in each 15-minute period during the period of plume passage. Peak concentrations were estimated from the regression equations shown in Figure 4-19. The peak concentrations predicted by the empirical model were sometimes significantly higher than the highest sample concentration at the site at some locations which was a function of how closely timed the samples were to the peak.

The trace of metals concentration was completed by interpolating between samples (i.e., the estimated or observed peak) by one of several methods. Near the peak, interpolation between measured points was guided by the normalized shape factor shown in Figure 4-9, which was assumed valid for all modeled sites given its consistency at five locations and its similarity to flow and concentration relationships. All metals samples were used, including those close to peak, even if an estimate of the peak was applied. Where possible, data were merged from closely-located sampling locations to fill gaps, adjusting for timing if necessary. If a sample was available during the 8- to10-hour core period, it was used. Outside the core period, concentrations were interpolated by a linear fit between observations. The empirical model applied this process to reconstruct a trace of the concentrations of all metals in total and dissolved form, starting with the arrival of the plume and extending not longer than 48 hours.

Figure 4-20. The Gold King plume was empirically modeled using observed water sample at 12 locations distributed within the Animas and San Juan Rivers. Sites were selected to be near USGS gages that were used for flow and near sites that were routinely monitored during the passage of the plume.

Table 4-2. Locations where the Gold King plume was empirically modeled. Sites are located near USGS gages and locations where water quality samples were routinely collected during the Gold King plume and in the months following. Samples from multiple providers were consolidated at associated sampling sites.

	Empirical Model Sites	State	Site Distance from Gold King Mine (km)	Nearest USGS Gage Used in Model	Associated Sampling Sites Used in Model
Cement Creek	Cement Creek	CO	12.5	9358550	EPA R8: 14th St. Bridge, CC48
Animas River	A72 (Silverton)	CO	16.4	09359020	EPA R8: A72
	Bakers Bridge	CO	63.8	09359500	EPA R8: Bakers Bridge GKM02
	Rotary Park (Durango)	CO	94.2	09361500	EPA R8: GKM04 MSI: Rotary Park CO River Watch
	NAR06 (SUIT)	CO	132.0	09363500	SUIT: NAR06
	ADW010 (Aztec)	NM	164.1	09364010	EPA R6: ADW010 NMED: 66Animas028.1
	FW040 (Farmington)	NM	190.2	09364500	EPA R6: FW040 NMED: 66Animas001.7
San Juan River	LVW020 (Farmington)	NM	193.0	09365000	EPA R6: LVW020, SJLP NMED: 67SanJuan088
	SJSR (Shiprock)	NM	246.3	09368000	EPA R6: SJSR
	SJ4C (Four Corners)	NM[1]	295.8	09371010	EPA R6: SJ4C UDEQ 160 Xing
	SJFF (Bluff)	UT	377.1	09379500	EPA R9: SJBB UDEQ: Sand Island
	SJMC (Mexican Hat)	UT	421.5	09379500	EPA R9: SJMH UDEQ: Mex Hat

[1] Sampling site SJ4C is located on San Juan River in New Mexico although map geographic location is Colorado.

A)

“Polluted Animas River” by Mor is licensed under CC BY-NC 2.0

B)

Photo: Southern Ute Indian Tribe

C)

Photo: Southern Ute Indian Tribe

Figure 4-21. Animas River at various locations during passage of the Gold King plume. A) upper Animas River, B and C) Southern Ute Indian Reservation between RK 104 and RK134.

There were uncertainties in all of these estimates. Errors could occur in establishing the timing, estimating the peak correctly, and, when there were few data points in the record, interpolating between the measured values. Generally, the modeling philosophy was to err on establishing concentrations that were too high rather than too low.

4.2.2 Simulation of the Gold King Mine Plume in the Animas River

Characterization of the Gold King Mine plume with the empirical model was strong as it traveled through the Animas River due to the variety of corroborating information, not the least of which was its visibility within the Animas (Figure 4-21). There was no confounding background turbidity, water quality samples were collected at a number of locations by multiple data providers, and stream gages and sondes anchored travel time. Flow in the Animas River was approximately 23.5 m^3/s (830 cfs).

Development of the WASP model was described in Chapter 2 and in Appendix B. WASP was not directly calibrated to observed or empirically-modeled concentrations; therefore, simulated concentrations were expected to vary between the two models. The Gold King plumes simulated with the empirical model and WASP at Animas River locations are shown in Figure 4-22.

The WASP and empirical models simulated the timing of the plume peak and the plume duration similarly. Metals concentrations predicted by both models were compared at individual locations. The two models simulated plume concentrations that were similar in the peaks, but were dissimilar in the general shape of the plume. WASP produced a generally bell-shaped plume with a lagging tail; higher metals concentrations were estimated earlier on the rising limb and persisted longer on the falling limb of the plume.

The empirical model simulated a sharper rise and fall based on the observations of the continuously-measuring sondes, stream gages, and the sampling in Durango. Most of the metals mass was carried in the central core of the plume, where concentrations rose and fell quickly as it passed a location. The core of the plume passed as a sharp advective front that lasted about 12 hours, and was remarkably persistent in shape through a long distance of travel.

WASP modeled a wider plume with more dispersion on the rising limb than was observed. This was caused by numerical dispersion, which is inherent to water quality models and widens and flattens the simulated plume while maintaining mass. Longitudinal dispersion of contaminants introduced at a point source within rivers is common. The lack of longitudinal dispersion as the Gold King plume traveled downstream is of interest. The plume maintained its size as it traveled downstream, maintaining its sharp advective front with minimal longitudinal dispersion. In implementing WASP in river systems, it is common to not introduce longitudinal dispersion and let the numerical dispersion account for natural dispersion in the system. The dispersion calculated by WASP was consistent with natural dispersion that would be expected in a river system. Additional discussion on dispersion and analyses are presented in Appendix B.

WASP predicted that low levels of metals concentrations persisted for at least 48 hrs and as long as 80 hrs in the lower Animas and San Juan Rivers (Figure 4-22). WASP may better reflect the experience of observers, who saw tinted water with low concentrations of metals for longer periods after the plume passed, especially longer after the plume than the empirical model would suggest (e.g. Figure 4-14). The two approaches offer a range of concentrations reflecting uncertainties in both modeling and data availability.

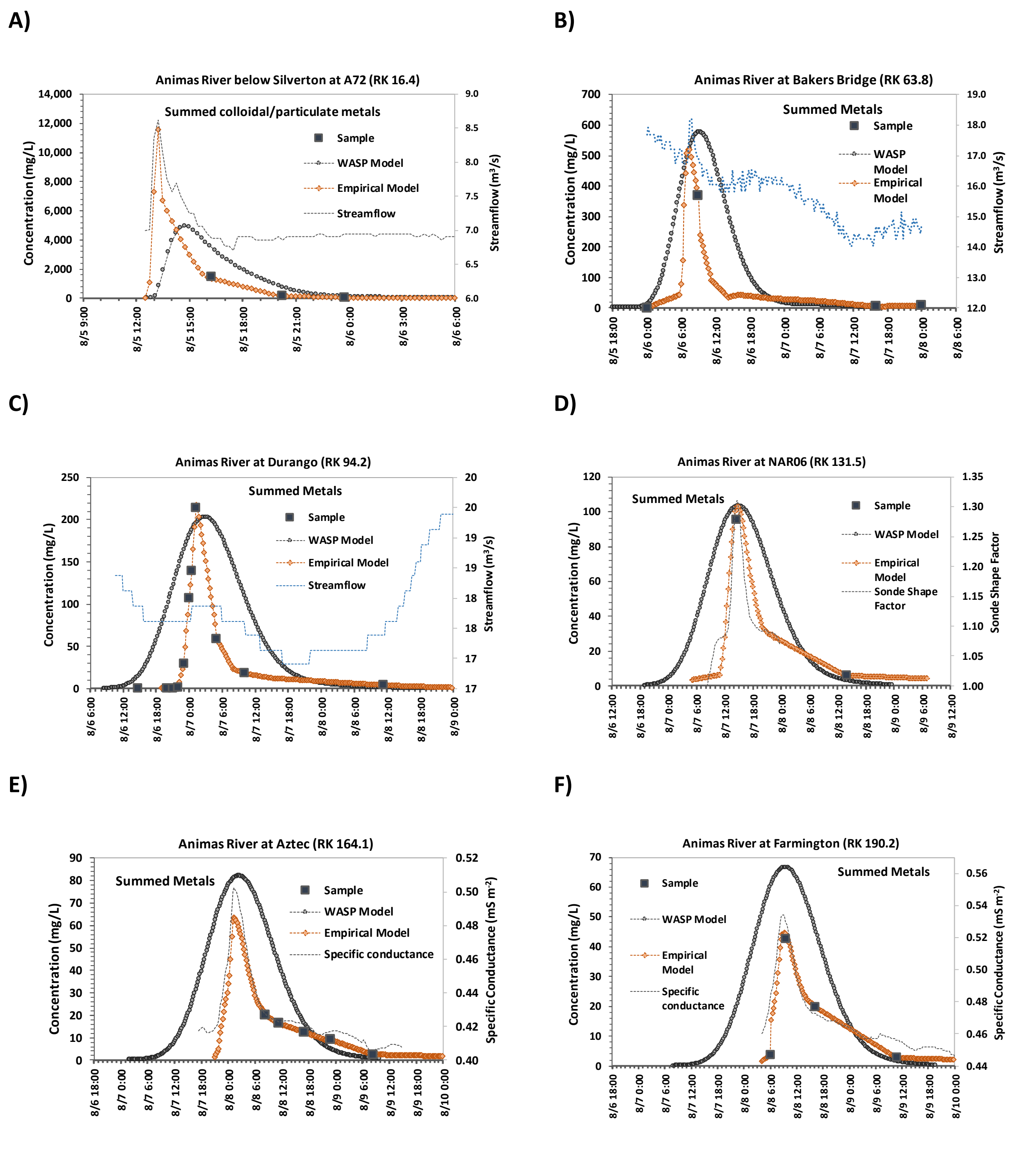


Figure 4-22. Gold King plume simulated by the WASP model and the Empirical Model for sites on the Animas River. Each site shows the empirical model and WASP concentration predictions for summed total metals (minus major cations) and an independent parameter used at the site to help guide reproduction of the plume shape. Samples are shown as squares. A) below Silverton (A72) at RK 16.4; B) Animas River at Baker's Bridge at RK 63.8; C) Animas River at Durango at RK 94.2; D) Animas River on the Southern Ute Indian Tribe site NAR 06 at RK 131.5; E) Animas River at Aztec at RK 164.1 and E) Animas River at Farmington at RK 190.2.

4.2.3 Simulation of the Gold King Mine Plume in the San Juan River

Quantifying travel time and concentrations of the Gold King Mine plume once it entered the San Juan River was more challenging than in the Animas River. The Bureau of Reclamation released water from the Navajo Dam to mitigate the effects of the plume in the San Juan River. The additional water created streamflow conditions in the San Juan that were consistent with a moderate storm, including high sediment loads that visually obscured the Gold King plume. The sediment loads also raised the natural "background" levels of metals carried in suspension and blurred the GKM release concentration signal that was readily measured in the Animas.

Flow in the San Juan River below the confluence with the Animas was approximately 47.86 m^3/s (1,690 cfs) almost 50% higher than typical for this time of year due to the unscheduled release from the Navajo Dam from August 8–10, 2015 (Figure 4-24). Like the Animas, the hydrologic pattern through the length of the San Juan was also very disrupted during, and for a period following, passage of the Gold King plume due to water use restrictions and the dam release. Flow in the Animas and the San Juan were approximately equal at their junction in Farmington, inferred from the difference between flow at the gage on the San Juan River at Farmington (USGS gage 09365000, RK 193.0) and the flow from the gage on the Animas River at Farmington (USGS gage 09364500, RK 189.6).

A)

Photo: UDEQ

B)

Photo: UDEQ

Figure 4-23. The San Juan River had a moderately high sediment load during the Gold King plume. A and B near Montezuma Creek (RK 345).

Although a large volume of water from the two rivers mixed at their confluence, it was assumed that the Gold King plume continued to travel as a coherent unit as documented in the Animas River. One sonde was deployed in the San Juan River at Farmington (Sonde 067SanJuan088.1, RK 204.4). Turbidity from the instrument, oscillated widely during the time leading up to, during, and after the passage of the plume (Figure 4-25). The simulated timing of the plume at the sonde location is superimposed on the sonde traces by centering the sonde shape factor (shown in Figure 4-9) at the peak arrival time suggested by the WASP model (Aug 8, 13:00). There was a small spike in turbidity of 200 NTU (Figure 4-25A) and a brief dip in pH (Figure 4-25B) at this time. The increase in turbidity induced by the Gold King plume was small compared to the background turbidity on this day. The signals in turbidity and pH suggest that the plume shape observed in Animas River sondes was maintained.

The WASP model was the only method that could determine the plume travel over the next 350 kilometers of river, because the plume was not visible far past Farmington. WASP was set up to run in two modes in the San Juan. One brought the Gold King plume into the San Juan River, assuming no background sediment and associated metals mass (i.e., as if the plume was moving through distilled water). This mode allowed plume metals to be assessed independently of the background metals, assuming the sediment load did not affect plume travel. In the second mode, the Gold King plume was mixed with the incoming metals load from the San Juan River above its confluence with the Animas so that WASP modeled what was actually in the river; this simulation should be closer to metals concentrations observed in samples. Simulated plumes at five San Juan River locations are shown in Figure 4-26. The upstream boundary condition for total particulate metals in the San Juan River was determined by subtracting Animas River metals concentrations from those observed in the San Juan immediately downstream from their confluence prorated by flow contributions.

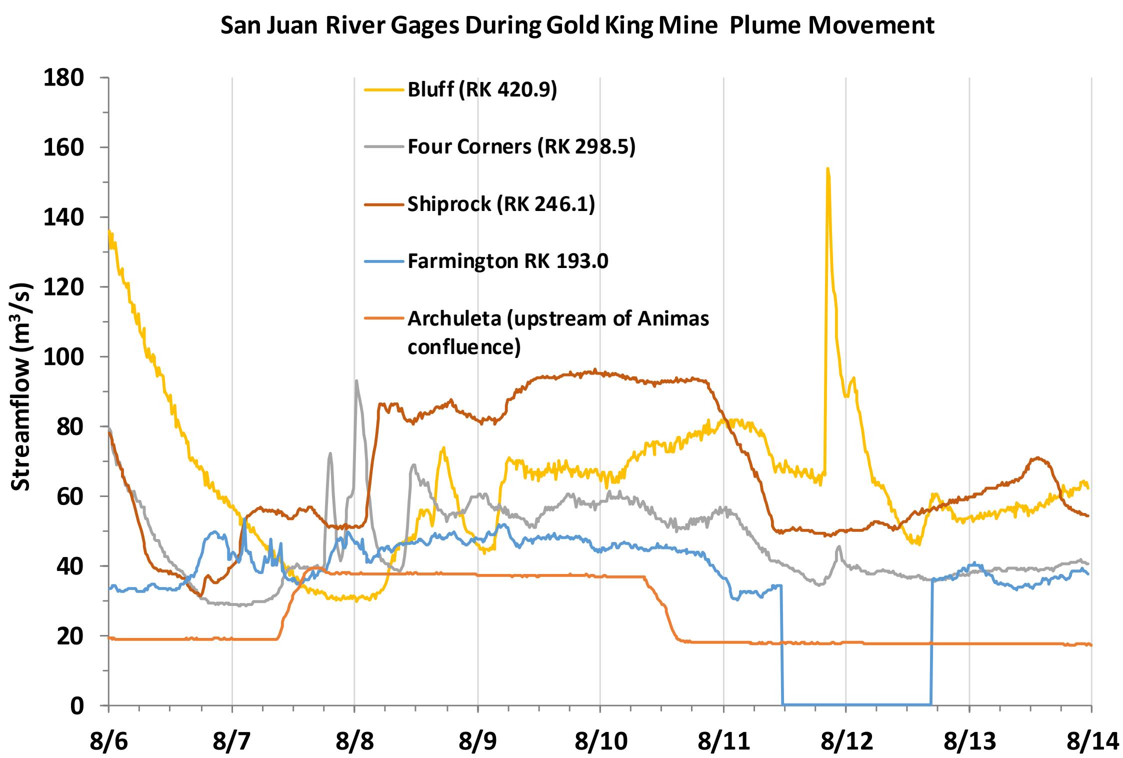
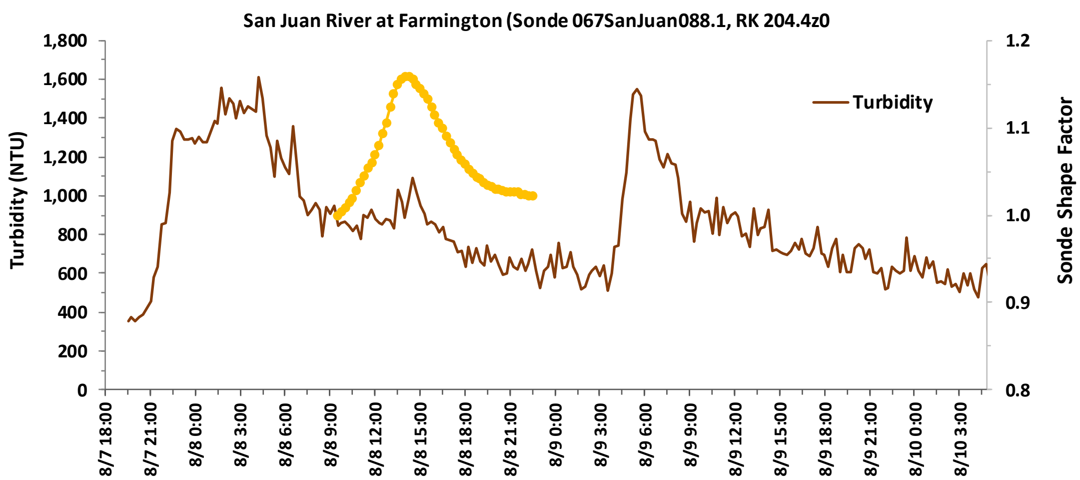


Figure 4-24. Hydrographs at USGS gages in the San Juan River during passage of the Gold King plume. Streamflow from August 6 to August 14, 2015 at Farmington RK 193.0, Shiprock at RK 246.1, Four Corners at RK 298.5 and Bluff at RK 420.9. Also shown is the San Juan River at Archuleta located approximately 61 km upstream of the confluence of the Animas and the San Juan Rivers.

The empirical model was developed in two modes for the San Juan River as well. One began at a baseline concentration established by water samples collected within the estimated plume period. The sonde shape factor was then used to simulate the plume with the peak centered at the WASP arrival time; this provided an estimate of plume-related metals. The increase in concentration due to the plume was equal to WASP's estimate. The second mode ignored plume shape and interpolated between samples only to represent the metals mass actually carried in the river during the time of passage of the plume.

WASP modeling indicated the Gold King plume continued to move as a coherent plume through the San Juan River, although at very low concentrations relative to background concentrations. The summed colloidal/particulate metals from Gold King at peak were estimated by WASP to be 25 mg/L at Farmington, New Mexico, declining to 10 mg/L as the plume traveled the 225 km to Mexican Hat, Utah. Background summed metals (minus major cations) were approximately 200 to 300 mg/L (not shown).

A)



B)

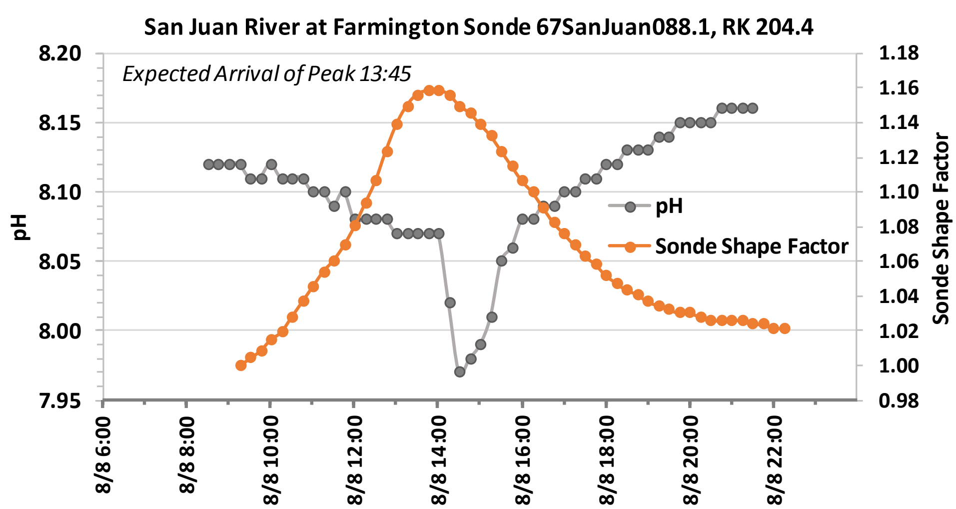


Figure 4-25. A) Turbidity measured at RK 204 in the San Juan River by the sonde at Site 67SanJua088.1. The plume is simulated on the turbidity trace by imposing the sonde shape peak at the WASP peak time. B) At the time of the WASP peak, there was a rise in turbidity, and a short drop in pH.

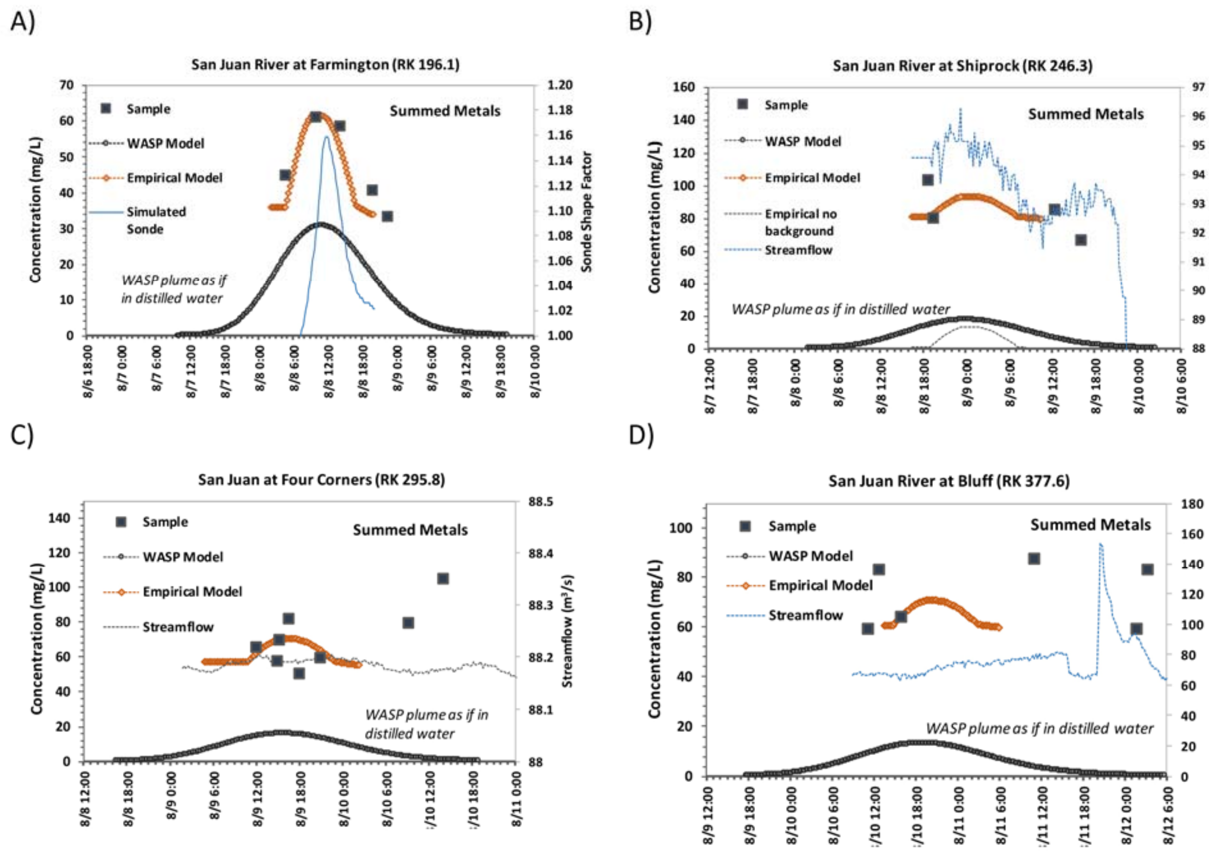


Figure 4 26. Plume simulations by WASP and the empirical model. A) San Juan River at Farmington at RK 196.1; B) San Juan River at Shiprock at RK 246.3; C) San Juan River at Four Corners at RK 295.8; D) San Juan River at Bluff at RK 377.6.

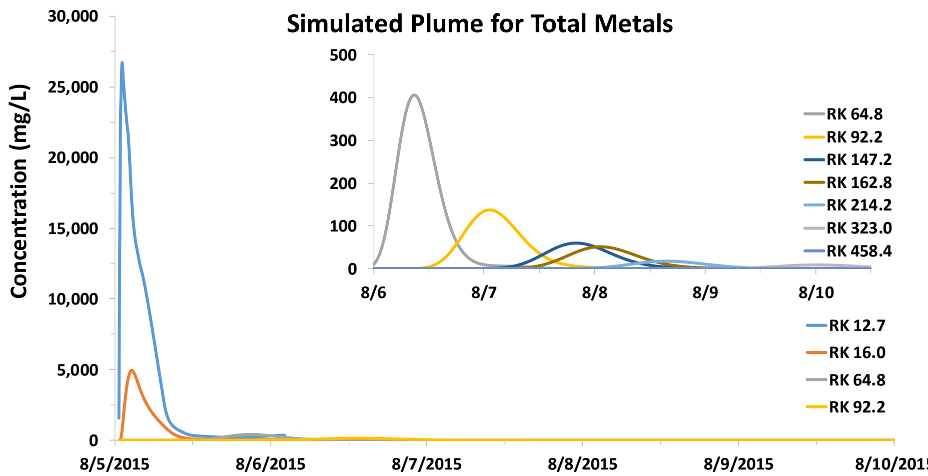
The empirical model ended simulations at Mexican Hat, as this was the last USGS gage before Lake Powell; metals concentrations and mass were very low. WASP also stopped simulations at Mexican Hat and the remainder of metals mass in transport was considered delivered to the reservoir.

4.3 Summary of Gold King Plume Characteristics of Travel

Peak metal concentrations were very high when the Gold King Mine plume entered the Animas River at Cement Creek. Peak concentrations dropped by four orders of magnitude by the time the Animas River joined the San Juan and continued to decline as it passed through the river system (Figure 4-27). Both the empirical and WASP models agreed on the magnitude and distances over which this decline occurred and predicted similar maximum concentrations. Chapter 5 will examine metals concentrations trends within the rivers and the processes and mechanisms that contributed to the changing metals composition in detail.

Although the Gold King Mine plume could be seen for 48+ hours at a location, the bulk of the metals mass in the plume appeared to have traveled in a much narrower window of about 12 hours, in a plume with a sharp advective front and strong internal coherence that did not break down over long travel distances in turbulent waters (Figure 4-27). This period was important for quantifying mass transport and exposure potential, but its relatively narrow window made it challenging for field crews to sample. The shape of the plume core remained remarkably consistent as the plume traveled over the approximately 190 km of the Animas River.

A)



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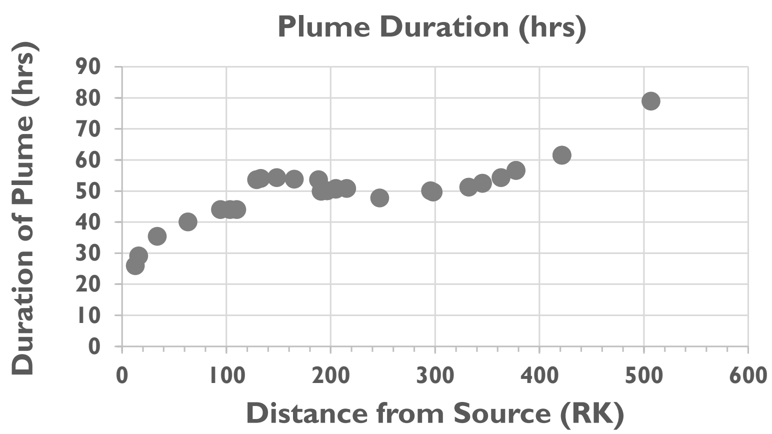


Figure 4-27. A) WASP simulated total metals concentrations. WASP estimated summed total metal concentrations plotted in relation to time as if stationary at selected locations identified as distance from Gold King source. Inset figure zooms to lower concentration scale. Total metal concentration decreased at downstream locations as the plume moved. The concentration trace in time is similar to a normal distribution but is skewed to a faster rise at the start of the plume. B) Plume duration modeled by WASP in hours increases due to dispersion and drag forces.

The plume traveled through the Animas and San Juan Rivers over a period of nine days at an average velocity of about 3.1 km/hr (2 mph). WASP appeared to produce a reliable record of the travel time, providing an arrival time of the peak at 2-km distances along the river. Both models generally agreed on the timing of the plume peak (Figure 4-28). Sonde data available in the lower Animas River anchored the time of travel through this river segment, which in turn solidified estimates of peak concentrations from samples. There was less evidence to corroborate travel time through the San Juan, but samples collected near the estimated arrival times of the plume appeared to show small increases in metals concentrations.

The travel time is shown in Figure 4-27. Statistics of the arrival and duration of the plume peak at a number of sampling locations distributed throughout the Animas and San Juan Rivers are provided in Appendix E. Travel times reflect the flow conditions during August 5–13, 2015.

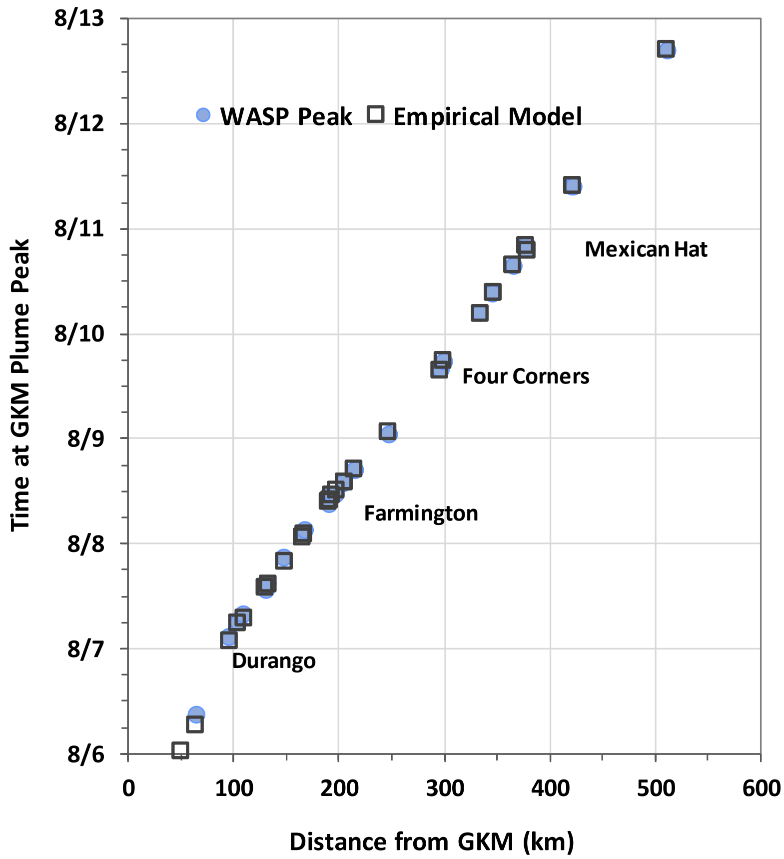


Figure 4-28. Arrival time of the peak of the Gold King plume simulated by WASP and the Empirical Model with distance from Gold King Mine. See Appendix E Table E-1 for time of arrival by site.

CHAPTER 5 . METALS CONCENTRATIONS OF THE GOLD KING PLUME AS IT TRAVELED

Modeling approaches were applied to build water sampling and other data into spatially- and temporally-detailed simulations of the Gold King Mine plume travel and metals concentrations. In this chapter, the metals concentrations and processes that affected them as the plume traveled are more closely examined.

The chemical makeup of the plume was dynamic as it flowed from its source in Cement Creek through the Animas and San Juan Rivers. Physical and chemical processes transformed the composition and amount of released material as the plume traveled. A chain of geochemical reactions triggered by the neutralization of the plume's acidity as it mixed with river water generated an intense yellow color that drew international attention. New equilibria continually evolved among the mix of metals remaining in solution. Precipitates were carried in suspension in the river or were left behind in the streambed.

As the plume moved into the Animas River, flow was low and typical of August. The large influx of metals entered the Animas, which had low turbidity and a background metals load made up primarily of dissolved cations, including Ca, K, Mg, and Na. By the time the plume had flowed through 190 km of the Animas River, the influx of metals to the San Juan River was relatively small. When the GKM release entered the San Juan River, flow associated with the plume was equivalent to a moderate storm event that included a relatively high sediment load with commensurate background metals concentrations and turbidity. As a result, the Gold King plume was experienced differently in the Animas and San Juan Rivers.

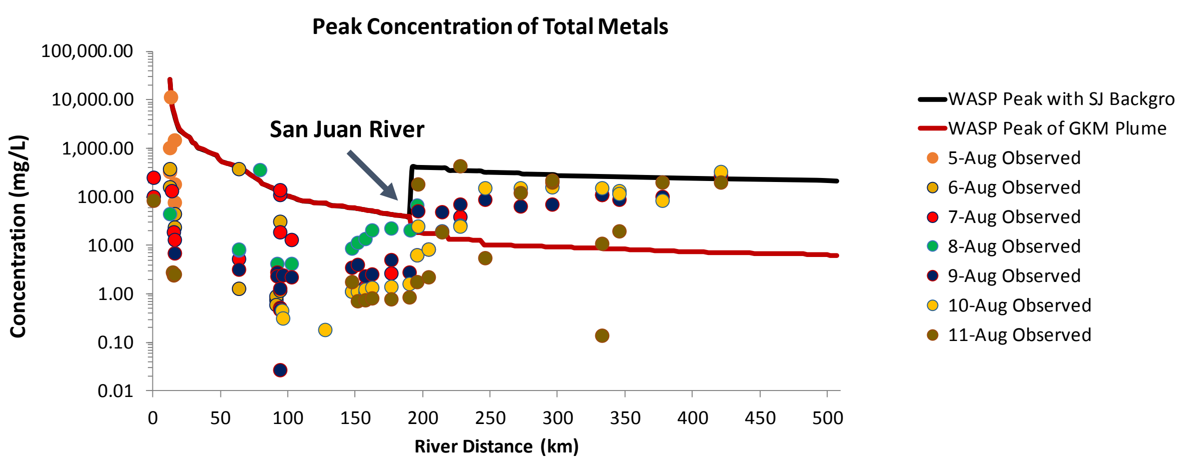


Figure 5-1. Summed total metals concentrations in the Animas River water column, collected from August 5 to August 11, 2015 during the Gold King Mine (GKM) plume passage. The lower/red line represents the Water Quality Analysis Simulation Program (WASP) modeling of peak total metal concentrations due solely to the release, as if flowing in distilled water, with all incoming boundaries at zero concentrations. The upper/black line is a simulation incorporating background total metals concentrations in the water column, based on observed data, in the San Juan (SJ) River upstream of the confluence with the Animas River, reflecting the sediment load in the river.

Summed total metals concentrations for samples collected in the Animas River from August 5 to 11, 2015 are shown in Figure 5-1, with peak concentrations modeled by WASP. The high metals concentrations initially introduced into the Animas River at the peak of the plume declined by orders of magnitude as the plume moved through the Animas River. Concentrations were much lower, though still elevated, as the plume passed from the Animas to the San Juan River at RK 192. Once the plume entered the San Juan River, observed metals concentrations increased.

A number of factors were responsible for the decline in metals as the plume moved through the Animas River; these did not play a large role in the San Juan River. Similarly, the Gold King plume was processed differently in the San Juan River. Given the differences in conditions and processes in the two rivers, metals concentrations will be discussed by river.

5.1 Metals Concentrations in the Animas River

Total and dissolved metals concentrations of samples collected in the Animas River during the Gold King Mine releases are shown in Figures 5-2 and 5-3, respectively. The wide range of metals concentrations at a location reflected the rise and fall of concentrations in the relatively short time of plume passage. The high concentrations of both dissolved and total fractions observed near the source had no precedent in historical sampling (also shown in Figures 5-2 and 5-3). Historical sampling occurred at a number of locations in the Animas River at RK 16.4 and in the Durango area from RK 90 to 110 to support acid mine drainage risk assessments. The USGS episodically sampled metals at flow gages throughout the Animas River. RCWWN also sampled a number of locations. Most of the historic data available for comparison were collected since 2002.

All of the metals in both total and dissolved fractions declined with distance as the plume traveled. Total concentrations observed during the plume period declined 2 to 3 orders of magnitude as the plume traveled through 190 km of the Animas River (Fig. 5-2). Zinc rapidly declined to levels seen frequently in the upper to middle Animas by RK 64. Indeed, concentrations of zinc were relatively low during the plume. Arsenic also reached previously observed concentrations by RK 64. Conversely, total lead and copper were elevated by about two orders of magnitude above any historical measurements as far as RK 100.

Dissolved concentrations were also well above any levels previously measured in the headwaters near the source and decreased by orders of magnitude as the plume moved downstream. Dissolved metals concentrations declined rapidly and were within historically-observed ranges from RK 100 southward.

Three important factors contributed to the decline in dissolved and colloidal/particulate fractions:

- Dilution reduced concentrations of all metals in both the total and dissolved fractions;
- Geochemical reactions reduced acidity and stimulated neutralizing chemical reactions that transformed dissolved metals into colloidal/particulates (total);
- Amorphous iron and aluminum oxyhydroxide solids precipitated in the reactions and deposited in the streambed, reducing metals concentration in the water.

The presence of amorphous minerals provided a substrate for dissolved trace metals to associate. It is unclear if these metals precipitated or sorbed to the amorphous mineral precipitates, but the presence of these conditions resulted in their settling to the underlying streambed, reducing the overall concentration of trace metals in the water.

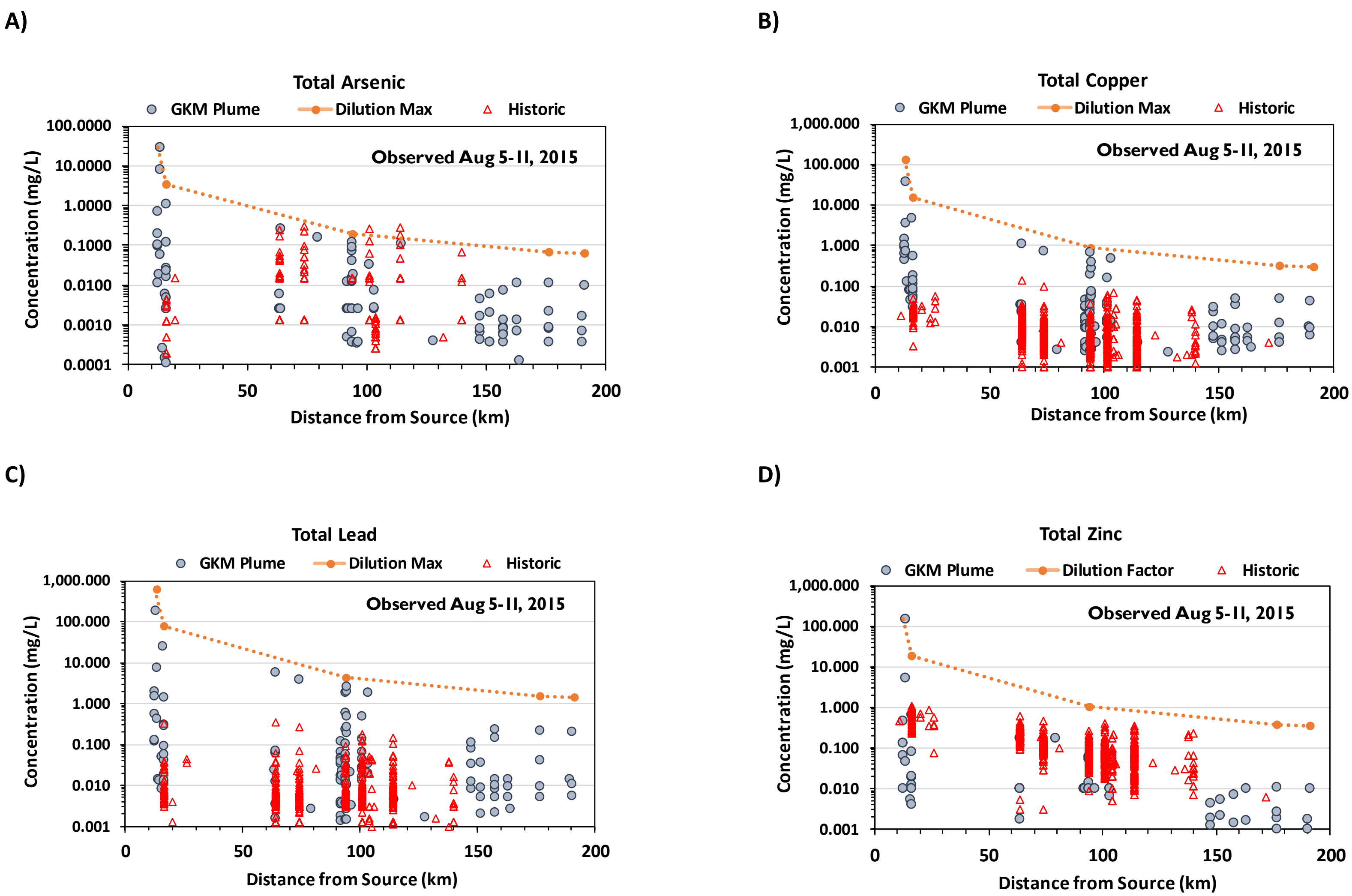


Figure 5-2. Total concentrations of A) arsenic, B) copper, C) lead, and D) zinc in water samples collected in the Animas River during passage of the Gold King Mine (GKM) plume (August 5–11, 2015). The orange dotted line indicates maximum concentration based on dilution of initial plume concentrations, accounting for incoming flow. Red triangles are historic data.

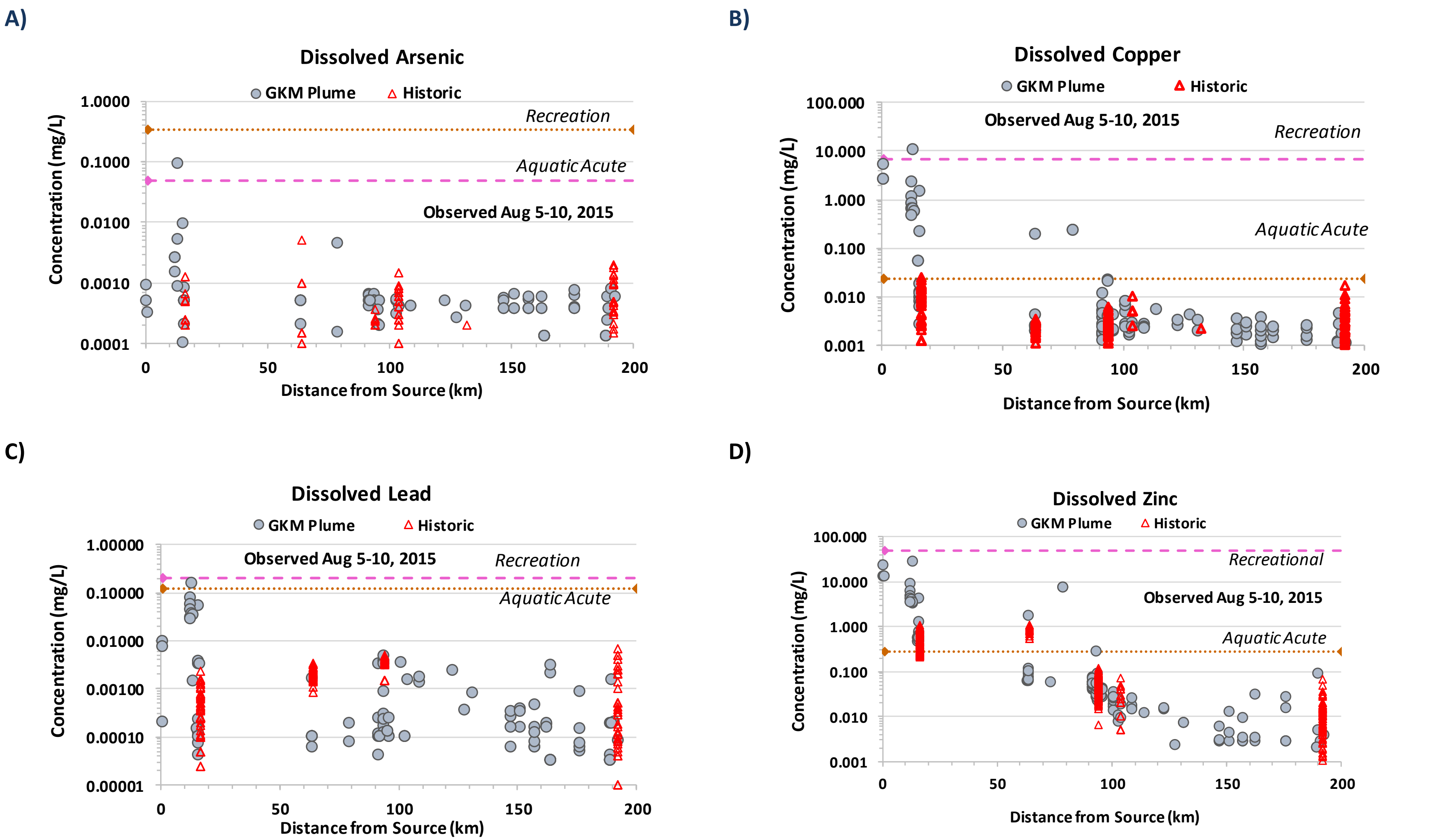


Figure 5-3. Dissolved concentrations of A) arsenic, B) copper, C) lead, and D) zinc in water samples collected in the Animas River during passage of the Gold King Mine (GKM) plume (August 5– 11, 2015). Red triangles are historic data. Water quality criteria concentration thresholds for recreation contact (EPA criteria) and acute aquatic exposure criteria (Colorado) for each metal are superimposed on the graphs.

5.1.1 Dilutions Effects on Metal Concentration

Dilution with the influx of fresh water was a major factor that accounted for at least two orders of magnitude decline in metals concentrations, with greatest impact in the headwaters. The relative effect of dilution on the initial metals concentrations introduced at Cement Creek is illustrated in Figure 5-4. Although dilution could be calculated directly at USGS gages, the WASP model was used to distribute the incoming flow through the river segments more evenly[1]. River volume was substantially increased within the first 4 km of plume travel as Cement Creek, Mineral Creek, and the Upper Animas converge at Silverton, reducing the initial plume metal concentrations by 87%. Dilution continued along the length of the Animas River, reducing plume concentrations to 0.22% of the initial concentrations as the plume reached RK 190 in Farmington. Dilution affected the concentrations of the total and dissolved fractions equally.

The effect of the dilution is evident in the water samples shown in Figure 5-2; the line of maximum concentration expected with dilution is superimposed on each graph. Metals declined following the expected dilution trend; no sample exceeded the predicted maximum. The fact that samples reached, but did not exceed the predicted maximum may indicate initial starting concentrations for the estimated for the Gold King plume in Cement Creek (described in Chapter 3) were reasonable. Observed water concentrations of all the metals fell well below the dilution maximum from the general distance from RK 100 to the confluence of the Animas and the San Juan River at RK 192 suggesting other factors also contributed to lower concentrations.

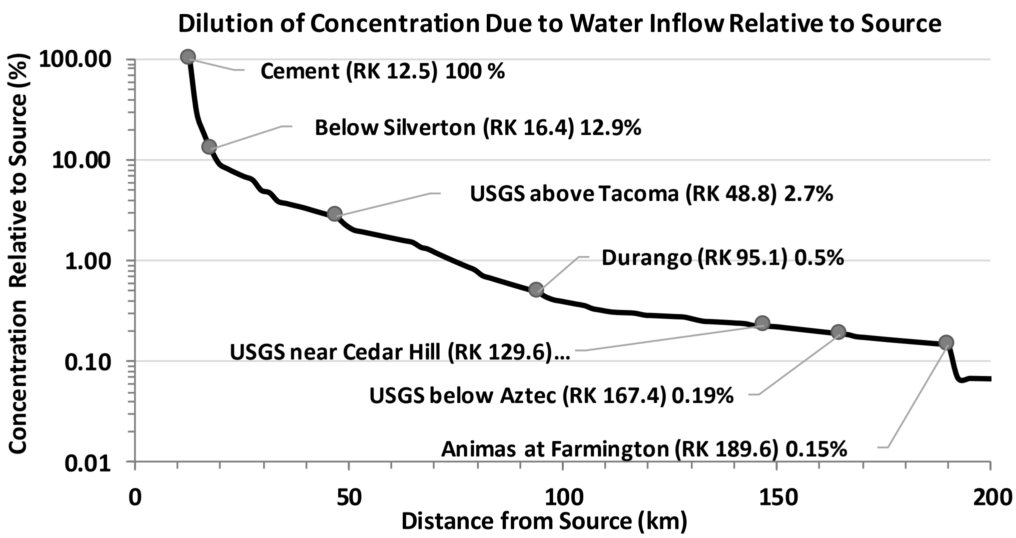


Figure 5-4. Dilution reduced metals concentrations as the Animas River gained water from incoming tributaries. The relative change from the initial peak concentration of the Gold King Mine plume before it moved from Cement Creek into the Animas River at RK 12.5 is shown. Dilution was based on incoming flow distributed by the Water Quality Analysis Simulation Program (WASP) model between USGS flow gages.

[1] WASP incorporates a simple hydrodynamic model solving the continuity equations with conservation of mass and momentum. WASP incorporates incoming flows and simulates the movement of the water that dilutes solute concentrations over distance.

5.1.2 Geochemical Reactions and Transformations

The Gold King plume was a large volume of acidic water that, upon neutralization, was supersaturated with large masses of Fe, Al, and Mn, and included elevated concentrations of other metals, including Zn, Cd, Cu, Pb, As, Ni, Mo, As, Se, Ag, and cobalt (Co). Neutralization of mine release waters typically triggers precipitation of Fe, Al, and Mn, as incipient oxide-solids and minerals.

Neutralization and pH in the Animas River. Both upstream and downstream of Cement Creek, the Animas River is buffered at moderately alkaline pHs by bedrock with carbonate and chlorite minerals (Desborough and Yager 2000; Yager and Bove 2002). When the Gold King plume flowed from Cement Creek into the Animas River, the pH of the plume increased rapidly. The dilution shown in Figure 5-4 is indicative of the plume mixing with the alkaline water of the Animas.

The pH of Cement Creek is routinely <4.5 and was probably closer to 3 when the plume entered the Animas River. While headwater streams range in pH from 4–6, pH in the Animas River mainstem is greater than 7.5 above Cement Creek (Besser et al. 2007). Typically, pH increases as the Animas flows southward, reaching about 8 by RK 64, 8.4 by RK 100 and 8.7 by RK 129. The pH at RK 132 reached 9 at the maximum of daily fluctuations recorded by sondes in the days following the plume (Figure 4-16).

The acidity of the Gold King plume was neutralized as it moved through the Animas River, as reflected by the change in pH. Observations of pH at or near the peak of the Gold King plume are shown in Figure 5-5 for multiple locations. Taken as general distances inferred from the graph, there was a virtually-linear increase in pH for 120 km until a pH of 8.2–8.5 was reached at approximately RK 120. Although the plume approached the background pH of the lower Animas River at approximately RK 130, pH dipped between RK 160 and 170, before returning to a pH of 8.2 (Figure 5-5).

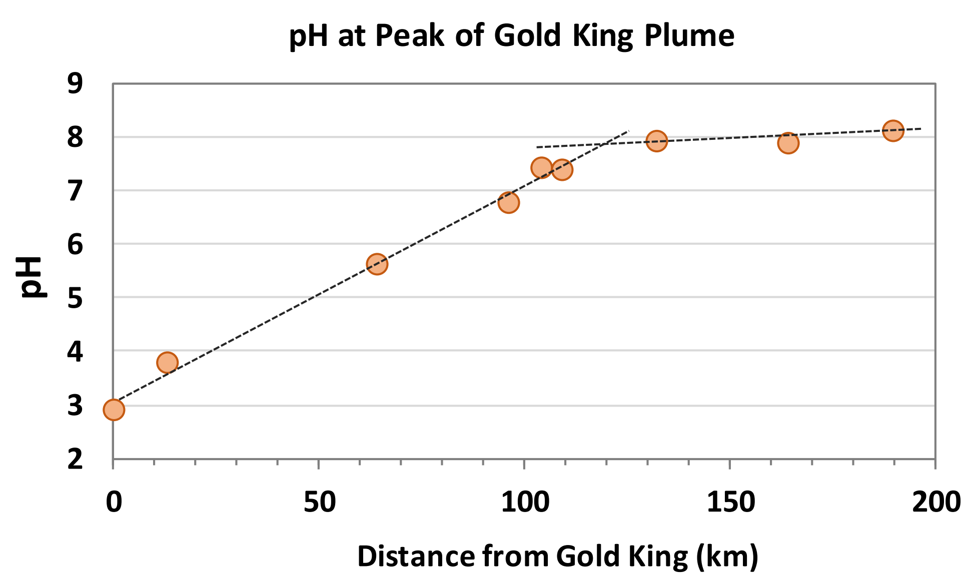


Figure 5-5. Observed pH at or near the peak of the Gold King Mine plume at locations in the Animas River. The river approached background pH at approximately RK 130.

Oxidation Reactions Formed Fe and Al (Hydr)oxide Solids. The rapid increase in pH as the plume mixed with the Animas River water dramatically accelerated oxidation of the major AMD solutes, in turn spurring precipitation of hydroxide solids, including Fe^{3+}, Al^{3+} and Mn^{4+} incipient oxide phases. The oxidation reactions precipitated minerals and generated colloidal solids as products, including amorphous and short-range-order iron (III) oxide-hydroxide [$Fe(OH)_3$], aluminum hydroxide [$Al(OH)_3$], and Mn oxyhydroxides. These primary reaction products caused the yellow coloration in the Animas River (Figure 5-6). The yellow coloring is a common byproduct of iron oxide precipitation in AMD and is generically referred to as "yellow boy". Yellow boy can be yellow, red, white, or black depending on the dominant metals. The high mass of Fe, combined with its color intensity, dominated coloration from Al and Mn.

The chemical reactions of AMD neutralization are well understood (e.g., Nordstrom 2011). The same principles are applied in treating AMD as naturally occurred as the plume traveled through the Animas River. Dissolution, sorption, and precipitation reactions depend on the chemical behavior of each element, solution composition and pH, aqueous speciation, temperature, dissolved oxygen (O_2), and contact-time with mineral surfaces (Nordstrom 2011). These same chemical reactions occur on a continual basis in the Animas River in the vicinity of Silverton from the ongoing contamination from acidic drainage in the headwaters including Cement Creek (Schemel and Cox 2005).

The oxidation of ferrous iron (Fe^{2+}) by dissolved O_2 was calculated as a function of pH using the kinetic data from Singer and Stumm (1970) and is provided in Table 5-1. At low pH, abiotic oxidation reactions occur very slowly. Given the low pH of Cement Creek, relatively little metal attenuation or oxidation likely occurred in the first hours as the plume traveled down the system, as reactions would have been very slow at pH <4. Reactions that would take years in Cement Creek would take only minutes to hours in the alkaline waters of the Animas River. The ferrous iron half-life by dissolved O_2 in equilibrium with air falls to 7 hours at pH 6 and 4 minutes at pH 7.

Table 5-1. Abiotic oxidation reactions of ferrous iron (Fe^{2+}). oxidation half-life ($T_{1/2}$) reactions by dissolved oxygen occur significantly more rapidly as pH increases.

pH (su)	$T_{1/2}$
0	65.89 years
1	65.89 years
2	65.84 years
3	61.01 years
4	7.32 years
5	30.05 days
6	7.22 hours
7	4.33 minutes
8	2.60 seconds
9	0.03 seconds

The large volume of acidic solution released from the Gold King Mine became a dynamic chemical reactor that mixed the metals solution over a distance of several hundred kilometers, resulting in pH and solution compositions that evolved as the plume traveled through the Animas River. Because of the large volume of AMD in the GKM release, the oxidation reactions proceeded over many hours and probably changed along the river, as reactions progressed. In the case of the Gold King plume, time is registered by distance at which phenomena were observed.

Detailed measurements necessary to support analysis and modeling of the Gold King Mine geochemistry were not collected during the plume. We can only describe the likely processes that occurred and support those interpretations with modeling performed with the data at hand. Data from water sampling were used to demonstrate the river scale patterns in pH and metals concentrations suggested by the geochemical principles just discussed. Additional geochemical analyses and methods are discussed in Appendix C.

To test whether the GKM release waters were over- or under-saturated, the solubility of calcite ($CaCO_3$) and/or dolomite [$CaMg(CO_3)_2$], as determined by the free energy of dissolution of the solid phase, were determined to be positive, negative, or zero (Stumm and Morgan 1996). Ionic strength, activity coefficients, and saturation indices (SIs) were calculated using available field and laboratory data, as well as thermodynamic data reported in Parizek and White *et al.* (1971). Saturation indices for calcite and dolomite were calculated throughout the Animas River and into the San Juan River, beginning with the Gold King plume in Cement Creek (Figure 5-7). The maximum calculated load of acidity in the GKM release was ~54,000 kg as $CaCO_3$.

As the plume traveled through the river system, negative SI values indicated that water was under-saturated with a mineral phase, and values near zero indicated the water was roughly in equilibrium with a mineral phase. Positive SI values suggested the mineral should precipitate from solution. The Animas River was variably under-saturated with respect to calcite and dolomite immediately downstream of Cement Creek for approximately 100 km, suggesting the presence of acidity (Figure 5-7). The Animas River remained slightly saturated with alkaline minerals for most samples at RK 150 and beyond, suggesting neutralization of acidity in these locations. The alkalinity computations of the release waters suggest that the dissolved acidity of the plume would be roughly balanced by Animas River flow over two days. The actual time for neutralization of the plume in the Animas could have occurred more quickly if the amount of alkalinity added with downstream tributary inflow was underestimated or the acidity load of the release itself was overestimated.

Photo: Southern Ute Indian Tribe

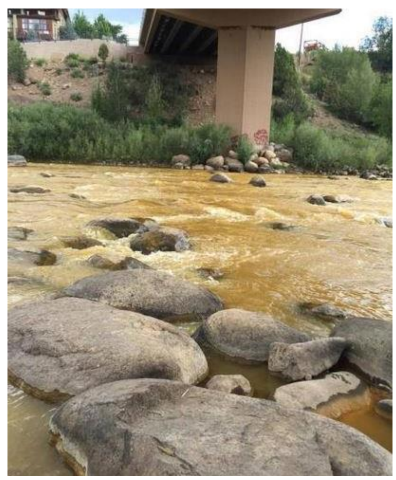


Figure 5-6. Photographs of the Animas River saturated with “yellow boy” iron and aluminum (hydr)oxides at various locations in the Animas River as the Gold King plume traveled. Geochemical reactions within the plume occurred with neutralization of acidity after mixing with the alkaline water of the river.

Nature of the Precipitates. The oxidation reactions progressed as the GKM plume moved through the system, creating a series of mineral phases, some of which were short-lived, unstable, and transitory under the evolving conditions within the plume, and some of which were more stable and persisted in streambed deposits. A variety of factors determined the mineral species that formed, including the composition of the metals in the plume as well as the availability of anions such as sulfate ($SO_4^{=}$) and bicarbonate (HCO_{3-}). A primary controlling factor in these reactions was the availability of hydrogen ions (pH).

When large volumes of AMD are introduced suddenly into the environment, the relatively slow crystallization processes required to form stable crystalline minerals do not have time to take place. The kinetics of the reactions in the Animas River enhanced oxidation and favored generation of ferric iron (Fe^{3+}) through oxidation of Fe^{2+}. The speed of these reactions fostered precipitation of amorphous hydrous ferric-oxide (HFO) solid phases and favored creation of solids as colloids in incipient amorphous to short-range-order crystalline phases (Figure 5-8).

Without detailed mineralogy and geochemistry sampling, the makeup of the Gold King plume could not be known with certainty. Metals precipitate at differing pH (Stumm and Morgan 1996), and the composition within the plume would have varied as neutralization progressed. As discussed in Nordstrom (2011), during the oxidation of dissolved Fe and neutralization of acid water, HFO solids precipitate, perhaps including micro- to nano-crystalline ferrihydrite (Fh), goethite [FeO(OH)], and schwertmannite. The precipitate is usually a mixture of phases of uncertain composition and degree of crystallinity. $Fe(OH_3)$ reaches saturation in a lower pH range (pH 4–5), depending on the Fe concentration. $Al(OH_3)$ reaches saturation with microcrystalline gibbsite and amorphous $Al(OH_3)$ forming at a pH of 5 (depending on the Al concentration). However, at a pH range of 5–7.5, a solubility limit is reached that corresponds to “amorphous” $Al(OH_3)$ (Nordstrom 2011). Thus, the mineral phases that emerged as the GKM plume traveled downstream imparted a varying signature along its course. The mineralogy of precipitates is explored more in Appendix C.

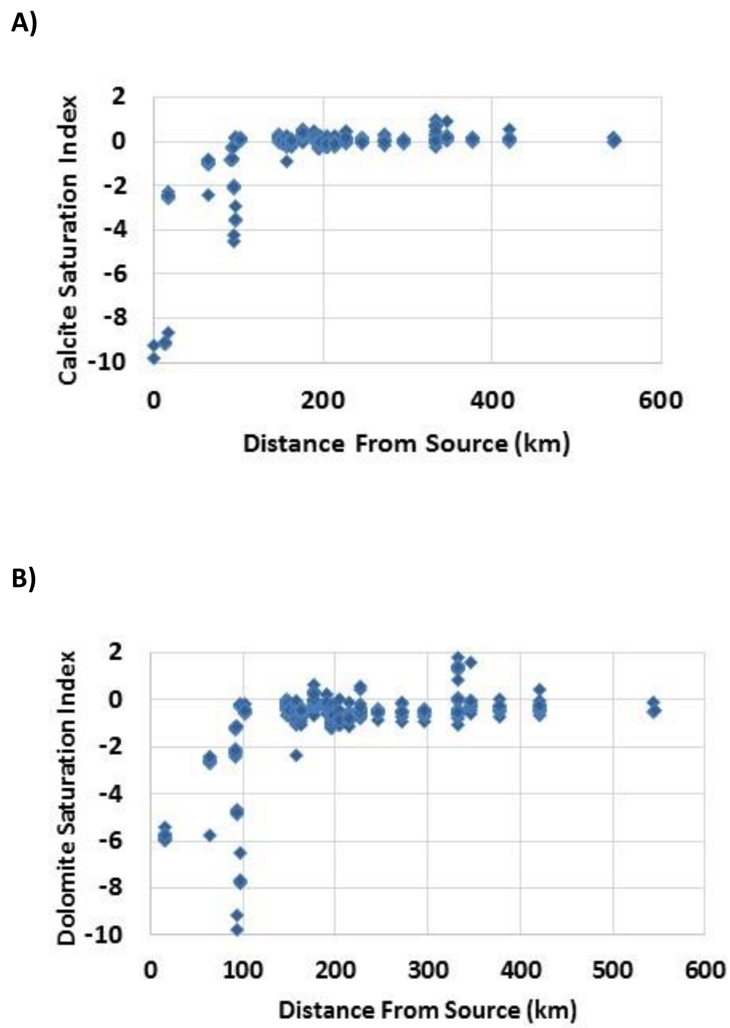


Figure 5-7. Saturation Indices (SIs) for A) calcite and B) dolomite as a function of distance from Gold King Mine. An SI of zero indicates saturation with the mineral phase; negative SI values indicate that the water is under-saturated with the mineral.

The precipitates from the Gold King plume were a mix of many incipient solids and minerals of various species and sizes. Short-range-order minerals tended to be smaller in size and more unstable. These amorphous colloidal precipitates can range in size from 0.001 µm to as large as 10 µm, with varying degrees of internal structure. Clearly, some single-grained colloids from the plume were likely small enough to pass through the standard 0.45-µm filter used for the majority of the laboratory processing of water samples to separate dissolved metals from total fractions. Thus, the dissolved fraction of the Gold King plume could have been overestimated in water samples if colloidal solids were counted in the fraction.

The colloids formed in the Animas River were electrostatically charged, favoring suspension in the water, but they could have also aggregated into larger particles that settled to the streambed. A wide range of particle sizes were present, as indicated by the color carried in the river (Figure 5-6), as well as the varied composition of material left behind in the streambed (Figure 5-8).

A)

Photo: Tom McNamara, La Plata County, Office of Emergency Management

B)

Photo: EPA

C)

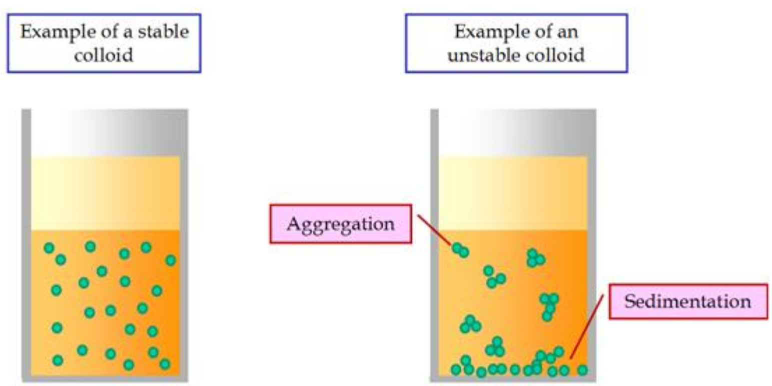


Figure 5-8. Characteristics of the plume precipitates. The iron and aluminum (hydr)oxides were probably mostly amorphous colloids, which are solid particles that range in size up to 10 µm, and were suspended in the acidic water. A) The Gold King Mine plume colloids "painted" rocks as shown. Fully dispersed colloids are like milk or paint, and can easily be suspended and transported in river flow. B and C) The particles can also aggregate and settle to the streambed due to electrostatic charges among particles. All are termed "yellow boy" and represent a mix of iron and aluminum oxide minerals.

Hydroxides and sulfates often occur in amorphous and several crystalline forms. Amorphous solids may be "active" or "inactive" (Stumm and Morgan 1996). Active forms are the very fine crystalline precipitates with disordered lattice generally formed incipiently from strongly-oversaturated solutions. An active precipitate may persist in metastable equilibrium with the solution and may recrystallize ("age") slowly into a more stable "inactive" form. Inactive solid phases with ordered crystal form from solutions that are only slightly oversaturated. The more active components left behind in the Animas River were more readily dissolved. Freshly precipitated and/or suspended soluble salt mineral phases that had been near equilibrium with solutes in the Animas River would have been active and likely, dissolved and re-precipitated as oxides, in the case of Al and Fe. Over days to years, depending on the chemical conditions, incipient solids that remained in the streambed long enough would recrystallize to stable, inactive mineral phases or be incorporated into organic matter.

Precipitating reactions that occurred concurrent with acid neutralization would be evidenced by an increase in the colloidal/particulate fraction of the metals mass and reduction in the dissolved metals mass as the plume traveled. The dissolved mass of metals at the peak of plume passage at seven Animas River locations determined by the empirical model is shown in Figure 5-9. Approximately 15,000 kg of dissolved metals were delivered from Cement Creek to the Animas River. Dissolved metals decreased with distance from Gold King Mine, while colloidal/particulate mass systematically increased. It appears that most, if not all, of the transition of dissolved metals in the plume occurred within 130 km from the source. The precipitation to colloidal/particulate mass followed the calcite trend shown in Figure 5-7, which indicates a change in solubility. Plume-related dissolved metals were sorbed into the colloidal/particulate metals mass by the time the plume reached its confluence with the San Juan River at RK 192 (Farmington, NM).

Trace Metals During the Plume. Metal ions present in solution such as Cu, Zn, Pb, Cd, and Ni readily bind to charged surfaces to achieve more chemically-stable solid forms (Stumm and Morgan 1996; Smith 1999). The metal ions present in acidic solutions "sorb" onto iron and aluminum oxide precipitates, as well as to reactive sites on sediments, especially clay particles and organic matter through chemical and electrostatic binding.

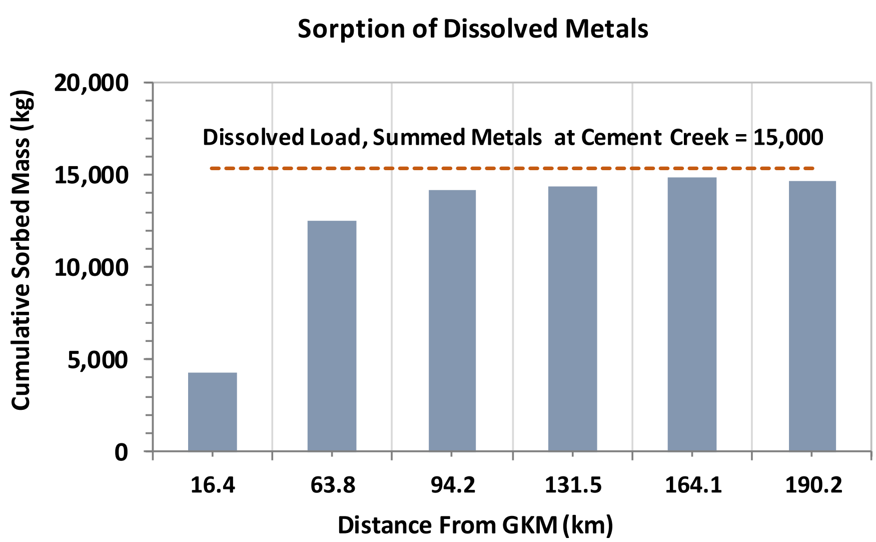


Figure 5-9. Dissolved load of metals simulated by the empirical model as the Gold King Mine plume traveled through the Animas River. The initial volume of dissolved metals (minus major cations) that was input to the Animas River from Cement Creek was 15,000 kg.

The mobility of most of the trace metals would have decrease dramatically with the increasing pH of the plume, as they were sorbed and/or entered the Al and Fe (hydr)oxide precipitate phase. The degree to which individual metals precipitated would have depended primarily on pH and secondarily, on mixture and concentration strength (Smith 1999). Each metal has a range of pH (termed the “sorption isotherm edge”) that determines its solubility. The isotherm sorption edge of some of the trace metals important in the Gold King plume are shown in Figure 5-10. Common metal contaminants from mine drainage that typically sorb, in order of strength from greatest to least are Pb, Cu, Zn, and Cd (Nordstrom 2011). For this group of metals, dissolution of metal ions is favored when environmental pH is lower and sorption to solid form is favored when pH is higher. Metal sorption may be transitory. Metals may return to solution if conditions such as pH, dissolved species, and temperature reverse to favor desorption reactions (Smith 1999).

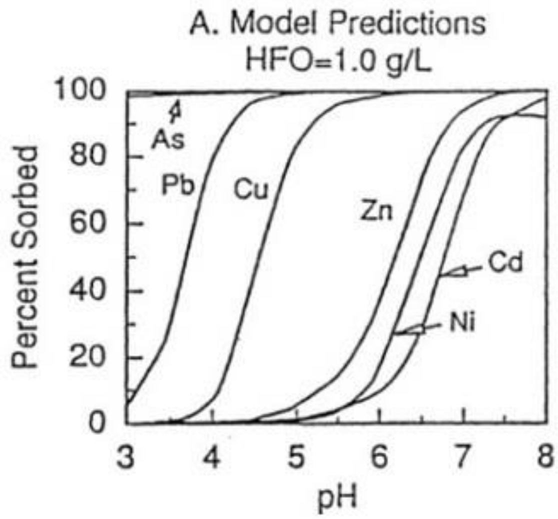


Figure 5-10. Solubility of metals is dependent on pH primarily; mixture and concentration strength are secondary factors. The pH range that defines the solubility (i.e., sorption isotherm edge) of six individual metals at higher concentrations of hydrous ferrous oxides (HFO) is shown (from Smith 1999). Lead and arsenic are insoluble at pH typical of naturally-occurring waters and are soluble in waters in the pH range of 3–4. Zinc, nickel, and cadmium are soluble in more naturally-occurring ranges of pH between 5–8; copper is intermediate.

Dissolution of metals from particles of soil and mine was eroded by the release may have occurred in the turbulent, low pH waters in Cement Creek in the first hours of plume travel. Water samples documented the sorption of trace metals during travel of the Gold King plume as pH changed. Figure 5-11 shows the relative sorption of samples at the peak of the plume modeled by the empirical model. Proportion sorbed was calculated as:

$$\text{Proportion Sorbed} = \frac{(\text{Total Concentration} - \text{Dissolved Concentration})}{\text{Total Concentration}} \qquad \text{(Equation 5.1)}$$

Increased sorption from the dissolved to the colloidal/particulate fraction occurred at distances concurrent with where pH passed through each metal’s sorption isotherm edge.

The longitudinal trend was consistent with insoluble metals sorbing more quickly than the more soluble metals. Iron, lead, and arsenic are generally insoluble in waters with pH less than 6. These metals were therefore expected to attenuate most rapidly (Nordstrom 2011). This was evident in Figures 5-3 and 5-11, where dissolved arsenic and lead were quickly gone in the distance where pH exceeded 4. Dissolved copper was largely sorbed when pH reached 6 at RK 94. Dissolved zinc and cadmium continued in dissolved form to RK 132 consistent with the achievement of the background pH (close to 8).

Calculations of sorption equilibration of trace metals, including Zn, Cu, and Pb, on $Fe(OH)_3$ surfaces yielded modeled concentrations that supported the observation that trace metal partitioning to freshly-precipitated colloids was a dominant mechanism in the lower Animas River that decreased dissolved concentrations of these trace elements.

Total and dissolved summed metals concentrations in the Animas River during the plume period from August 5 to August 10, 2015 are shown in Figure 5-12. Water sample concentrations are plotted with the empirical model's trace of summed metal concentrations representing the estimated maximum for each fraction. Total and dissolved metals concentrations declined by orders of magnitude as the Gold King plume moved through the Animas River.

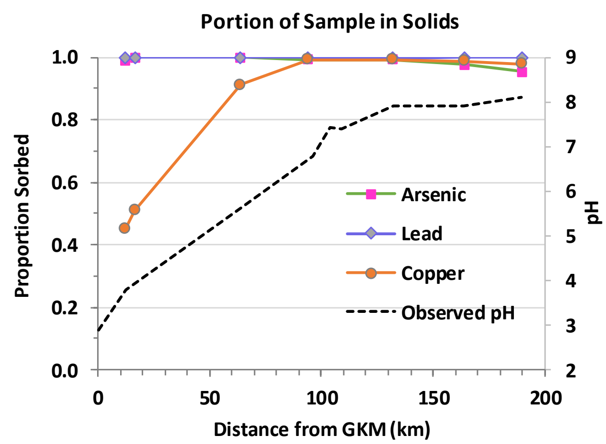
At least two orders of magnitude of the decline in both total and dissolved could be accounted for by dilution. Formation of colloidal precipitates moved dissolved ions into colloidal/particulate minerals measured in the total fraction. Reduced total concentrations also signaled loss of metals mass to the river bed. The fate of the metals mass and its distribution will be quantified in Chapter 6. Metals remaining in suspension continued into the San Juan River, flowing as a coherent plume.

5.2 Metals Concentrations at the Confluence of the Animas and San Juan Rivers

As the Gold King plume left the Animas River, the dissolved metals were sorbed into the colloidal/particulate precipitates and dissolved metals were at background concentrations. Dissolved concentrations at the plume peak, as determined by the empirical model, and estimated pre-event concentrations, based on historical observations, are provided for the Animas River at RK 190.2 in Farmington in Figure 5-13. Dissolved iron and aluminum in the GKM plume remained elevated at levels 2–3 times greater than pre-event conditions in the lower Animas River. Dissolved concentrations of most other metals were similar to or lower than pre-event observations.

Although reduced from the high loads introduced into the headwaters of the Animas River, the colloidal/particulate metals load was still visible and measurable as the plume moved into the San Juan River after 72 hours and 190 km of travel (Figure 5-14).

A)



B)

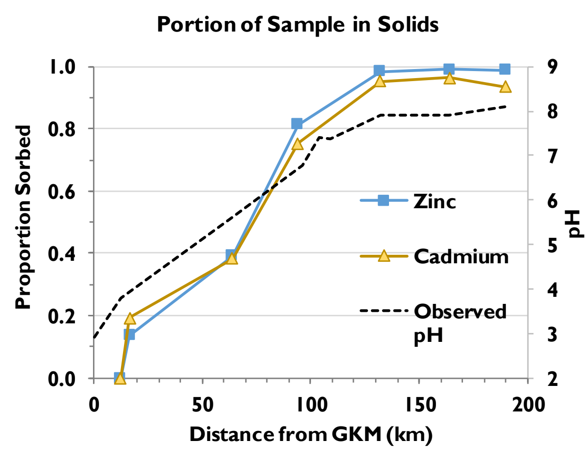


Figure 5-11. Observed sorption of metals relative to pH in the Animas River determined from water sample concentrations (Total-Dissolved/Total). The sorption of A) lead, copper and arsenic and B) cadmium and zinc relative to observed pH is shown. Observed river water pH was translated to distance based on Figure 5-5.

A)

B)

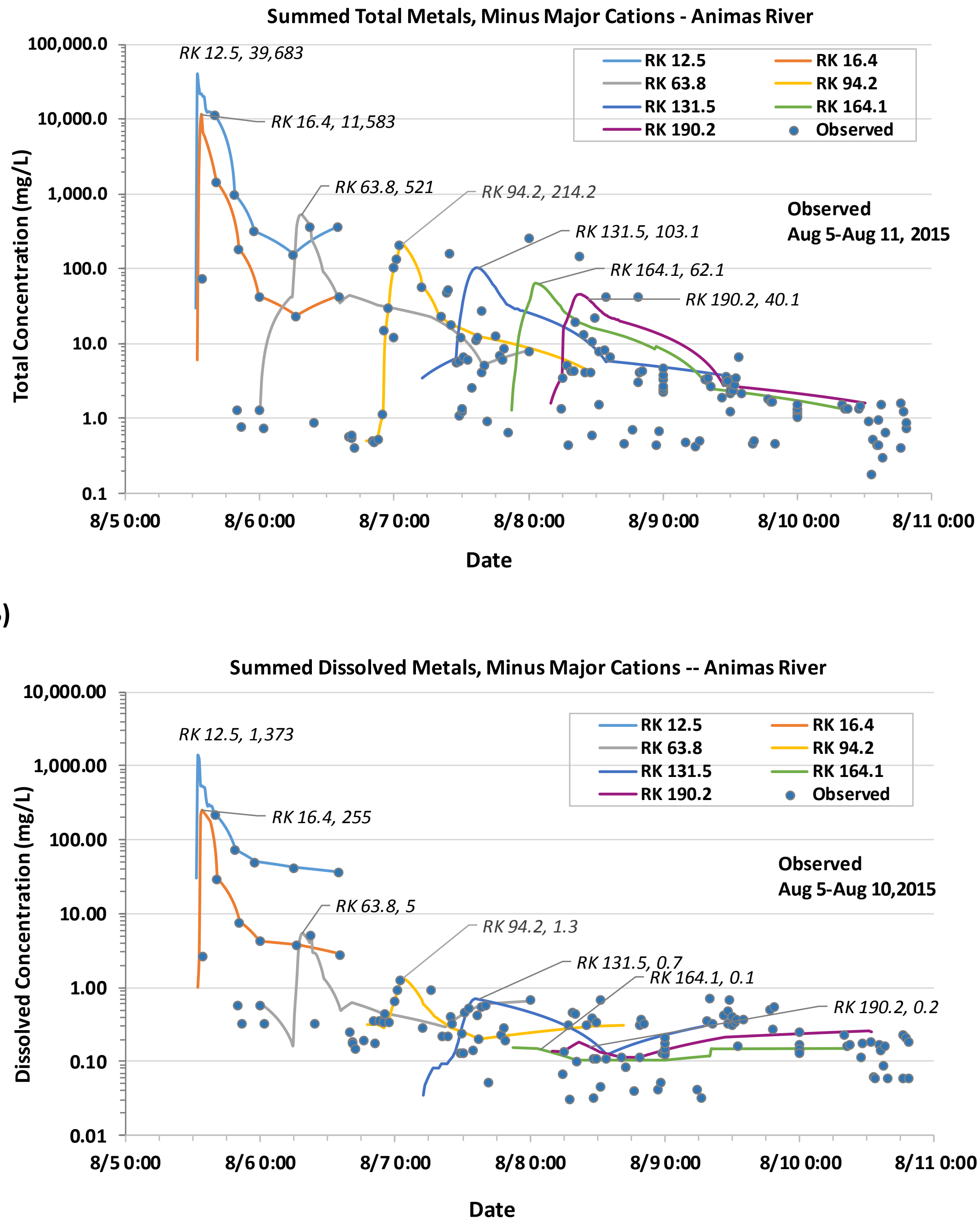


Figure 5-12. Observed and empirically-modeled summed A) total metals and B) dissolved metals, minus major cations, in the Animas River as the Gold King Mine plume passed from August 5–10, 2015.

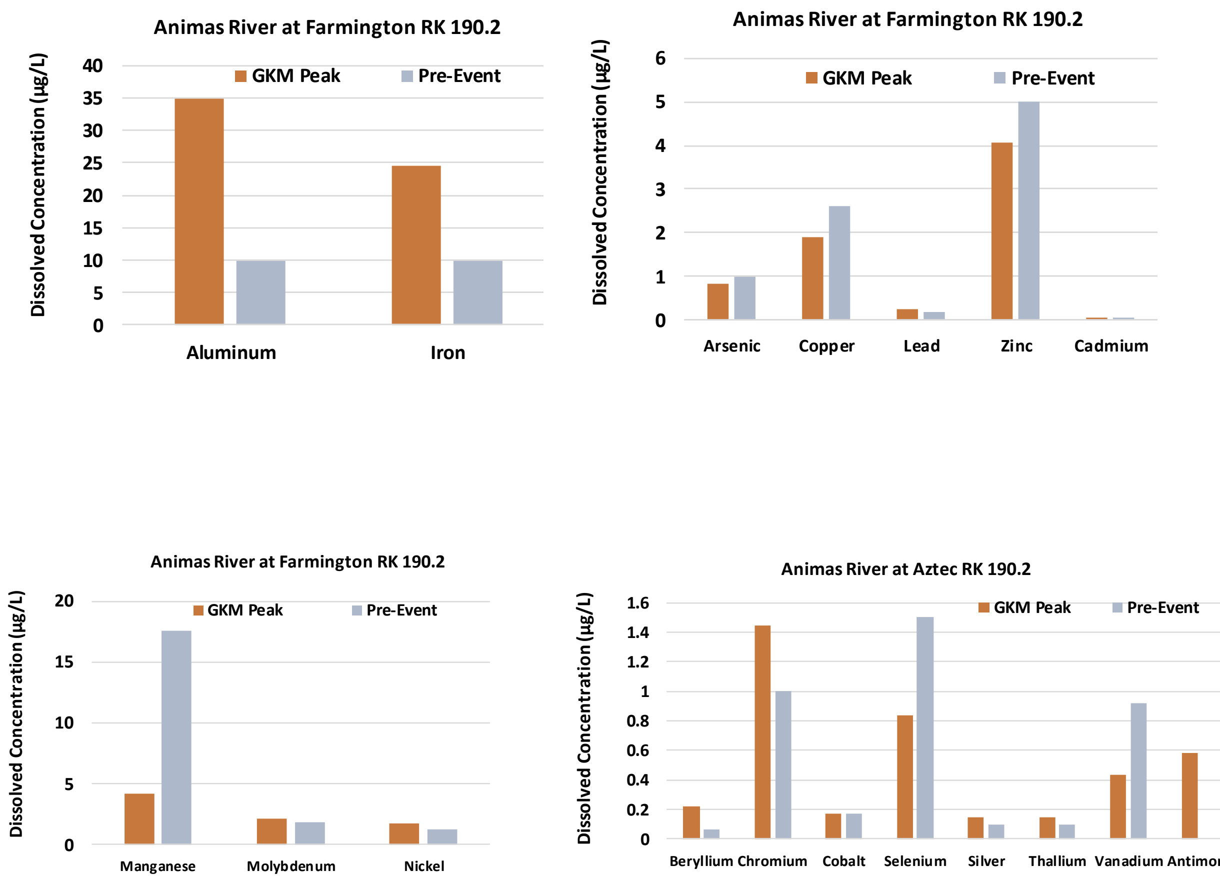


Figure 5-13. Dissolved concentrations of metals at the peak of the Gold King Mine (GKM) plume in the Animas River at RK 190.2 before entering the San Juan River. Concentrations estimated by the empirical model and compared to pre-event concentrations, computed as the average of historical samples.

5.3 Metals Concentrations in the San Juan River

The Gold King plume was experienced differently in the San Juan River. The Bureau of Reclamation (BOR) had released water from the Navajo Dam into the San Juan River, anticipating the arrival of the plume. Both the San Juan River, with the dam release, and the Animas River, with curtailment of withdrawals, had relatively high flows during the plume. The rivers joined at close to an equal flow of approximately 23.8 m^3/s (840 cfs).

The elevated flow in the San Juan River also brought a significant sediment load. The San Juan River often carries more sediment than the Animas River, as visible in the Figure 5-14A. Suspended sediment measurements taken on August 9 at locations in the Animas and San Juan Rivers as the GKM plume passed showed a significant elevation in suspended sediment in the San Juan River associated with the increased flow, which continued to increase as the river flowed westward (Figure 5-15).

A)

Photo: GoogleEarth

B)

Figure 5-14. Confluence of the Animas and San Juan Rivers. A) GoogleEarth image of confluence at lower flow. Under lower flow conditions, the Animas River normally enters with somewhat higher flow and less turbid waters. The Navajo Dam 74 km upstream of the confluence controls flow to this point in the San Juan River. B) GKM plume movement from the Animas to San Juan Rivers in Farmington. Flow in both rivers was relatively higher than normal for the time of the year, with the San Juan providing about 50% of the mixed volume.

Mixing with sediments was the major factor determining the effects of the GKM plume in the San Juan River. The plume became increasingly difficult to visually detect or measure as it traveled and mixed with the background sediment load in the San Juan. Metals naturally present in the sediment affected the ability to detect the plume with standard water sampling and laboratory techniques. Plume metals were amorphous colloid/particulates. Metals in the background sediment load were particulates from natural weathering products and soil particles. After digesting the samples during laboratory processing, these metal species could not be distinguished from one another. Analysis techniques were subsequently adapted to distinguish the Gold King plume from natural sediments in the San Juan River.

Total metals concentrations at the peak of the plume in the Animas River at RK 190.2 are compared to those in the San Juan at RK 196.1 in Figure 5-16. Peak concentrations were estimated by the empirical model and background estimates were the lowest observed concentrations 21 days after the plume; no historical total metals concentrations were available for comparison.

Total concentrations of the metals remained substantially elevated relative to background in the Animas as the plume neared its confluence with the San Juan River at RK 193. However, mixing of the Animas plume metals with sediments significantly affected the impact of the Gold King plume on

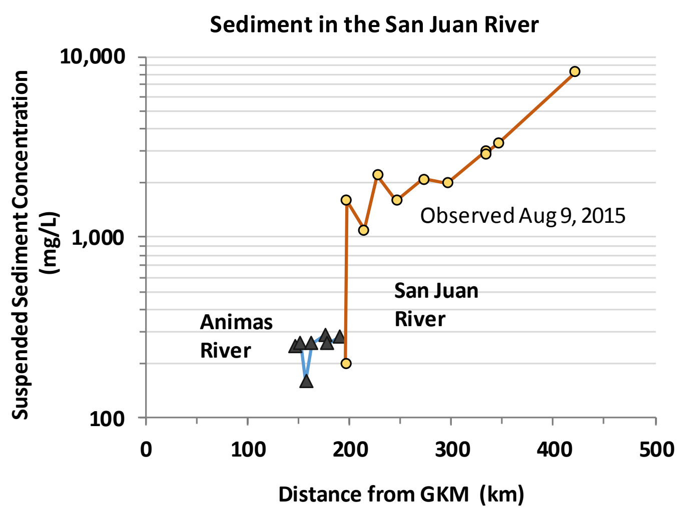


Figure 5-15. Total suspended sediment measured at a number of locations in the Animas and San Juan Rivers as the Gold King Mine (GKM) plume passed. Total suspended sediment increased 10-fold when the Animas River joined the San Juan River at Farmington (RK 192) and continued to increase as the San Juan River flowed westward.

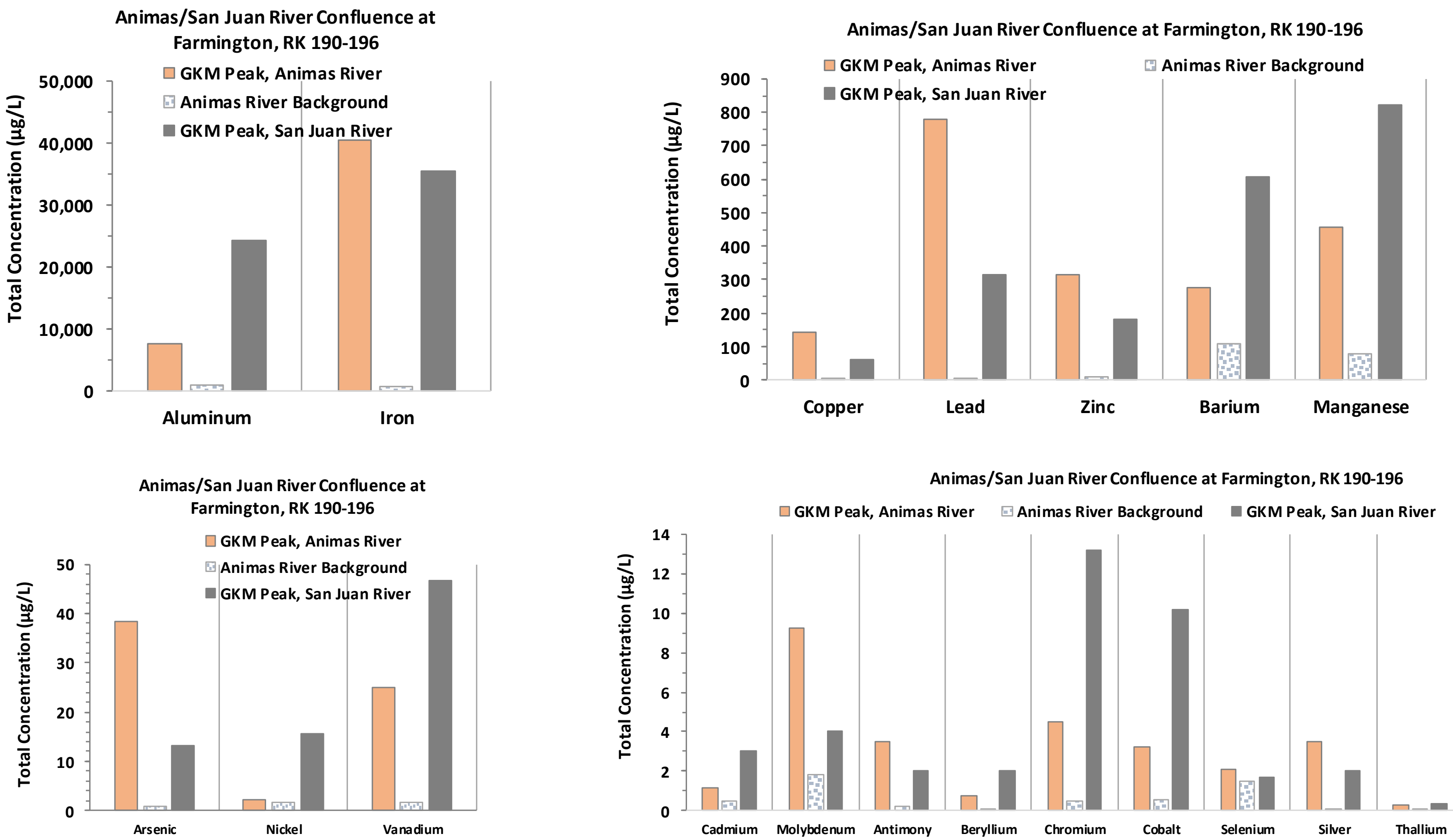


Figure 5-16. Total metal concentrations at the peak of the Gold King Mine (GKM) plume in the Animas River at RK 190.2 and in the San Juan River at RK 196.1, as determined by the empirical model. These concentrations are compared to estimated background concentrations in the Animas River based on samples. Panels group metals with similar concentration ranges.

metals concentrations in the San Juan River. Two distinct patterns are evident in Fig. 5-16. For metals with higher concentration in the Animas, concentration decreased with dilution. This occurred with Pb, Zn, Cu, and As present in higher concentrations and with Mo and Ag that were present in low concentrations. Conversely, a number of metals had higher concentrations in the San Juan relative to the Animas, presumably associated with the sediment. This pattern was observed with Al, Ba, Mn, Cd, Ni, Cr, Co, and V.

5.3.1 Longitudinal Trends in Metals in the San Juan River

Unlike the Animas River, metals concentrations tended to increase in the San Juan with sediment as it flowed westward during the time when the Gold King plume passed through. Total metals concentrations observed in the San Juan River during passage of the Gold King plume from August 8 to 11 are shown in Fig. 5-17. A limited amount of historical data was available at several locations.

Metal concentrations were generally within the historical range of variability at the limited number of locations where data were available. Many of the metals were already lower than the background San Juan concentrations when the plume entered from the Animas (e.g. Fig. 5-16). Concentrations of the four focus metals increased with distance of travel through the San Juan following the increasing sediment load as the plume traveled westward. Metals concentrations only decreased in samples collected within or near Lake Powell which was the final receiving water for what remained of the Gold King plume.

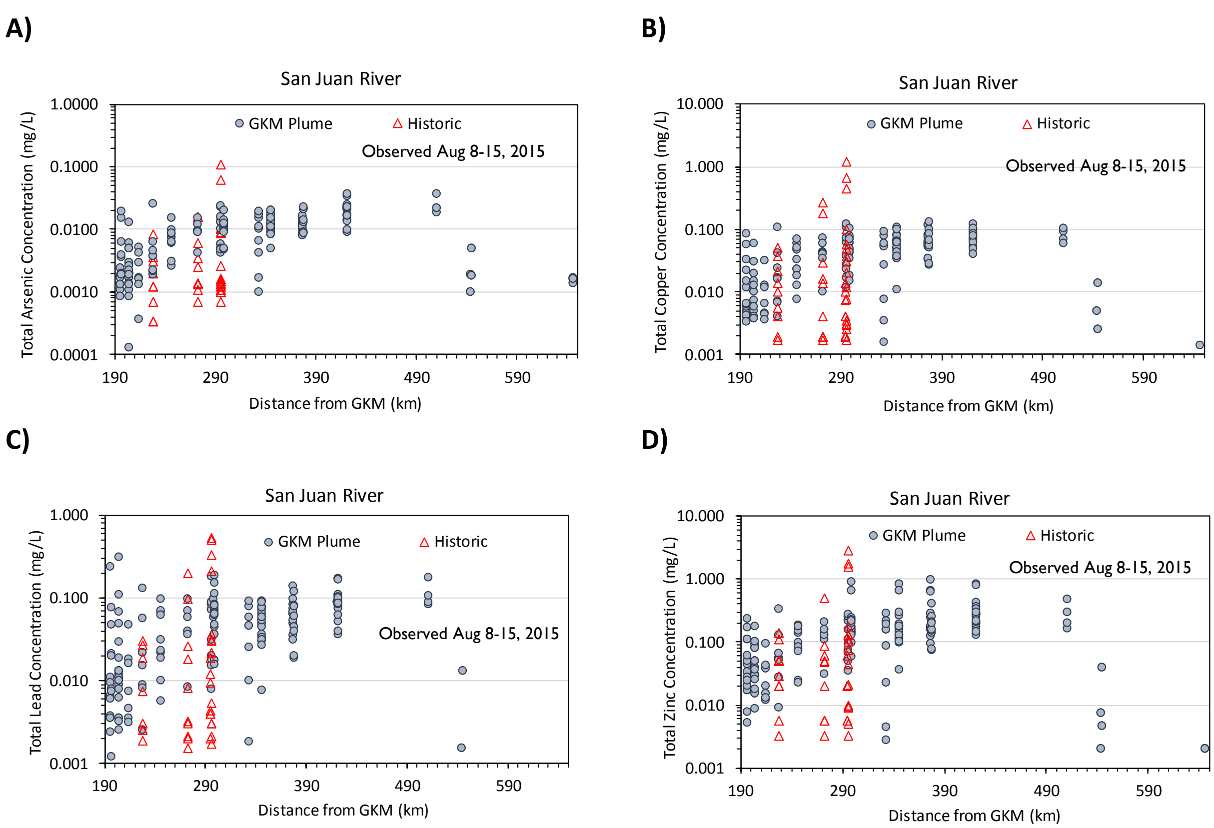


Figure 5-17. Total metals concentrations of A) arsenic, B) copper, C) lead, and D) zinc in water samples collected from the San Juan River August 8–15, 2015, as the Gold King Mine (GKM) plume passed. Historic data are shown as red triangles.

5.3.2 Metal Signature from the Gold King Plume in the San Juan River

With lower metals concentrations in the Gold King plume and higher background metals concentrations in the San Juan River, the plume metals were difficult to detect. Given the importance of the background metals load, a method was developed to isolate Gold King release metals from background metals. This approach accounted for the high background concentrations of metals that were also a significant component of the metals released from the mine. The relationship between concentrations of trace metals and with aluminum and iron from the same water samples were useful for this purpose.

The rationale for this approach was that aluminum and iron are abundant crustal elements and exist in relatively-consistent proportions in the rocks, soil, and sediments that weather from them. Because aluminum and iron are abundant metals, their concentrations in water should also be indicators of sediment content when direct measures of sediment are not available. There was a direct correlation between concentrations of aluminum, iron, and suspended sediment in the samples collected during the Gold King plume (Figure 5-18) and generally. Sediment was present in moderate concentrations during the plume compared to concentrations observed during larger storms.

There were relatively few samples collected prior to, during, or after the Gold King release event in which metals and sediment concentrations were measured. However, water samples routinely reported concentrations of aluminum and/or iron with the trace metals. Therefore, trace metals were correlated with iron or aluminum concentrations as a signature of the expected background metals conditions that would systematically vary with the level of sediment carried by the river. Similar techniques have been used in distinguishing metals-contaminated sediments from geologic background using so-called “fingerprinting” from local geological chemical makeup (Covelli and Fontolan 1997; Reimann and Garrett 1997, 2005; Amorosi et al. 2014).

The correlation between total aluminum and four trace metals in samples collected in the San Juan River are shown in Figure 5-19. The trace metals showed proportional increase in concentration commensurate with aluminum, and by inference, with

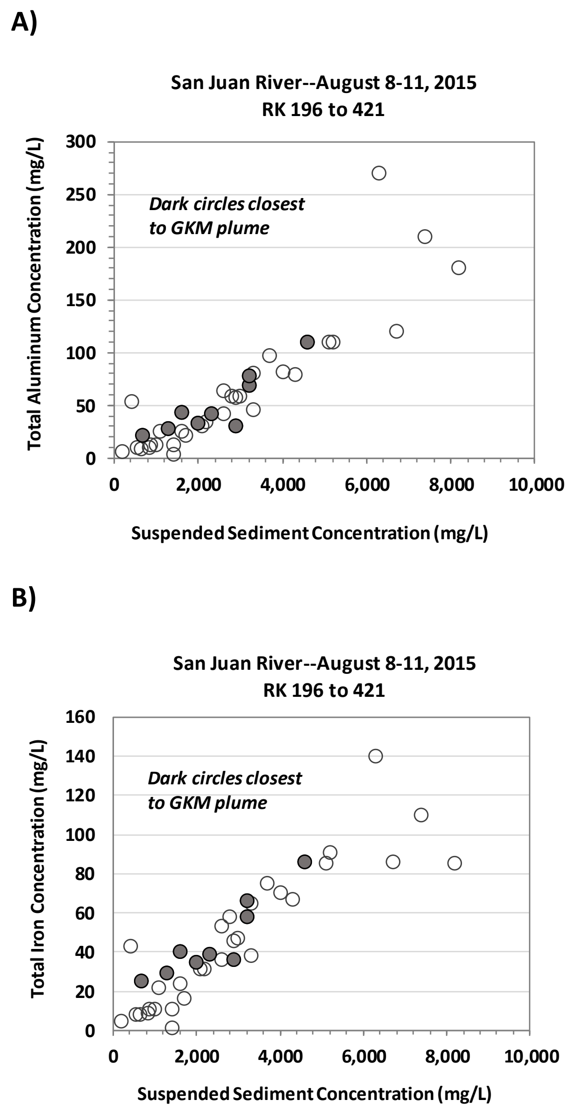


Figure 5-18. Relationship of A) total aluminum and B) total iron concentration to suspended sediment concentration in the San Juan River from August 8–11, 2015. Samples were collected from RK 196 to RK 421, during the passage of the Gold King Mine (GKM) plume.

sediment concentrations. Similar strong relationships exist for iron, but are not shown. The strong trends between the concentrations of the abundant and trace metals reflected their relative abundance in the chemical composition of the Mancos Shale, with the slope of the regression reflecting water concentration rise with increasing amounts of sediment. When sediment concentrations were high, trace metals were present in predictably higher concentrations.

This correlation technique allowed maximum use of the post and pre-release metals concentration data to isolate Gold King metals within the varying background conditions of the San Juan. Three monsoonal storms occurred in August and September 2015 following the Gold King release that represented significant stormflow. These storms increased sediment and metals far higher than observed in the plume and expanded the range for the correlation relationship for aluminum to 1,000,000 µg/L (1,000 mg/L). Historic samples also fell within the basic relationship. Historic records of sediment in transport in the San Juan River have recorded suspended sediment concentrations as high as 330,000 mg/L, indicating the graph could go much higher.

This correlation technique was the main method used to confirm the passage of the GKM plume in the San Juan River given the background levels of metals associated with the sediments in this portion of the river system. Concentrations of metals sampled during the plume are highlighted in Figure 5-19 as the yellow and gold triangles. The concentration of aluminum during passage of the plume ranged from 10,000 to 100,000 µg/L, of which 8,000 µg/L was delivered with the Gold King plume (Figure 5-16). Based on the non-plume data, lead would normally range from 20 to 100 µg/L at this level of aluminum (Figure 5-19). Lead concentrations up to 300 mg/L were measured in a few plume samples indicating passage of the plume. Conversely, total copper, arsenic, and zinc were within or close to the normal range of variability during plume passage. Gold King plume effects were not persistent, as metals concentrations returned to the baseline relationship quickly after it passed.

Dissolved metals also increased with sediment and exhibited similar baseline relationships to aluminum (Figure 5-20). The dissolved metals concentrations in plume-associated samples were not elevated relative to aluminum. This was consistent with comparisons of metal concentrations in the Animas River to background (Figure 5-13). Note that variability is high at low concentrations, and the technique could only identify very large excursions in this range.

The correlation technique was also used at individual sampling locations where sufficient data was available. Total lead and arsenic were plotted in relationship to total Al at six locations along the San Juan River in Figures 5-21 and 5-22, respectively. The same general relationship of trace metals to aluminum was evident at each location, but there was a spatial trend indicating that lead was elevated relative to aluminum in the three locations (RK 196 to 296) closest to the Animas River (Figure 5-21). Lead fell into the apparent background relationship with aluminum in the lower San Juan River sites from RK 346 to 421. Failure to capture elevated lead could be due to the lack of sampling during passage of the peak, but there was relatively good coverage of the plume at RK 421 (Mexican Hat). Similarly, arsenic appeared elevated at RK 204 in Farmington, but not at downstream locations (Figure 5-22).

The Gold King plume was difficult to directly identify from water samples in the San Juan River. Plume metal concentrations were within the range of variability observed in background metals concentrations as the plume passed. Modeling was used to quantify the timing of travel and metal concentrations in the San Juan River. The plume was isolated and empirically modeled in the San Juan at Farmington (RK 196) by integrating samples from several nearby locations adjusting for travel time. Total summed metals minus cations are shown in Fig. 5-26. At this location, there was a persistent background of total metals minus cations of 45 mg/L and the plume that increased concentration by approximately 35 mg/L.

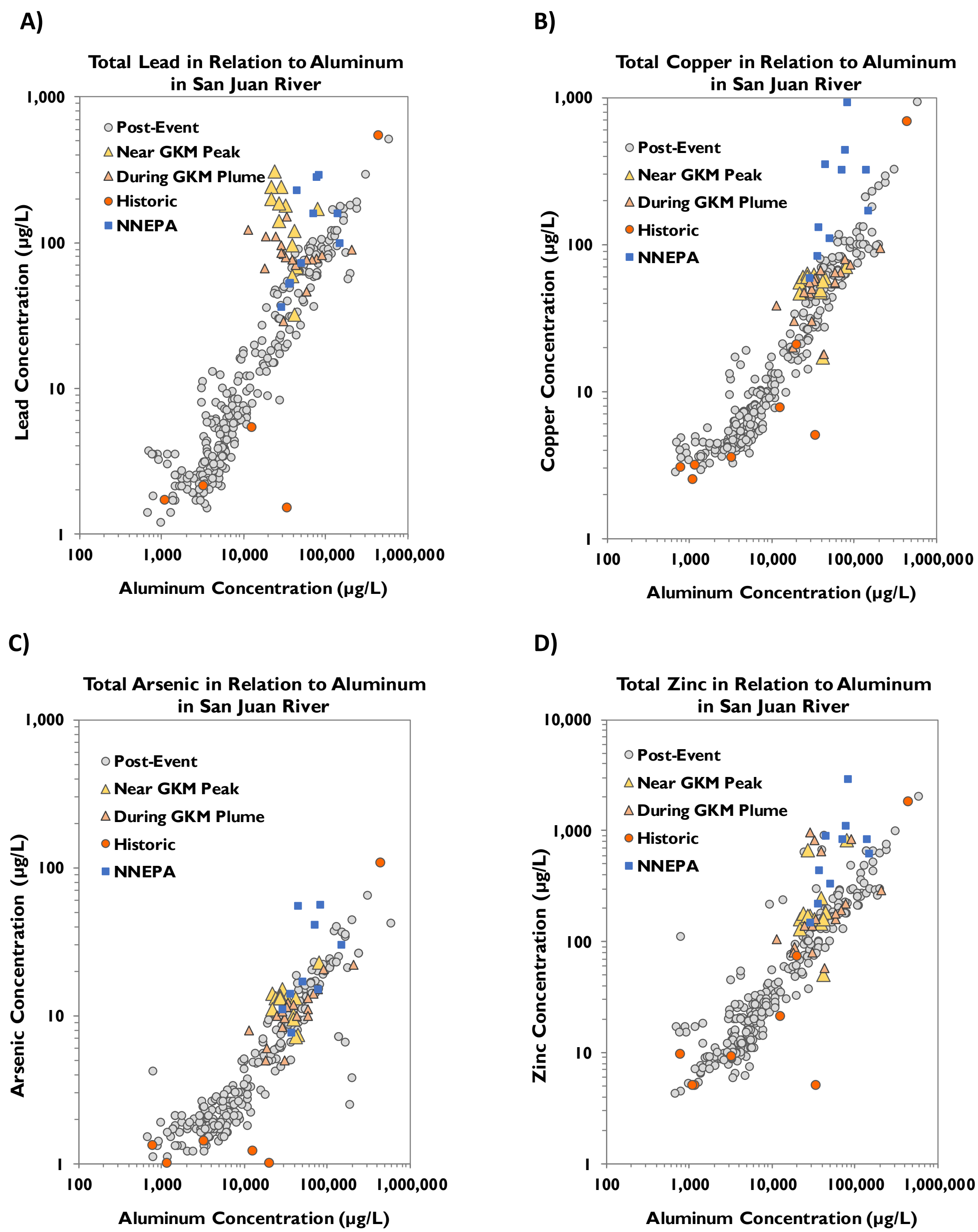


Figure 5-19. Relationship between total A) lead, B) copper, C) arsenic, and D) zinc and aluminum in water samples collected throughout the San Juan River. Gold/yellow triangles were samples collected during the passage of the Gold King Mine (GKM) plume, and gray circles were samples collected from August 15, 2015 to November 2016 (Post-event). Blue squares are Navajo Nation Environmental Protection Agency (NNEPA) historic data, and red circles are historic data from USGS and other sources.

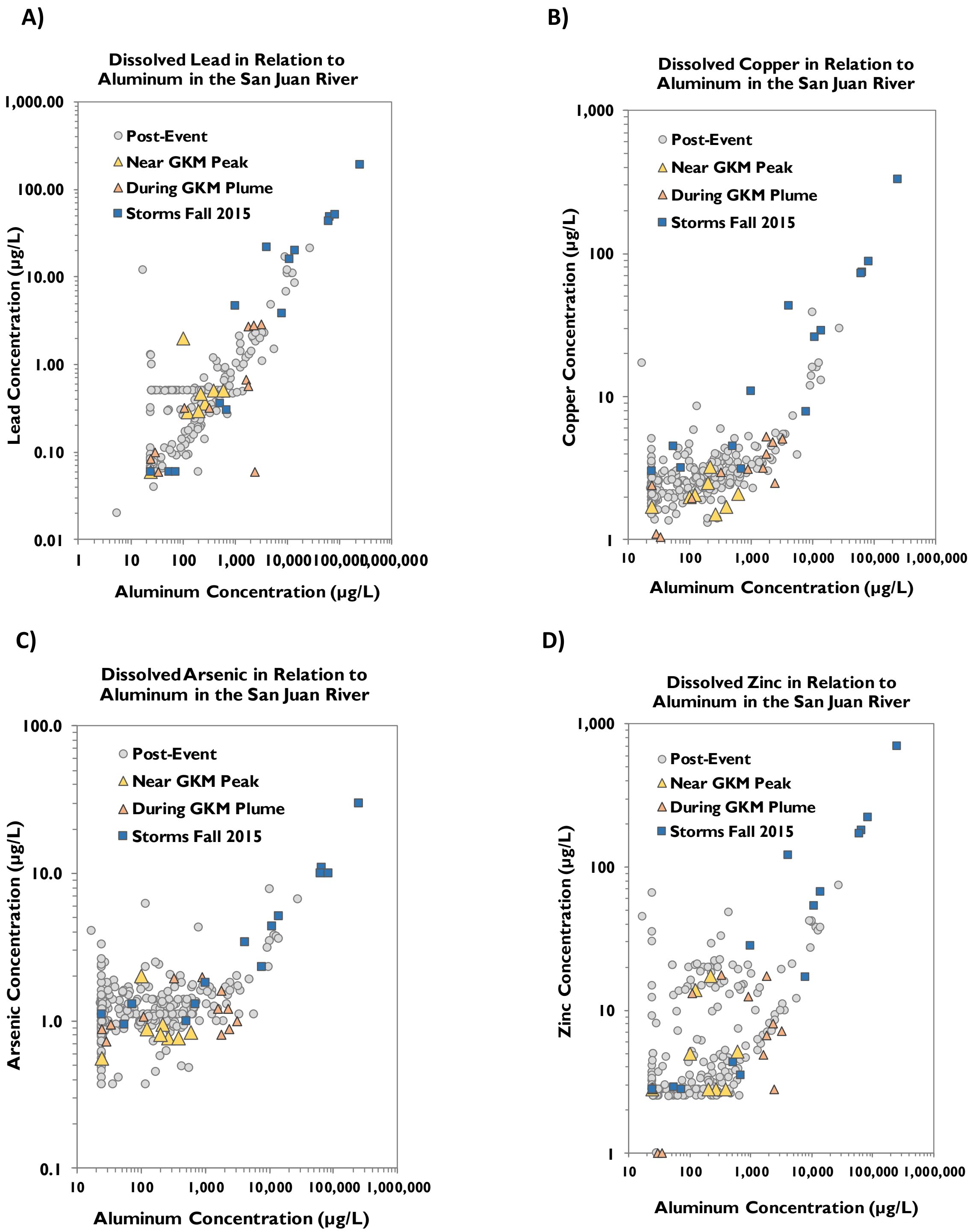


Figure 5-20. Relationship between dissolved A) lead, B) copper, C) arsenic, and D) zinc and aluminum in water samples throughout the San Juan River. Gold/yellow triangles were samples collected during passage of the Gold King Mine (GKM) plume and gray circles were samples collected August 15, 2015 to November 2016 (postevent). Blue squares are samples collected during three large storms in Fall 2015.

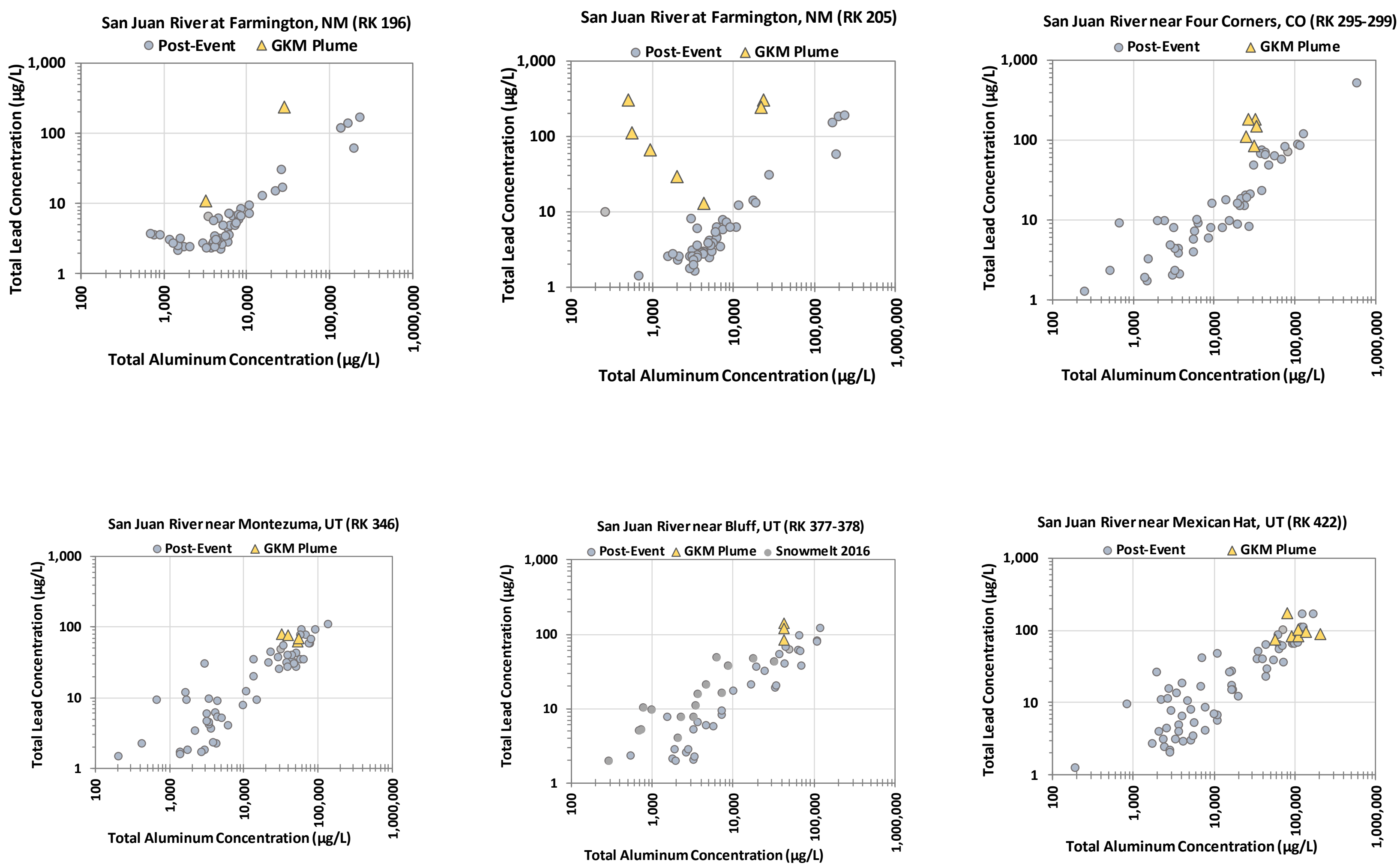


Figure 5-21. Correlation of total lead with aluminum concentration (ug/L) in water samples collected at 6 locations on the San Juan River. Samples collected as the Gold King plume passed are gold/yellow triangles and post-event samples collected from mid-August through November 2015 are gray circles.

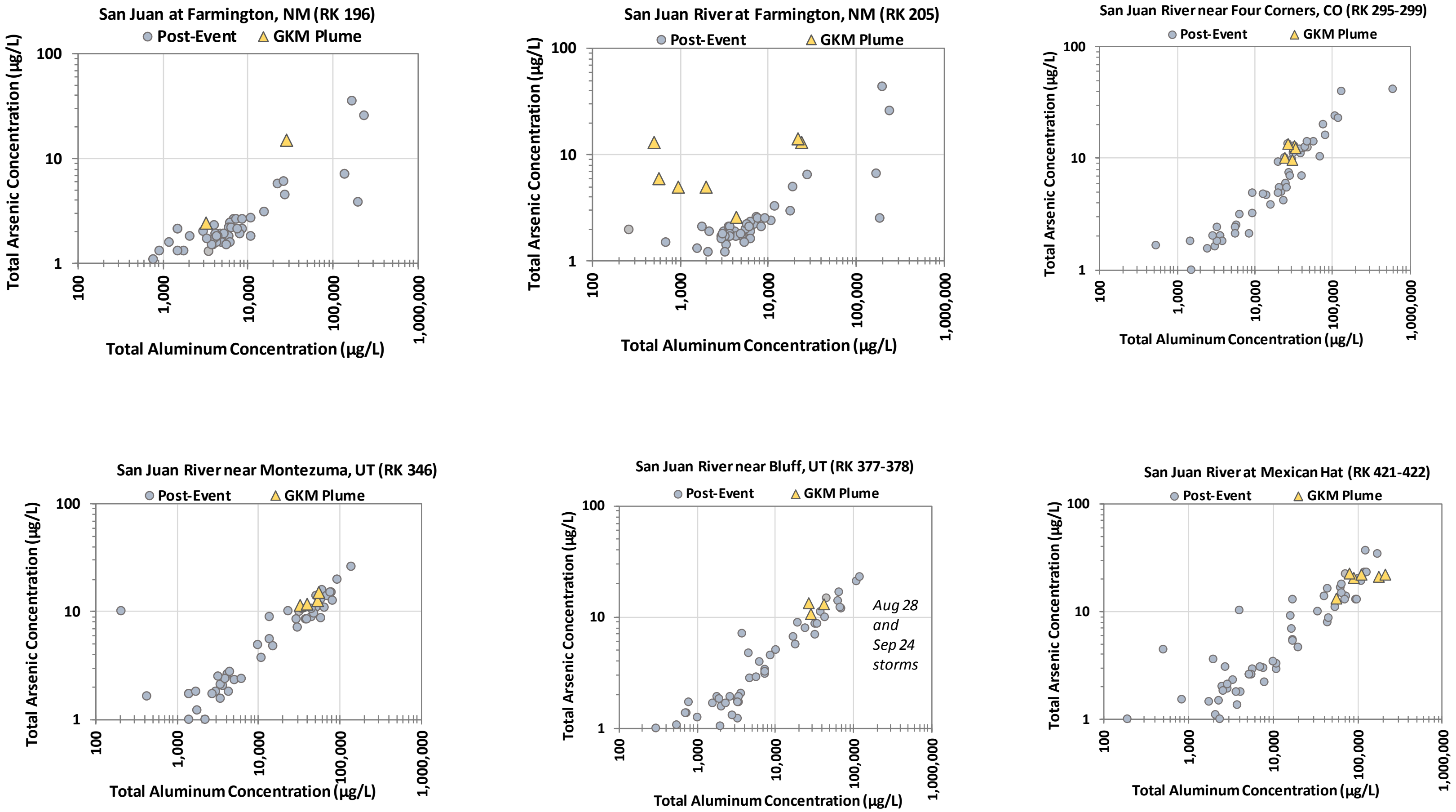


Figure 5-22. Correlation of total arsenic with aluminum concentration (ug/L) in water samples collected at 6 locations on the San Juan River. Samples collected as the Gold King plume passed are gold/yellow triangles and post-event samples collected from mid-August through November 2015 are gray circles.

5.3.3 Relationship of Metals Concentrations in Water to Sediment and Geology

Background metals concentrations in the water of the San Juan River were related to the naturally-occurring background composition of metals found in the earth's crust and weathering products, including soils and sediments. The surficial geology of much of the San Juan River and parts of the lower Animas River watersheds is predominantly Mancos Shale.

The general composition of metals in the Mancos Shale is shown in Figure 5-23. Shale elemental composition was obtained from a synoptic survey of the chemical analyses of rocks and soils collected in a variety of geomorphic and soils locations in a USGS study in Southwestern Colorado and Utah (Tuttle et al. 2007). An average value was calculated as a general indicator of the metals content in this lithology. Of the abundant elements, Al is a larger component than Fe, and Ca is the predominant major cation, but the most abundant element is silicon (Si). Of the trace elements, Ba, Mn, V, and Zn are the most abundant. However, most of the trace elements, including Pb, Cu, and As are present in lower, but characteristic amounts.

The hypothesis of the correlation technique based on aluminum and iron to identify the Gold King release contaminates within the background metals composition is that sediment and water concentrations should strongly reflect the underlying soils and geology (e.g. Amorosi *et al*. 2014.) Water samples collected from the San Juan River at RK 196 have concentrations of abundant and trace metals that are consistent with their content in rock and weathering products. Metals concentrations in water collected during a large storm on Sept 24, 2015, when sediment concentrations were high are shown in relation to the elemental composition of the Mancos Shale in Figure 5-24. Al and Ca are the dominant metals in water. The trace metals align across a spectrum from low concentrations (e.g., Se, Mo, and Be) to high concentrations at several hundred ppm (e.g., Mn and Ba). Cu, Pb, Zn, and As are present in moderate concentrations. Correlations between the relative abundance of metals in water and the chemical makeup of the Mancos Shale are strong for abundant and trace metals ($R^2 = 0.76$ and 0.86, respectively.)

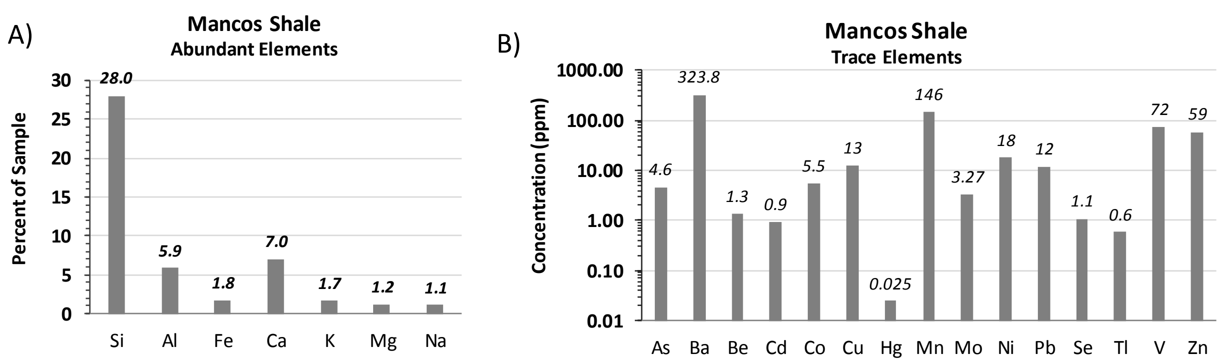


Figure 5-23. A) Abundant and B) trace element composition of the Mancos Shale. Shale composition was based on an average of a USGS study of Mancos Shale elemental composition (Tuttle et al. 2007) in which synoptic surveys of soils and rock obtained from multiple geomorphic and soil profile positions were reported.

The same patterns in water to sediment relationships observed at RK 196 are also observed at other locations. Figure 5-24C compares samples collected during the same storm at RK 196 at Farmington, New Mexico and at RK 296 in Four Corners (where the states of Colorado, New Mexico, Utah, and Arizona meet). The regression slope is essentially the same at the two locations, but the intercept was higher at RK 296 reflecting the higher sediment loads that occur as the San Juan flowed westward. Generally, the level of sediment in the river on any given day will move the y-intercept of the relationship up and down the y axis, but the relationship between the x and y parameters will maintain the same slope. Metals concentrations of water samples collected near the peak of the Gold King plume at RK 196 showed the same prevailing association of metals to the background Mancos Shale composite on Figure 5-24D. Pb, Zn, Cu, and As were expected to be higher than background given the larger concentrations received from the Animas River (Figure 5-16), and were more prominent during the plume than expected relative to the background (Figure 5-24D).

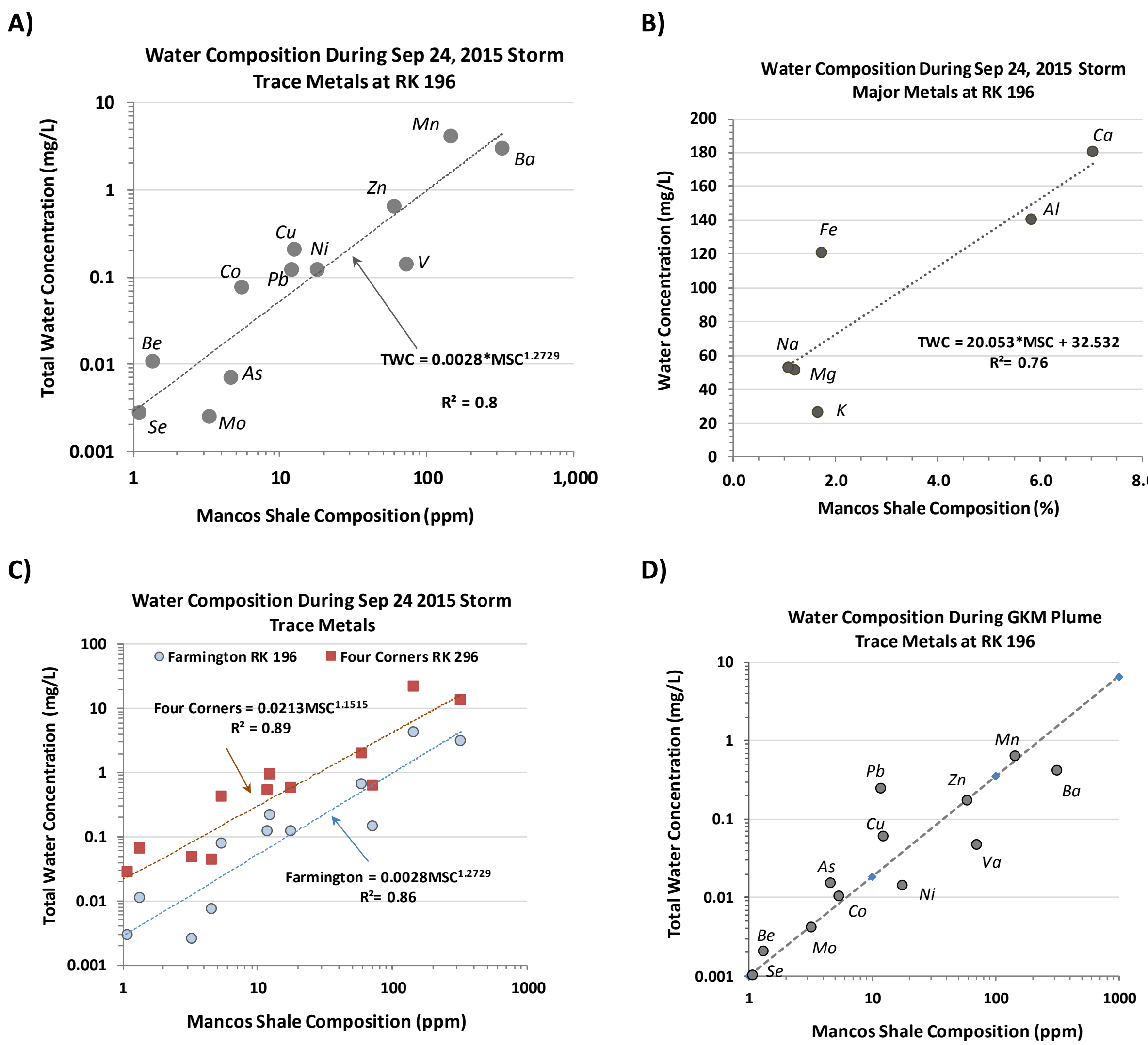


Figure 5-24. Water concentrations of metals in the San Juan River plotted in relation to elemental composition of the Mancos Shale (MSC) (see Figure 5-23) for: A) trace metals at RK 196 during the large storm on September 24, 2015 when suspended sediment concentration was high are compared to MSC expressed in ppm; B) major metals compared to MSC expressed in % as reported by USGS; C) trace metals compared to MSC expressed in ppm at two locations during the Sep 24, 2015 storm, and D) trace metals compared to MSC during the Gold King Mine plume at RK 196.

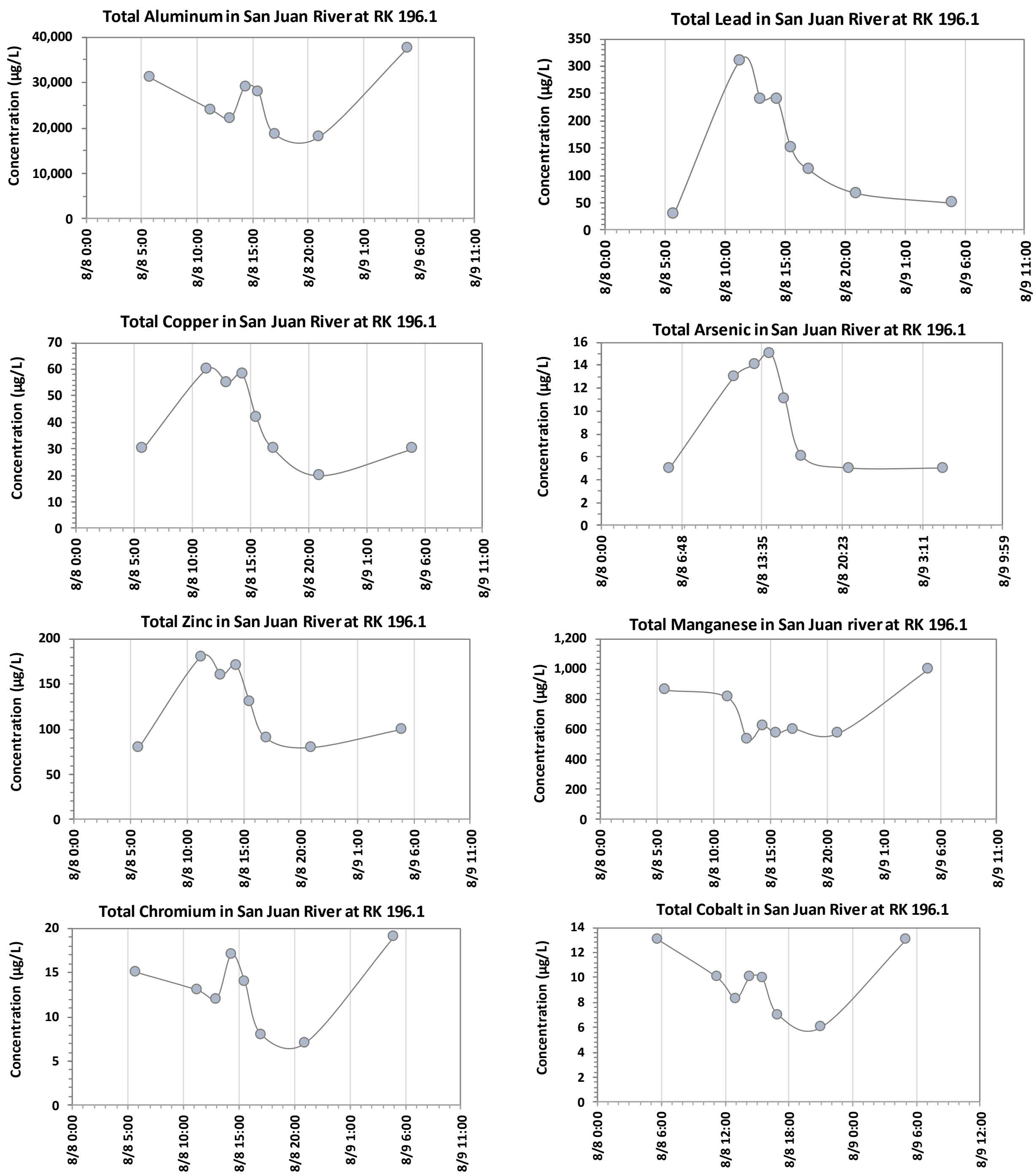


Figure 5-25. Concentration trace of metals (total) in the San Juan River at Farmington (RK 196.1) during passage of the Gold King plume. Samples collected from RK 196.1 to 204.5 were combined by adjusting to the time at RK 196.1 based on travel time.

5.3.4 Gold King Plume Concentrations

The Gold King plume was more difficult to quantify in the San Juan River than the Animas River due to the higher background metals concentrations associated with the background sediment-related metals. Turbidity measured by the sonde at RK 204.4 (Figure 4-25) and the correlation technique (Figures 5-19, 5-21 and 5-22) showed that Gold King plume metals were detectable in water samples as the Gold King plume moved through the San Juan River, at least as far as Four Corners, New Mexico, although at lower concentrations than observed in the Animas River and within a background of sediments.

Figure 5-25 shows measured water concentration of 8 metals in the San Juan River in the Farmington, New Mexico area during passage of the Gold King plume. The concentrations are composited from samples collected between RK 196 and 205 by adjusting time to match the plume at RK 196.1 based on travel time. The peak of the plume was estimated to have occurred on Aug 8, 2015 at approximately 13:00 by the WASP model. The total concentration of all metals rose and fell in a period of approximately 12 hours with a sharp rise and fall that was consistent with turbidity at the sonde (Figure 4-25) and the relative concentration trace of the sonde shape factor (Figure 4-9). The “bump” was observable but relatively small for most metals. The increase in lead, zinc, copper, and zinc was more significant. For example, lead increased from a baseline of approximately 30 to 250 µg/L.

The WASP model was the central tool for simulating the movement of the Gold King plume through the San Juan River. WASP established the time to peak at empirically modeled locations and recommended the relative increase in peak at that location. The empirical model established the baseline concentration from samples collected during the time of the plume and simulated the sonde shape factor with the default WASP increase. This was then adjusted to observed samples where available. The summed total concentration of metals (minus major cations) at RK 196.1 is shown in Figure 5-26.

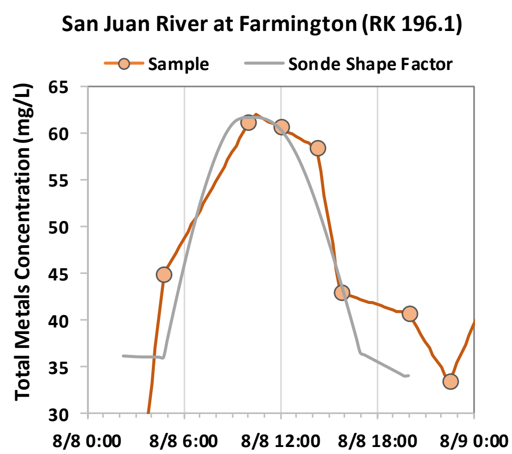


Figure 5-26. Total metals concentration simulated at RK 196 by the empirical model during passage of the Gold King Mine plume. The normalized sonde factor positioned at the Water Quality Analysis Simulation Program (WASP) estimated peak arrival time is also shown. Samples from several locations between RK 193 and 204 were composited by adjusting the time of the sample to this location, accounting for plume travel time.

The empirically estimated Gold King plume peak increase above background is shown in Figure 5-27. The peak increase was similar through the length of the San Juan, while the background metals concentrations increased in the westerly direction with increasing sediment (Figure 5-15). Estimated plume peaks of individual metals associated with Gold King release declined sharply in the first 50 km of travel to RK 246 (Shiprock, New Mexico) and then remained relatively steady (Figure 5-27B, C). Most of the increase in summed concentrations of plume-related metals was aluminum (Figure 5-27A). Lead concentration continued to decline through the San Juan, while zinc, copper, arsenic, and cadmium remained about the same. Cobalt increased as sediment increased moving westward. WASP estimated a general decrease in plume-associated summed total metals from 25 to 10 mg/L, as the river moved westward. This trend was consistent with the correlation analysis, where lead and arsenic were similar to background metals in plume-related samples from RK 296 to RK 421.

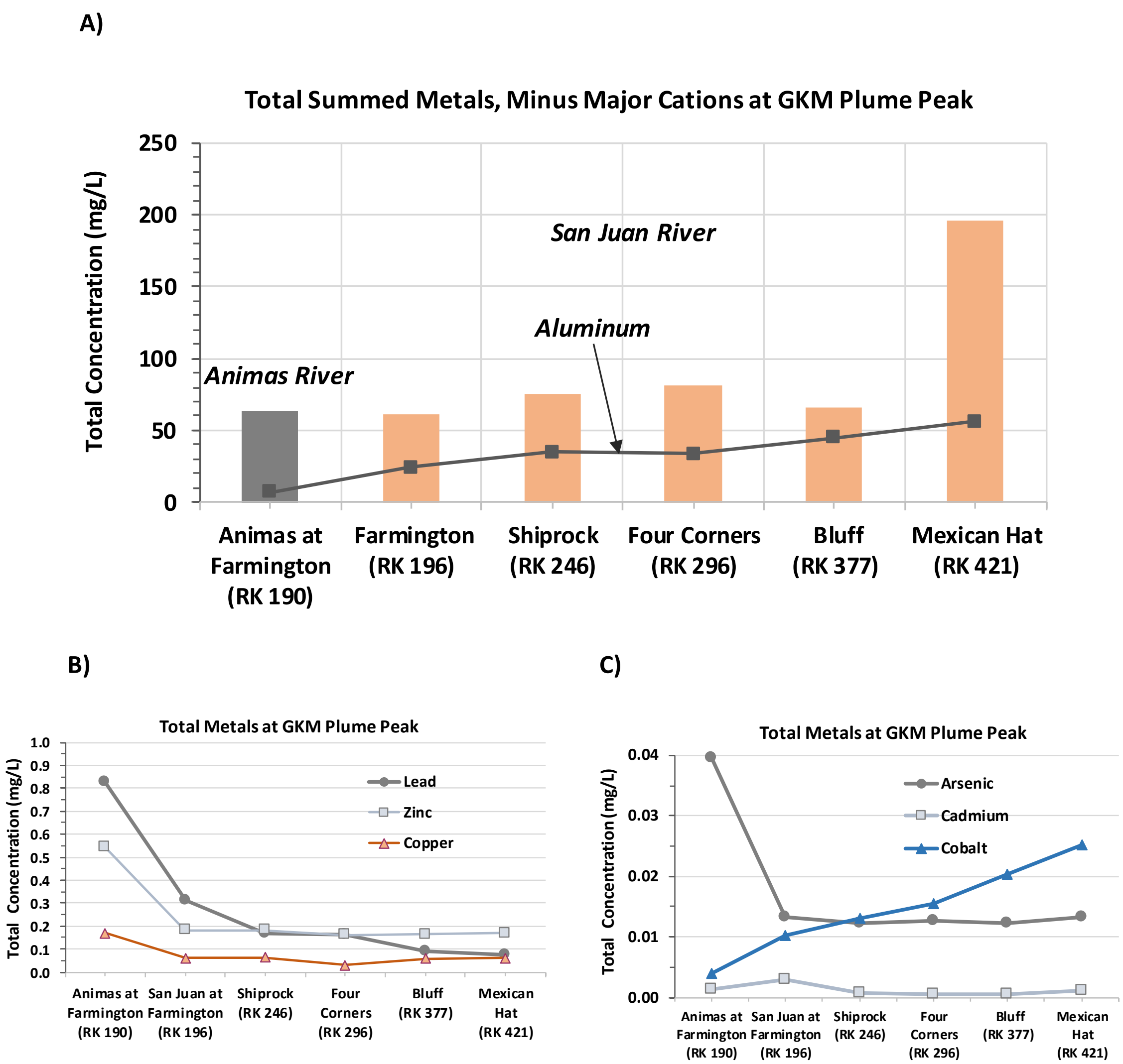


Figure 5-27. Total metals, minus major cations, summed in the Animas River at RK 190 and in the San Juan River at five locations at the peak of the Gold King Mine (GKM) plume. A) Concentration above background of summed metals (bars) and aluminum (line). Panels B) and C) show concentrations of individual metals, grouped by generally similar ranges of concentrations.

5.4 Summary of Metals Concentrations

Metals concentrations in the Gold King plume varied significantly over the river distance traveled from the source at the Gold King mine in the headwaters of the Animas River to the receiving waters of the San Juan River in Lake Powell. Patterns, dynamics and magnitude of concentrations has been explored in Chapters 4 and 5. In summary, metals concentrations in the Gold King plume declined from high initial concentrations in the headwaters to the lowest levels observed in the lower Animas near its confluence with the San Juan River. Dissolved concentrations declined as metal ions were sorbed into colloidal/particulate precipitates, a process that was completed within the Animas River before the plume reached the San Juan. Concentrations of many of the metals increased in the San Juan River, with the addition of metals associated with background sediment levels.

Metals concentrations remained relatively constant as the plume moved through the San Juan. Total and dissolved metals concentrations simulated by the WASP model are shown for the length of the GKM plume travel in Figure 5-28.

Total concentrations declined through the entire pathway of the plume, with the largest decrease in the upper to middle Animas. The decline in total metals concentrations signaled losses of mass from the water to the streambed. Deposition of Gold King plume metals is addressed in Chapter 6.

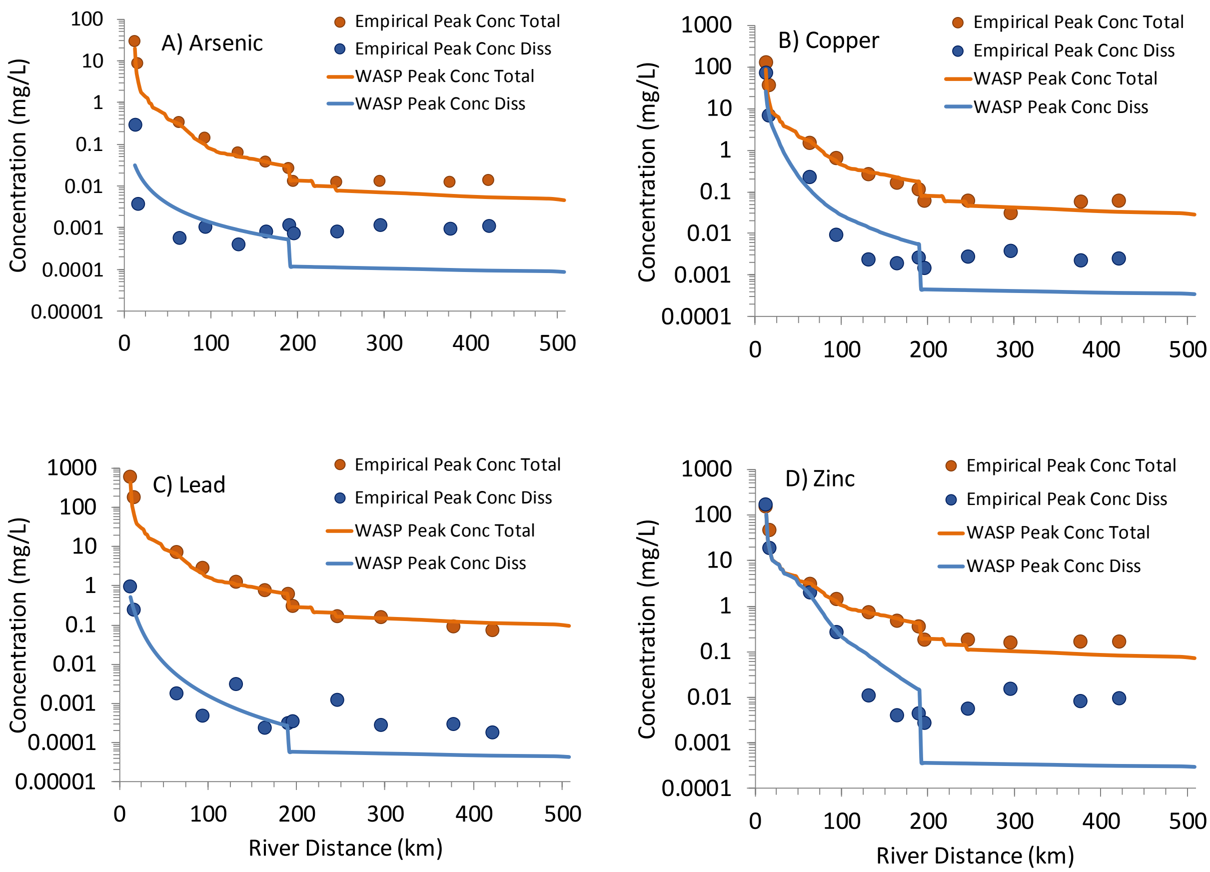


Figure 5-28. Concentration (on log scale) plotted against river distance (km) for four metals: A) arsenic, B) copper, C) lead, and D) zinc. The circles are calculated peak concentrations (orange = total and blue = dissolved) based on the empirical model. Upper/orange line is the peak simulated total concentration and the lower/blue line is the peak simulated dissolved concentration.

CHAPTER 6 MASS TRANSPORT AND DEPOSITION OF THE GOLD KING MINE RELEASE METALS

The Gold King Mine metals mass delivered to the Animas River from Cement Creek was approximately 490,000 kg. Material initially entrained from the waste pile outside the mine or from within the stream, as the moderate-sized flood wave passed, was likely a mixture of inert and contaminated metals attached to clays and sediments. Dissolved metals within the plume precipitated into incipient mineral colloidal/particulate solids that likely had a range of metals species, particle size, and suspension characteristics that influenced their transport and potential for deposition within the river system (Figure 6-1).

Concentrations of metals in the water were shown to decrease as the plume flowed southward in Chapter 5. Although dilution contributed to declining metals concentrations as the plume moved through the Animas River, deposition of mass was also a significant factor that removed particulates and aluminum and iron (hydr)oxide colloids and sludge from the water.

The metals mass of the Gold King Mine release decreased as the plume traveled through the length of the Animas and San Juan Rivers, depositing colloidal and particulate metals through most of their length. Deposited metal contaminants were of concern for effects on aquatic and terrestrial biota, agricultural and human uses, and for the potential for later release back into the water in high-flow events, creating a second wave of contamination.

In this chapter, the fate of the mass of metals released from Gold King Mine as it traveled through the Animas and San Juan Rivers is addressed. The mass of metals in transport, deposition of the plume metals to the streambed, and the effects of the deposits on metals concentrations in the sediment are characterized.

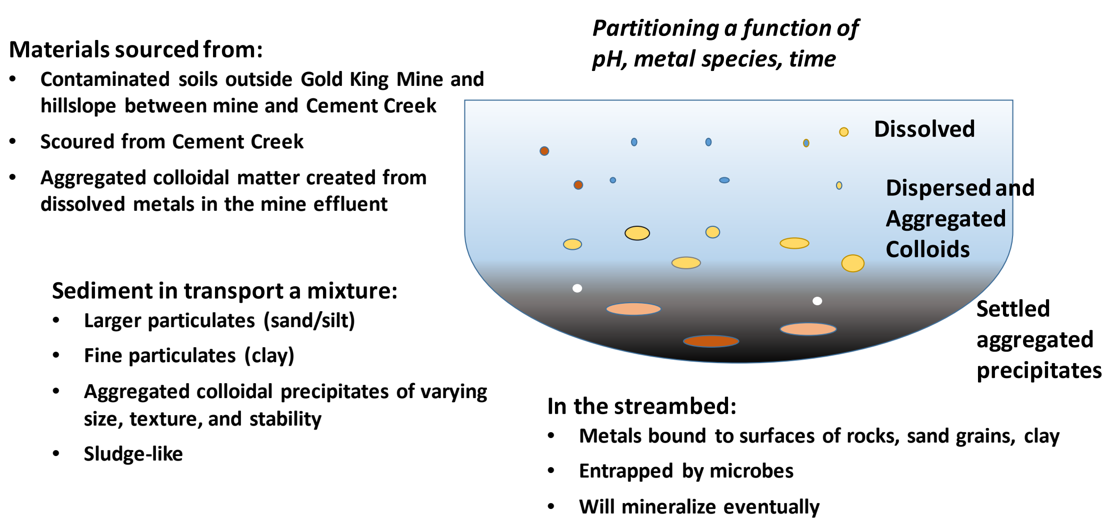


Figure 6-1. Metals were carried in a variety of forms in the Gold King plume including eroded material entrained in the flood at the mine source and minerals formed as precipitates within the plume.

6.1 Metals Mass Transport by the Gold King Plume

The fate of the GKM release mass was determined from the modeled simulations of plume concentrations. After initializing the mass and concentrations of metals delivered from Cement Creek to the Animas River (see Chapter 3), the empirical and WASP models each produced a time trace of metals concentrations as the plume moved past a location (as discussed in Chapters 4 and 5). The empirical model replicated the plume's total and dissolved metals concentrations at 12 locations, based on flow taken from the nearest USGS gage and the observed or estimated metals concentrations in each 15-minute during the period of plume passage.

The WASP model was initialized at the start of the Gold King Mine release in the headwaters of the Animas River and dynamically simulated the flow of water and the metals concentrations through the plume's 550-km length of travel in river segments averaging approximately 2 km in length. WASP added water, transitioned metals from the dissolved to colloidal fraction, and settled particles to the streambed. WASP's particle settling was calibrated based on mass estimates produced by the empirical model, but otherwise produced independent simulations of the plume. The WASP settling velocities used in analysis to simulate movement of the Gold King Mine plume through the Animas River were calculated by taking the empirically estimated total mass of metals and calculating the settling velocity based on the fraction of mass lost between different stations (using total length traveled and stream velocity). The WASP model then incorporated the settling velocities into the fate and transport structure. The total metals mass was then able to be calculated from WASP-simulated concentrations and flows at any given location in space.

6.1.1 Animas River Plume Mass

The mass of summed metals in transport in the Animas River is shown in Figure 6-2. The Empirical and WASP models produced similar, though not identical estimates of mass as the plume traveled. The models were in general agreement on the amount and general distribution of metals mass through the Animas River. Both suggest that there was a steep decline of metals mass through the upper Animas between RK 12.5 (Cement Creek) and RK 100 (Durango), and a smaller, though steady, decline through the lower Animas to the confluence with the San Juan River. WASP and the empirical model estimated mass at RK 190.2 at 60,000 kg and 53,000 kg, respectively. This remaining mass flowed into the San Juan River at RK 193.

A simple average, comparing the independently derived estimates at 11 sites, finds that the two estimates of mass were within 4%. However, the empirical model found that more mass was deposited through the upper and middle Animas River to Durango (RK 100) than WASP predicted. WASP distributed a greater portion of the plume mass through the lower Animas from RK 100 to RK 193. WASP consistently estimated greater mass in transport, which could be expected, given the model's longer duration plume (e.g., Figure 4-22). The empirical model more closely simulated the narrow core of metal concentrations evident in the measured samples (see Section 4.1.4). There were uncertainties associated with each model, and the two provided a range of estimated mass.

The empirically modeled mass of summed metals in dissolved and colloidal/particulate form in the Animas River is provided in Figure 6-3. The mass of As, Pb, Cu, and Zn are shown in Figure 6-4. The individual metals followed the same overall pattern as the summed metals, with most of the mass deposited within the upper Animas from RK 16.4 to RK 94.2. Zinc mass followed a different pattern than the other metals, increasing somewhat in the river length where most of the acid neutralization and geochemical reactions occurred.

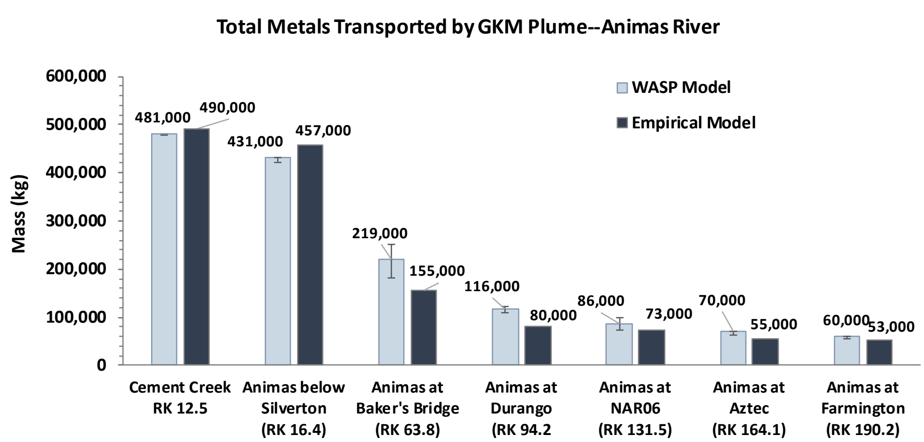
The upper Animas River was the direct recipient of the metals mass released from the Gold King Mine and the mass eroded between the mine entrance and Cement Creek before joining the river at Silverton. The release mass was probably initially composed of entrained particulates, with relatively little incipient iron and aluminum hydroxide precipitates, as they had not had time to form and coagulate. Flow in the Animas

River was insufficient to transport the larger particles that had been suspended in the higher relative flow in Cement Creek. There was deposition of mass in the first 4 km of travel between the confluence with Cement Creek and the USGS gage at RK 16.4 below Silverton. The models suggest that between 7–10% of the plume mass was deposited in this 4-km reach.

Most of the decline of the Gold King Mine metals mass occurred in the upper and middle Animas River, with 49–66% of the mass lost from the water in the segment between RK 16.4 and RK 63.8 at Baker's Bridge. By RK 100, the metals mass in the water was 16 to 24% of what was initially released to the Animas River.

Within the Animas River, the metals mass transported during the Gold King plume was derived almost exclusively from the mine effluent and the material eroded outside of the mine by the release (e.g., from the waste pile outside the mine's entrance). Exceptions to this included the background metals, such as major cations (i.e., Ca, K, Mg, and Na), that generally comprised the background constituents in the water, and barium and selenium, which gained mass as the plume moved through the Animas River.

A)



B)

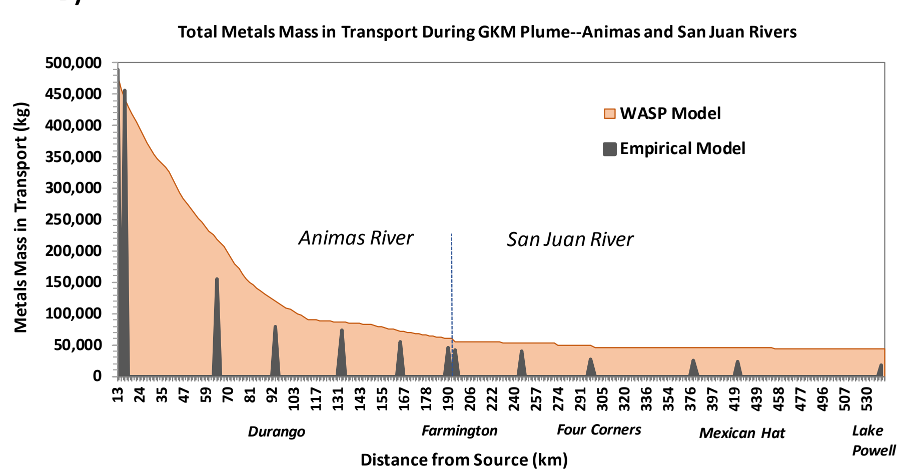


Figure 6-2. The summed total metals mass transported at locations in A) the Animas River and B) the Animas and San Juan Rivers during the Gold King Mine (GKM) plume passage, as simulated by the Water Quality Analysis Simulation Program (WASP) and empirical models.

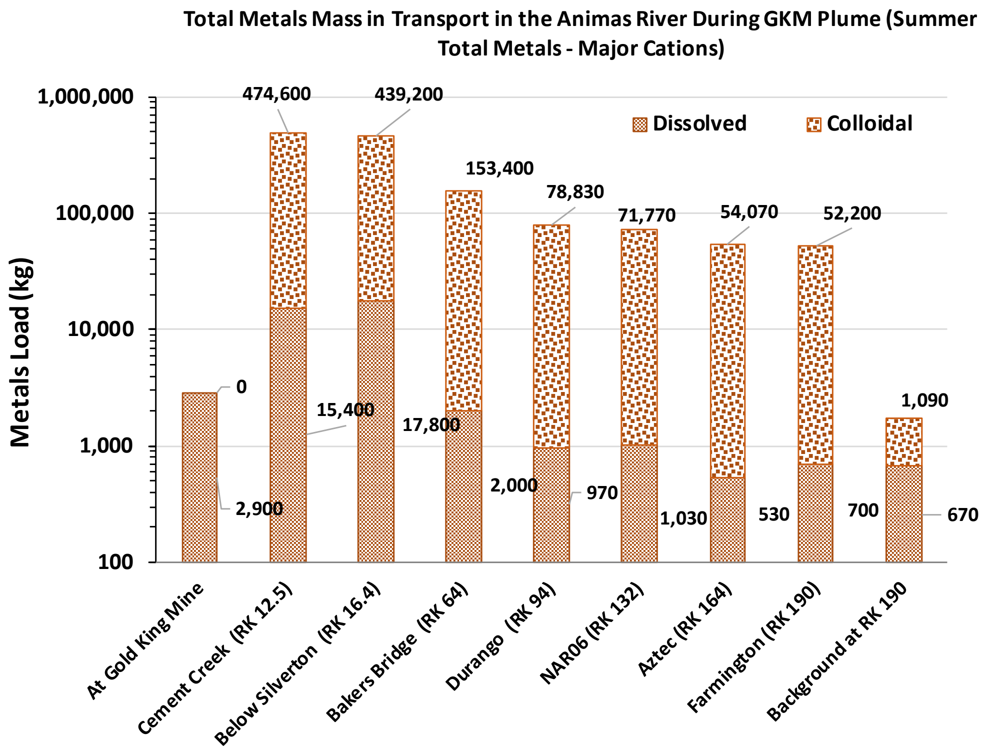


Figure 6-3. Total and dissolved summed metals mass estimated by the empirical model at eight locations in the Animas River during the Gold King Mine (GKM) plume. Estimated background metals concentrations in the Animas River at Farmington was based on dissolved concentrations in historic samples.

6.1.2 Metals at the Confluence of the Animas and San Juan Rivers

Once the Gold King plume entered the San Juan River, the metals concentrations and mass were affected by the metals associated with higher sediment loads in the river, which came with the increased flow from the Navajo Dam release. The water from the dam release diluted plume concentrations arriving from the Animas River by an additional 50%. However, the benefits of water dilution were reduced by the naturally occurring levels of iron, aluminum, and trace metals in the sediments carried in the San Juan River. Sediment-associated metals augmented the mass and increased plume concentrations (see Figure 5-18) and mass (Figure 6-5) of many of the metals as the plume flowed into the San Juan River. Concentrations of other metals were reduced, but not to the extent that would have occurred with just water dilution. The effects of sediment on concentrations translated to effects on mass.

The relative mass of metals in the GKM plume and the San Juan River are estimated in Figure 6-5. Because flow in the San Juan and Animas Rivers was nearly equal during passage of the plume, the metals mass arriving from the upper San Juan (above the confluence) was predicted by subtracting the estimated mass at RK 196.1 from that estimated for the Animas River at RK 190.2. This calculation provided the background metals concentrations in the San Juan River at the time of the GKM plume passage; no samples were collected from the San Juan above the confluence during the plume. The length of the plume in the San Juan River was limited to 16 hours, when the plume was most evident from sonde recordings, to minimize additional upstream load.

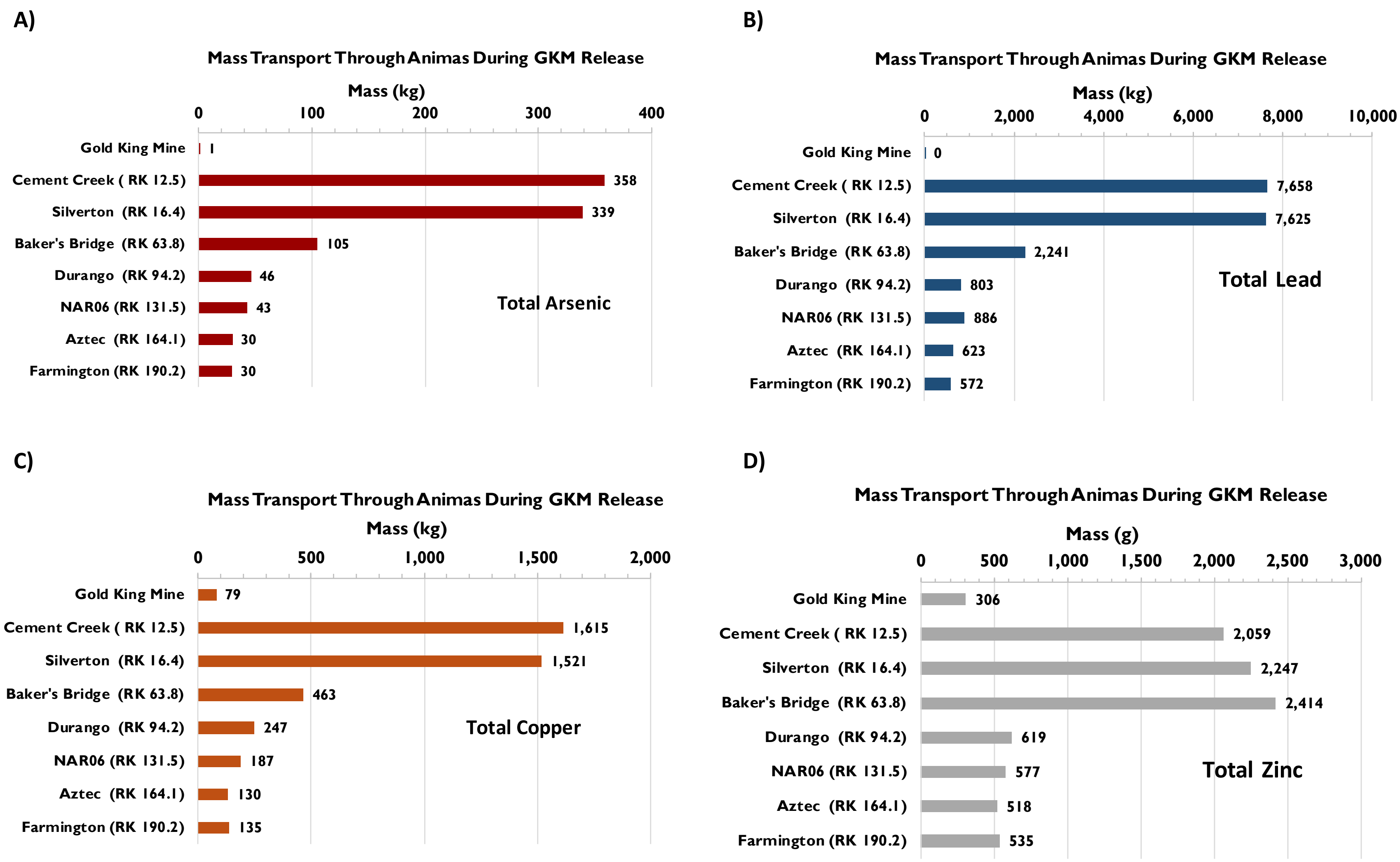


Figure 6-4. Mass of total A) arsenic, B) lead, C) copper, and D) zinc transported at each location in the Animas River during the Gold King Mine (GKM) plume.

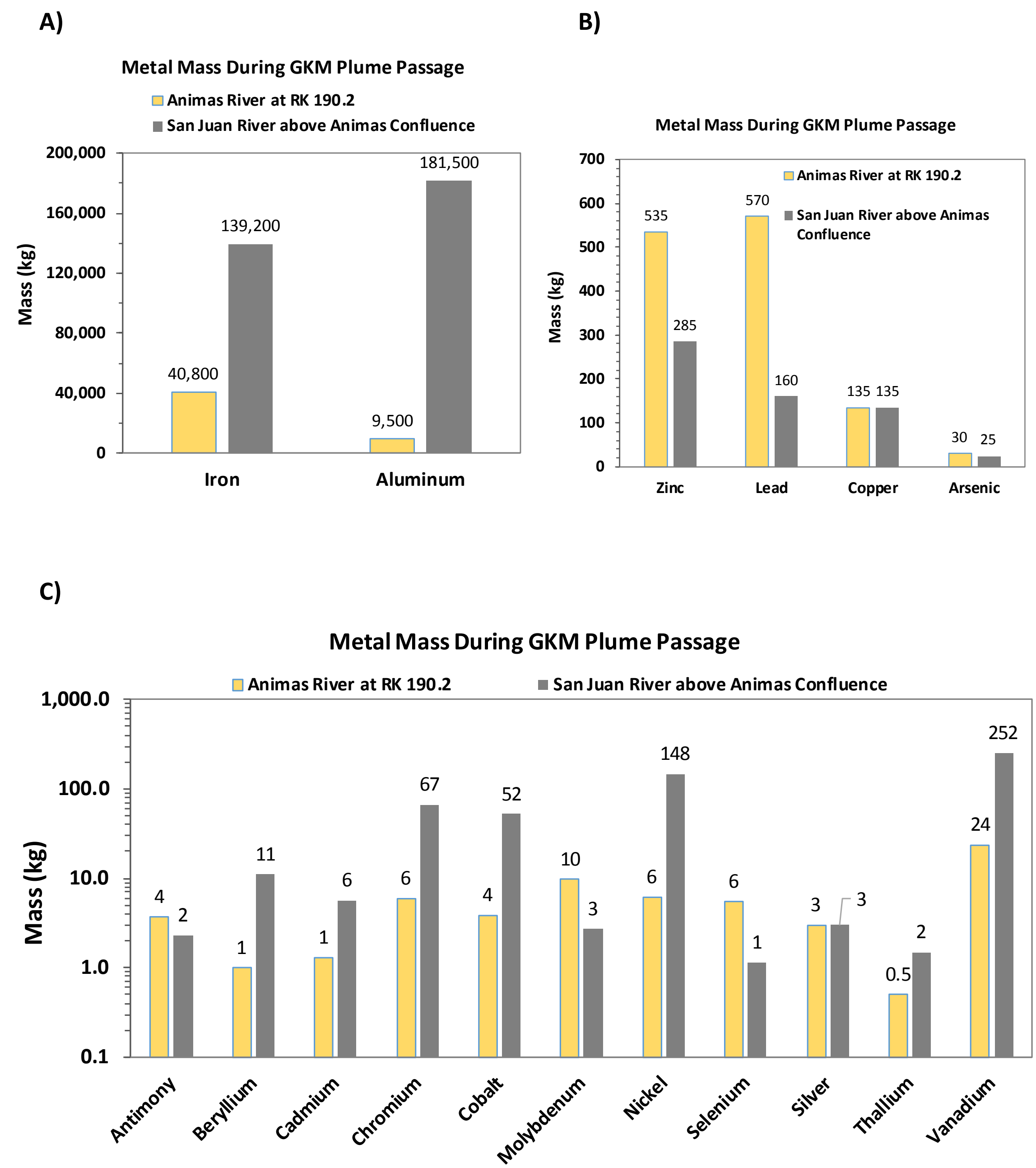


Figure 6-5. Metals mass of A) aluminum and iron, B) zinc, lead, copper, and arsenic, C) other trace metals at the confluence of the Animas and San Juan Rivers during Gold King Mine Plume (GKM) passage. The metals mass simulated by the empirical model during the plume period at RK 190.2 was subtracted from the mass at RK 196 to estimate the mass of metals contributed by the San Juan upstream of the confluence. Flow in the two rivers was similar during plume passage.

The mass of many metals carried by the plume increased in the San Juan River during plume passage, reflecting the additional sediment source. Aluminum and iron were the dominant metals in the Gold King plume and were also the dominant metals in background sediment loads. When the plume entered the San Juan River, the mass of aluminum and iron increased approximately 5 to 20 times, respectively (Figure 6-5A). The mass of most of the trace metals was larger in the San Juan than in the Gold King plume, with the exception of molybdenum, selenium, and antimony, which were present in small quantities (Figure 6-5C). Of the more major metals, lead and zinc were the only metals with significantly larger mass during the plume than was observed in the San Juan River (Figure 6-5B). The plume brought close to 570 kg of lead, which was a net increase of approximately 410 kg or 2.6 times what was in the background in the San Juan River. Zinc was about 90% greater in the plume than in the upper San Juan.

6.1.3 San Juan River Plume Mass

Unlike the Animas River, where there were no background metals in the river during the Gold King plume, the background sediment and metals in the San Juan River masked the passage of the plume, both visibly and in water measurements. The substantial background mass had to be accounted for in assessing the effects of the plume. The total mass of metals carried during the 16 hours of plume passage increased substantially as the river flowed westward and sediment loads increased (Figure 6-6). This duration of the plume period was selected based on observations at the sondes in this portion of the river. The WASP model, set to a background of zero concentration, was used to estimate the mass attributable to the Gold King plume. The empirical model simulated the mass in transport based on water samples. The total mass carried in the San Juan during the plume period is shown in Figure 6-6A, along with the Gold King plume mass as a portion of the total mass. The mass of individual metals in the San Juan River during the GKM plume passage is provided in Figures 6-6B and 6-6C.

As the Gold King plume traveled through the San Juan River, the background metals mass increased, while the plume metals mass decreased slowly over a long distance. Iron and aluminum climbed with the sediment load. The higher plume mass of lead at the confluence of the Animas and San Juan Rivers (noted in Figure 6-5) elevated mass as far as RK 296 (Four Corners), but the signal was lost further downstream.

During the limited period of plume travel, the total mass of metals in the San Juan River (minus major cations) increased from about 150,000 kg at RK 193 in the Farmington, New Mexico area to over 400,000 kg at Mexican Hat, New Mexico (RK 421), as shown in Figure 6-6. During the same period, the Gold King plume accounted for 55,000 kg of metals at Farmington, declining to 45,000 kg at Mexican Hat (Figure 6-7); the empirical model estimated plume metals mass at these two locations at 41,600 kg and 23,800 kg, respectively. Both models suggest that Gold King metals deposited at a low rate through the length of the San Juan River, with the largest mass deposited in the immediate reach below the confluence of the Animas and San Juan Rivers in Farmington. Figure 6-8 illustrates this pattern for four major metals in the plume.

Modeling stopped at RK 510, because there were few samples and no additional flow gages beyond that location to calibrate the models; those that were available were unable to detect the plume within the background. However, the mass delivered to Lake Powell was able to be estimated by extending the rate of loss predicted by models over the remaining distance.

6.1.4 Plume Mass Delivered to Lake Powell

The San Juan River enters Lake Powell approximately 550 km (river distance) from the Gold King Mine and approximately 360 km from the confluence with the Animas River. The rate of decline observed between modeled locations in the lower San Juan for the final 40 km was used to estimate the metals delivered to the lake. Between 24,000 kg (as estimated by the empirical model) and 45,000 kg of metals (as estimated by WASP) were delivered to Lake Powell by the Gold King plume (Figure 6-7) over a 2-day period beginning August 13, 2015. The Gold King Mine plume metals were mixed with almost 450,000 kg of background metals transported with the sediment during this moderate flow event in the San Juan River. (Figure 6-6).

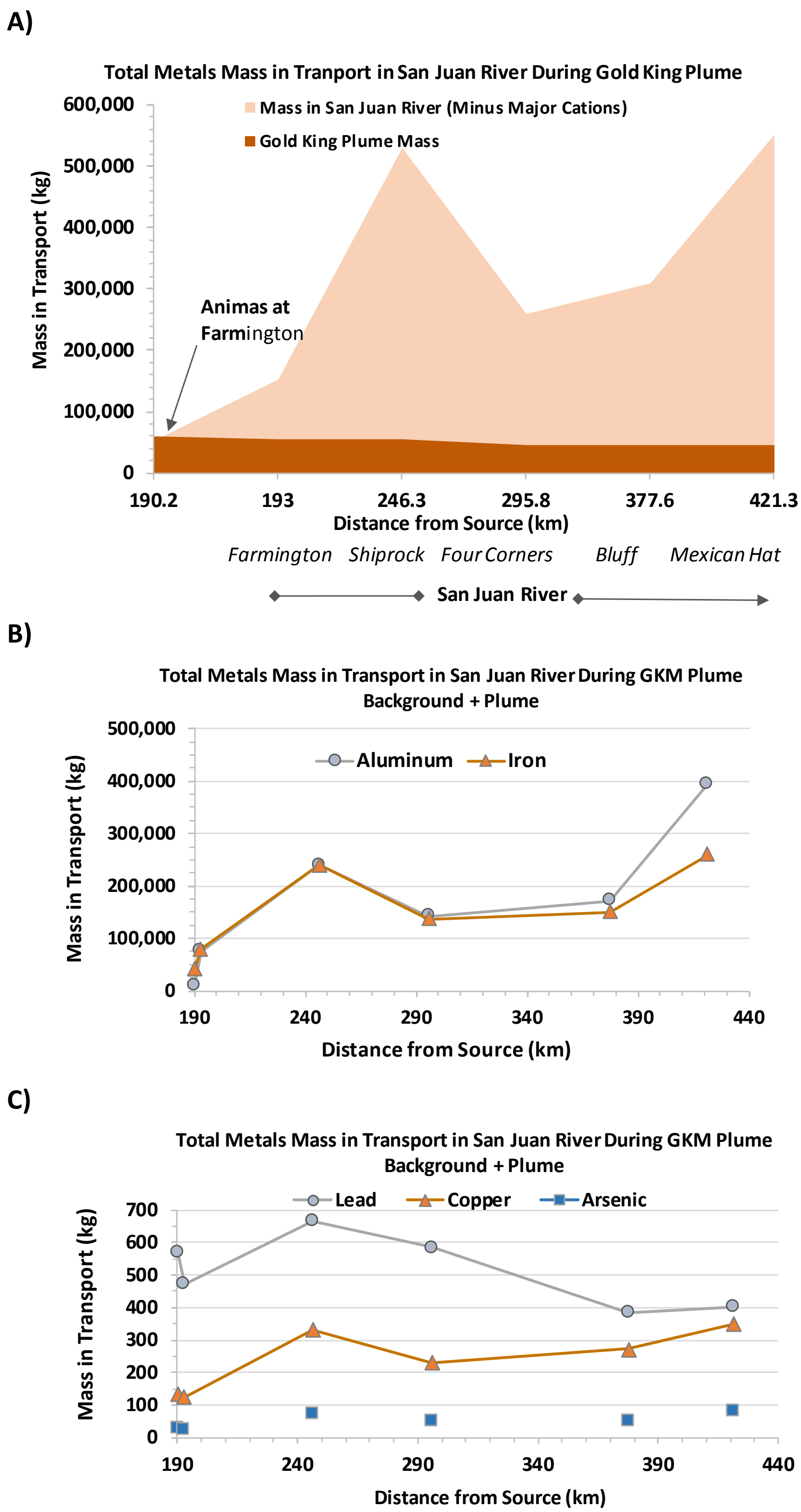


Figure 6-6. Mass transport of metals in the San Juan River during passage of the Gold King Mine (GKM) plume.

A) Empirical model estimates of the total mass load of metals carried in the San Juan River when the Gold King plume passed through. The Water Quality Analysis Simulation Program (WASP) model estimated the Gold King plume mass within the total mass.

B) Mass of total iron and aluminum, and C) total lead, copper, and arsenic transported in the San Juan River during the Gold King Mine plume, as estimated by the empirical model.

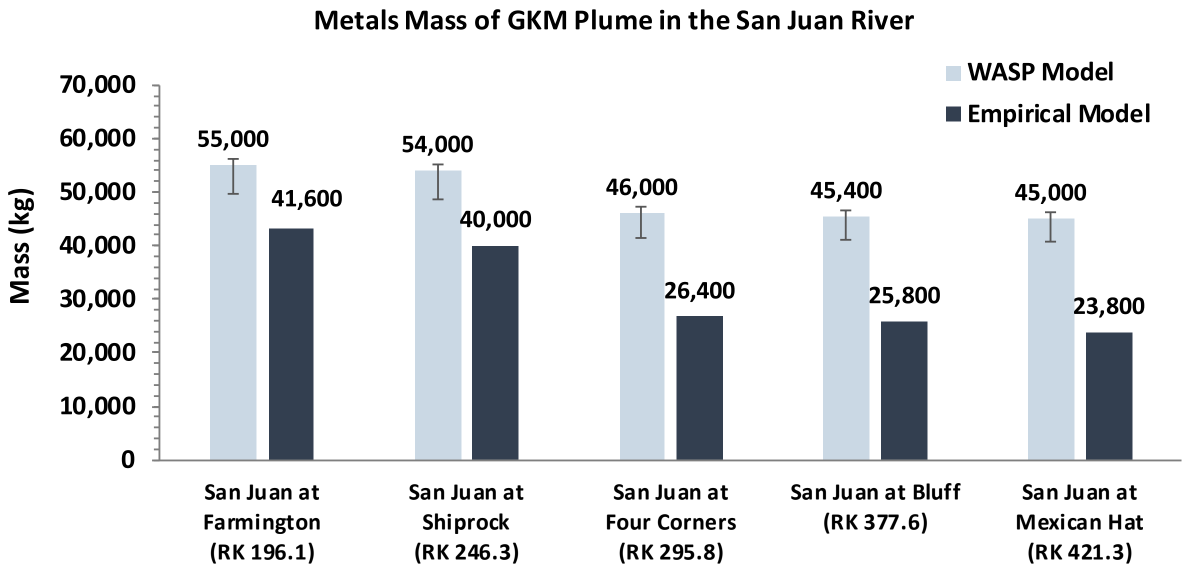


Figure 6-7. Gold King plume mass at selected locations in the San Juan River estimated by the WASP and empirical models.

6.2 Deposition of Gold King Plume Metals

The reduced metals mass of the Gold King plume as it flowed down the Animas and San Juan Rivers means that material was deposited in the streambed over the length of those rivers. Deposited material was a varied mix of particulates, colloids, and mineral precipitates that would have varied spatially within the rivers, both laterally and longitudinally. Figure 6-9 shows various forms of deposited mass observed in the rivers, including sludge-like deposits on the channel margins, sediments deposited onto the streambed, strand lines of colloidal material painted onto rocks in the stream, and aggregated colloids that settled in slow velocity areas.

Plume simulations suggest that a large portion of the Gold King release mass was deposited within the upper Animas River from RK 16.4 below Silverton to RK 94.2 (Durango). The mass estimated to have been deposited between plume simulation locations in the Animas River by the WASP and empirical models is shown in Figure. 6-10. Between 45 and 66% of the original GKM plume mass delivered from Cement Creek to the Animas River was deposited in the steeper canyon that begins below Silverton at approximately RK 25 to RK 63.8. WASP transported more mass through this segment, depositing it in the lower gradient reach downstream between RK 63.8 and RK 94.2. Deposition continued, but at a lower rate, in the lower Animas River from RK 94.2 to its confluence with the San Juan River in Farmington, New Mexico at RK 193. The models varied somewhat in the rate of deposition in segments within the lower Animas.

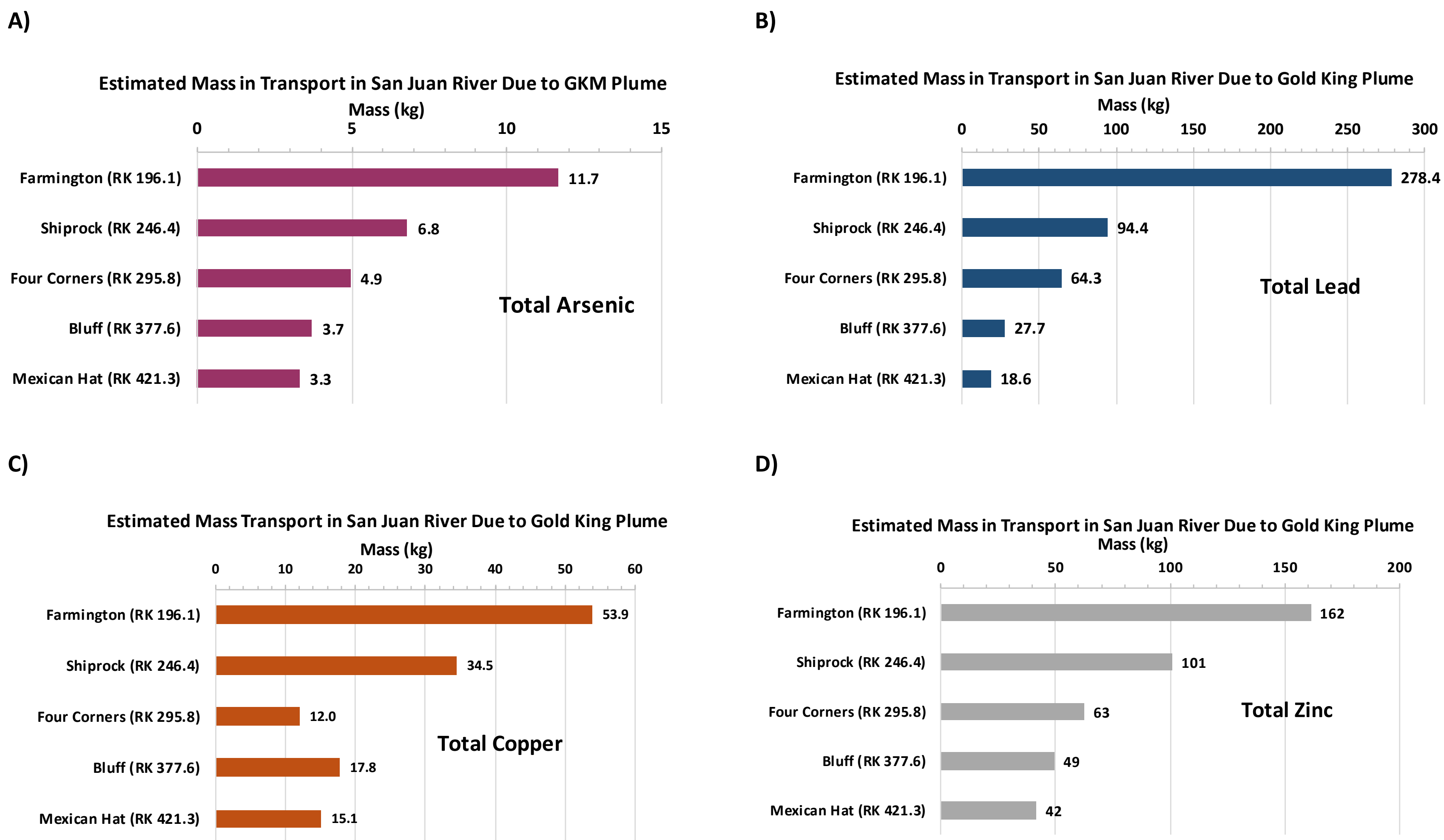


Figure 6-8. Mass of individual metals in the San Juan River in excess of background due to the Gold King Mine (GKM) plume, as estimated by the empirical model. Total mass of A) arsenic, B) lead, C) copper, and D) zinc, in kg.

Photo: USEPA

Photo : New Mexico Environment Department

Photo: Kenneth Williams, Lawrence Berkely Lab, DOE

Photo: USEPA

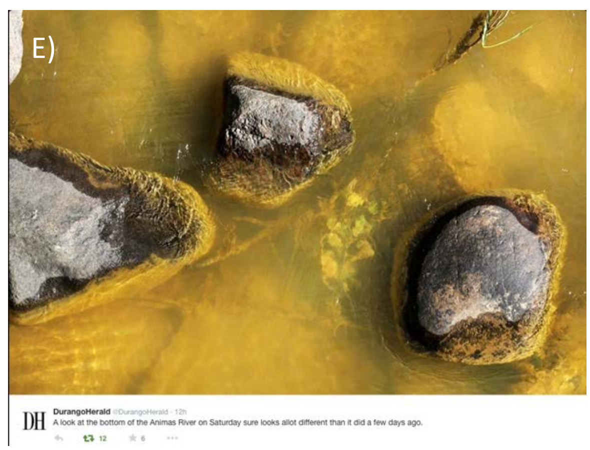


Photo: Jerry McBride/Durango Herald

Figure 6-9. Colloidal/particulates metals transported in the Gold King Mine plume deposited in a variety of forms. A) Colloids with very small particles suspended in the water would easily travel in suspension but could "paint" rocks as strand lines. B) Colloids aggregated and deposited as sludge-like deposits. C) Material settled in the channel as flow receded, settling particles and colloids with it. D) Aggregated colloids settled in slow velocity channel margins like this one near Aztec, New Mexico. E) Amorphous masses collected in drained slow zone.

Figures 6-11 through 6-14 are images showing Animas River reaches before, during and after passage of the plume (i.e., in 2014, August 2015, and October 2015, respectively). This sequence of images demonstrates that metals mass settled within the stream in slower areas along the channel edges and behind obstructions. Within the braided reaches of the Animas River below Silverton to Baker's Bridge, relatively higher flow during the plume occupied side channels. As flow receded, deposits of yellowboy were left outside the active channel, where they dried and could potentially be remobilized in subsequent high flows (Figure 6-12A and B; Figure 6-13). Even in the straight and relative swift flowing channel in the upper Animas River, deposits can be seen along the channel margins and irregularly within the main channel behind obstructions that slow the flow (Figure 6-12C and D). In a meandering reach north of Durango, Colorado, sludge-like deposits were left at the high water mark along the channel banks (Figure 6-14).

Most of the Gold King Mine release mass was probably left in the slow-velocity areas, along the channel margins near the banks, while swifter flowing zones were cleaned out. Distribution would have been spotty, increasingly so with distance traveled. Ground level photos show the nature of GKM plume deposits, which endured in locations that were isolated from the fast flowing waters in the main channel (Figure 6-15).

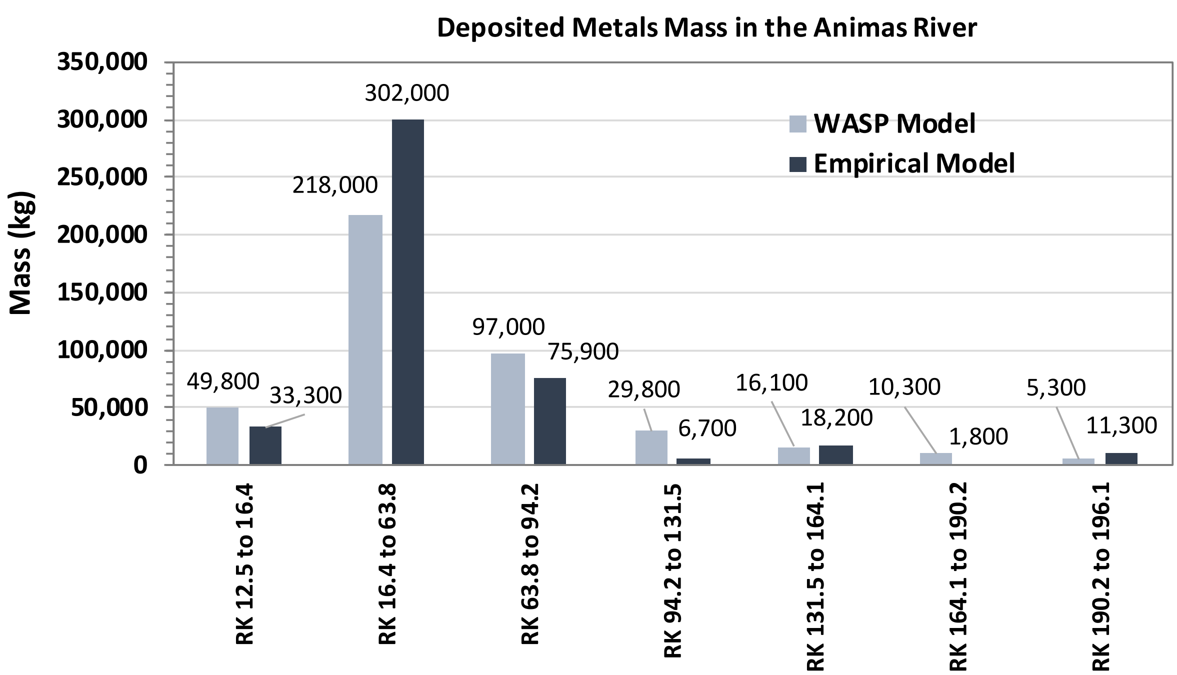


Figure 6-10. Metals mass deposited between plume simulation locations, as estimated by the Water Quality Analysis Simulation Program (WASP)and the empirical model.

A)

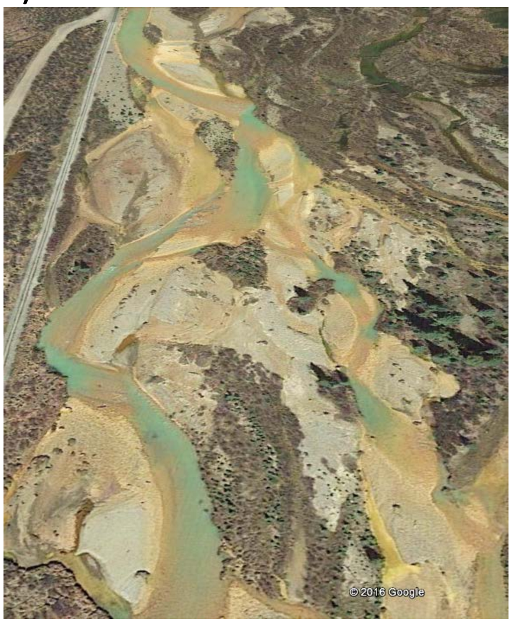


Photo: GoogleEarth Oct 15 2015

B)

C)

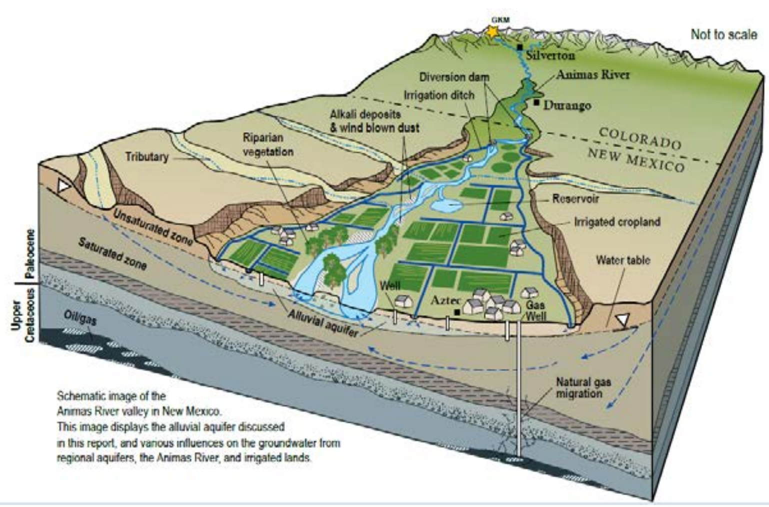


Image: New Mexico Bureau of Geology and Mineral Resources (Image from Timmons *et al.* 2016)

Figure 6-11. Deposition of Gold King Mine metals reflected valley-scale geomorphic characteristics that determined the dynamics of river flow. Deposition largely occurred in the headwaters of the Animas River between Silverton and Durango, as the river descended through the mountainous, confined topography (Precambrian lithology) to the widened valleys associated with sedimentary formations. The Gold King plume is shown traveling through the A) Upper Animas River valley between the Cement Creek/Animas River confluence and the start of the canyon below Silverton (~4 km) and into B) the canyon reach between Silverton and Baker's Bridge (~45 km). C) Depositional zones collect higher concentrations of deposits at several locations along the Animas.

A) 2014

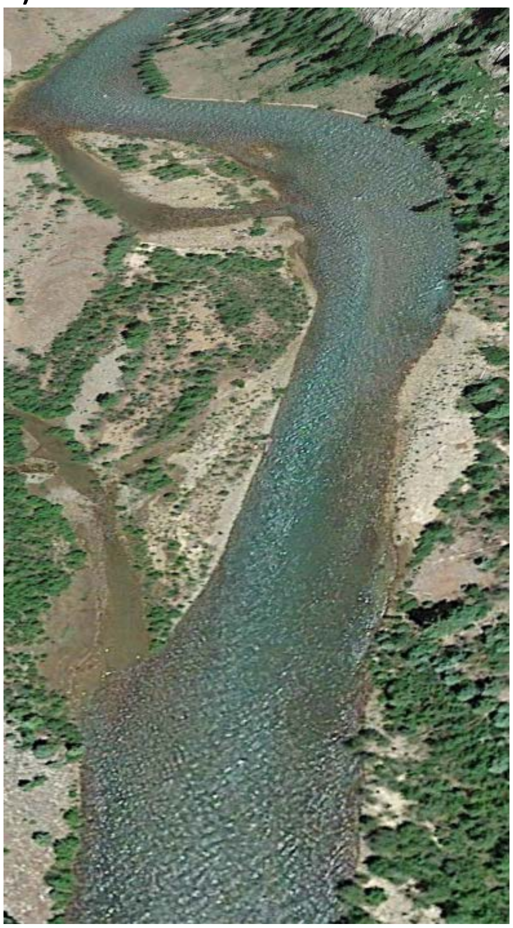


Photo: GoogleEarth

B) Oct 2015

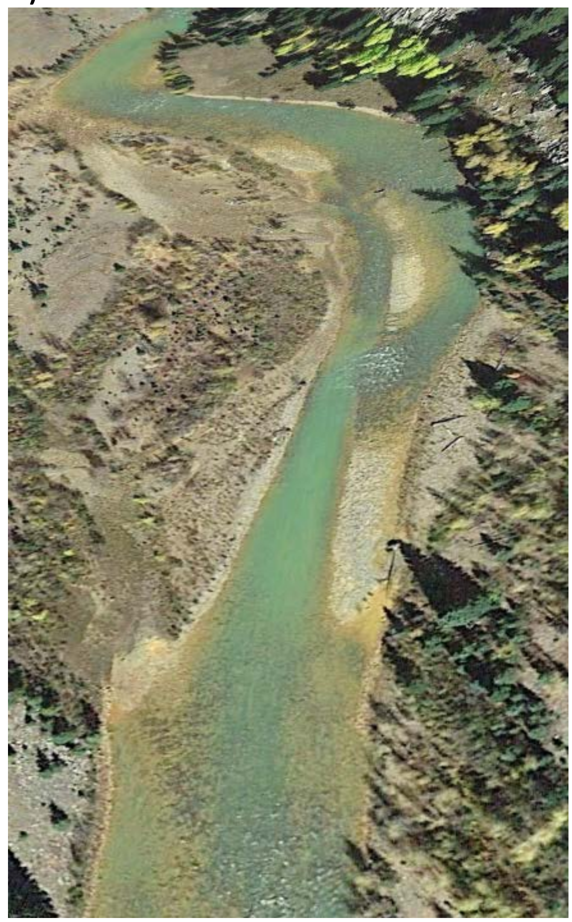


Photo: GoogleEarth

Figure 6-12. Aerial photography of two Animas River segments between Silverton (A72 at RK 16.4) and Baker's Bridge (RK 64) before and after the Gold King Mine release. A) and B) show a reach 12 km downstream from Silverton (RK 28) and C) and D) show a reach further into the canyon, 32 km downstream from Silverton at RK 48. Typical areas of deposition for natural sediments are channel margins and side channels (shown as dark finer deposits in 2014) and "yellowish" deposits in the photography three months after the Gold King Mine plume. D) Deposition can also be seen behind flow obstructions in the main channel.

C) 2014

Photo: GoogleEarth (2014)

D) October 2015

Photo: GoogleEarth October 2015

Figure 6-12. Continued. Aerial photograph of a reach of the Animas River 32 km down river from A72 below Silverton before and after Gold King Plume. C) 2014 photography at somewhat higher flow. D) October 2015. Gold King deposits can be seen along the channel margin and behind flow obstructions in the main channel where velocity is locally slower.

A) June 2014 B) August 2015 C) October 2015

Photo: GoogleEarth Photo: GoogleEarth Photo: GoogleEarth

Figure 6-13. Aerial photograph of the braided reach of the Animas River downstream from where Route 250 crosses the Animas River at Baker's Bridge (~RK 64) in A) June 2014, B) August 2015 immediately post-Gold King Mine passage, and C) October 2015.

A) **2014**

Photo GoogleEarth

B) **August 2015**

Photo: Bruce Gordon EcoFlight

C) **2014**

Photo GoogleEarth 2014

D)

Photo GoogleEarth 2015

Figure 6-14. Meandering channel north of Durango. A) The meander sediment bar pictured was B) photographed from the air as the Gold King plume passed. The same sediment bar is shown C) in 2014 from Google Earth imagery, and D) in October 2015. Gold King deposits were observed on the banks and bar in this reach.

A)

Photo: Colorado Parks & Wildlife

B)

C)

D)

Photo: Jerry McBride Durango Herald

Figure 6-15. Channel margin deposits of Gold King Mine plume precipitates in the Animas River. Deposits tended to remain along the edges of the channel as swifter water cleaned the main channel (A, B, and D). C) A close-up of the channel margin shows deposit of plume precipitates within 5 to 10 feet of the bank.

6.2.1 Composition of Deposited Mass

Large quantities of incipient amorphous iron and aluminum solids and micro-crystalline minerals precipitated in the Gold King Mine release waters intermingled and reacted with Animas River water. When minerals precipitate from solution, more soluble mineral phases generally precipitate for a combination of thermodynamic and kinetic reasons (Steefel and van Cappellen 1990). As the precipitates formed in the GKM plume in the Animas River, some precipitates remained in suspension, and some coagulated, settled, and adhered or cohered to the river bottom as seen in Figure 6-15. The mineral makeup of the precipitates was estimated from thermodynamic modeling of titration of “Plume + Background Mean” water, with the calcite alkalinity that is present in the Animas River (Figure 6-16).

For iron, a mineral ripening sequence that may have occurred is amorphous $Fe(OH)_3$, short-range-order ferrihydrite, ferrihydrite, and then goethite (or hematite), which might form directly from ferrihydrite or by dissolution and reprecipitation. For aluminum the sequence might have been amorphous $Al(OH)_3$, microcrystalline gibbsite, and then gibbsite. Cations initially in alunite and jarosite would likely have entered the more stable gibbsite and ferrihydrite phases, respectively, as the deposits “aged” post-deposition. Ultimately, these ions were likely bound to more stable minerals and their aqueous concentrations maintained at low levels, as suggested by the modeling described in Appendix C.

Importantly, post-plume adjustments to the composition of deposits should be expected. Some incipient minerals may have dissolved as river chemistry returned to a background equilibrium. Other incipient minerals continued to “age” over time as the less-stable initial phases slowly recrystallized to more stable phases. In all deposits there was a net transfer of metals from incipient phases to stable phases; thus, the deposited minerals from the Gold King plume were likely “active,” and would continue to affect metal concentrations in the water as they adjusted to more stable phases. Importantly, where the river bottom was dominated with incipient phases, the water would have tended to have higher solution concentrations post-plume. Alternatively, if the river bottom was dominated by stable oxides, the stable oxides would have acted as a sink for any elevated metals the water received from dissolution of the incipient phases. This post-deposition “activity” within the incipient minerals of the channel deposits had important implications for water quality in the months after the plume and is assessed in Chapter 9.

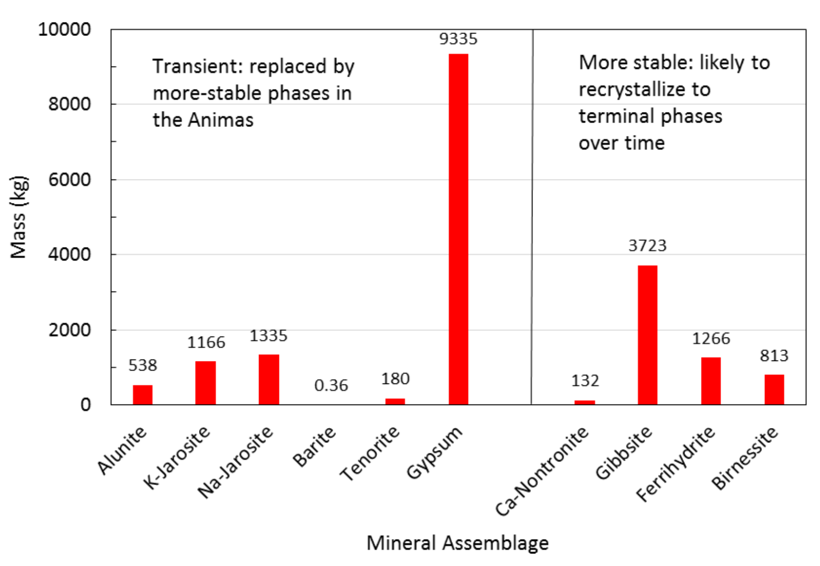


Figure 6-16. Masses of minerals precipitated from the Gold King Mine plume as it was delivered from Cement Creek and intermingled and reacted with Animas River water. Masses are estimated from thermodynamic modeling of titration of “Plume + Background Mean” water, with calcite alkalinity that is present in the Animas River. See Appendix C for more discussion.

6.3 Concentrations of Metals in Streambed Sediments

The metals content of plume deposits is understood from field sampling of the deposited material sitting on top of the streambed and underlying surficial layers of sediments. Many of the post-event samples were biased towards deposits, such as those shown in Figures 6-11 through 6-15 (rather than random sampling), in order to determine the material characteristics and risk to the public of the GKM release. Any data defining the mineralogy of these deposits, however, have not been available. Metals deposited from the Gold King plume as oxides and other incipient minerals were routinely quantified as elemental concentrations in the sediment sample, without distinction of mineralogy or metal species. The method used to extract sediment metals in this effort entailed refluxing of samples in hot concentrated acid, so the concentrations reported here reflect partial to complete dissolution of most sediment minerals.

Figure 6-17 shows concentrations of four metals from sediment samples collected throughout the Animas and San Juan Rivers after the Gold King plume. Also included on the figure are historical sediment concentration data collected by the USGS at gaging stations, data reported in the Animas AMD study reported by Church et al. (1997), and EPA Superfund data collected to support mine remediation activities in the Animas River headwaters.

There was wide variability in metal concentrations at locations where multiple samples were collected both historically and in Gold King Mine-related samples. Variability among post-release samples probably reflects the spatial variability in deposition evident in Figures 6-11 through 6-15. Samples with the highest concentrations were collected by CDPHE in the vicinity of RK 90; documentation of these samples states the samples may reflect “extreme” conditions. After the Gold King plume, sediment metals concentrations were high within the mining district in the Animas River headwaters and declined over two orders of magnitude through the Animas to its confluence with the San Juan River. Sediment metals concentrations were very low in the San Juan River compared to the Animas and varied relatively little along the length of the river (Figure 6-17). The historical samples show the same pattern as post-event samples.

Also shown on Figure 6-17 is a vertical bar that represents the range of metals concentrations sampled in natural surficial deposits and soils of the western United States in a synoptic survey conducted by the USGS (Shacklette and Boerngen 1984). This range is provided for perspective on the metals carried in these two rivers. Metal concentrations within the headwaters of the Animas River are as high as anywhere in the western United States, reflecting the geology and related mining impacts. Conversely, metal concentrations in the San Juan River are on the low end of the naturally occurring metals concentrations, if not below the observed range.

There were many locations in the Animas River, especially downstream from Baker’s Bridge (RK 63.8) and extending throughout the length of the middle and lower Animas River where post-Gold King Mine release sediment concentrations exceeded any historical measurements or occurred at locations where there were no previous measurements. Notably, all four metals shown in Figure 6-17 were particularly high at the sampling locations in the middle and lower Animas River.

6.3.1 Animas River Bed Sediment

Sediment concentrations of the same post-event samples and historical sampling at USGS gages in the Animas River are shown in Figure 6-18, along with sediment metals concentrations estimated from WASP model simulations. A regression fit to the historical USGS data was used to establish the baseline sediment metals concentrations in the Animas and to that was added the deposited metals concentrations estimated by WASP to obtain post-event sediment metals concentrations. Figure 6-18 may underestimate more recent bed concentrations in the Silverton, Colorado area, as AMD effects have increased since 2009, after much of the USGS data was collected.

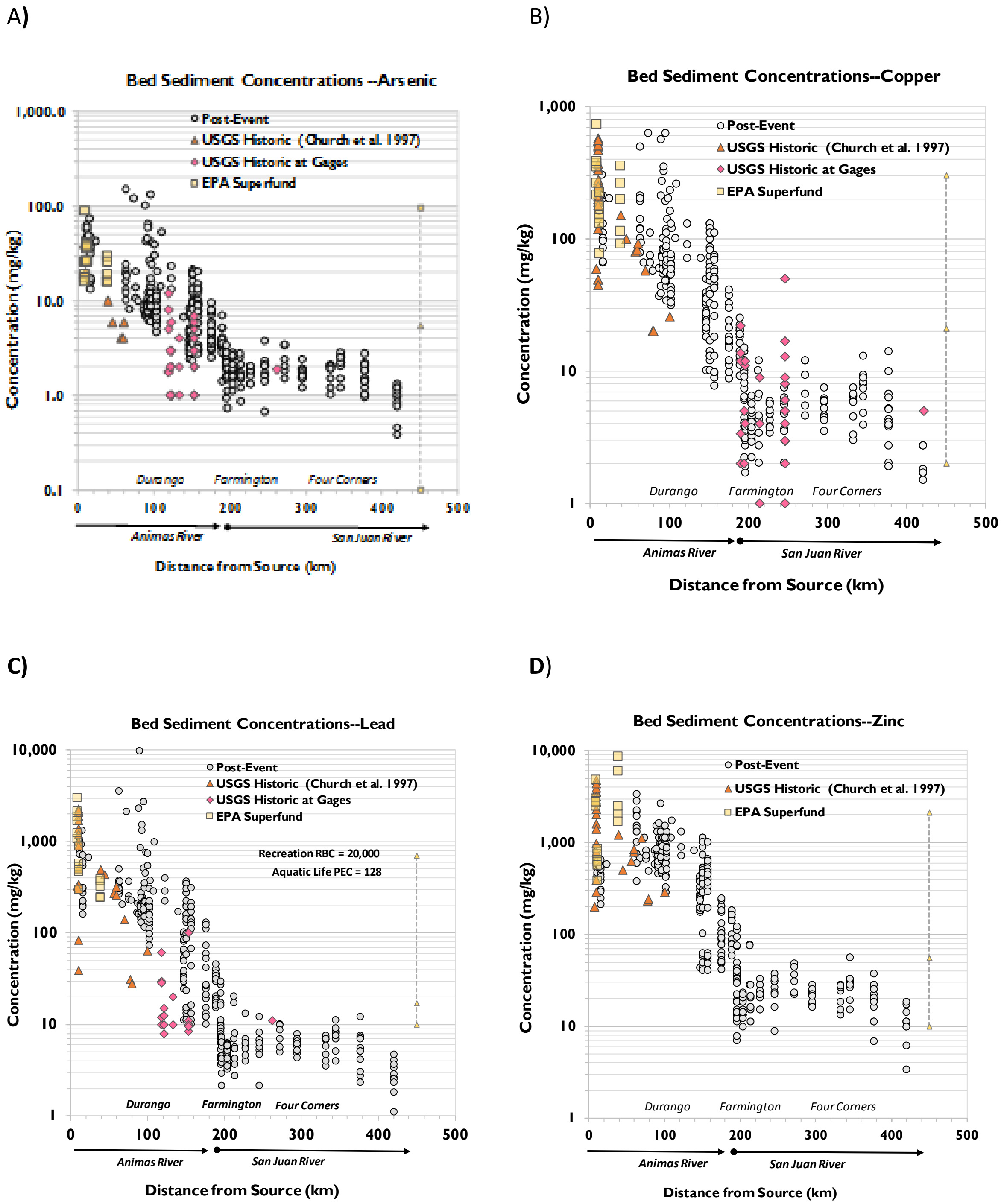


Figure 6-17. Bed sediment concentrations in the Animas and San Juan Rivers for A) arsenic, B) copper, C) lead, and D) zinc. Data included historical and post-Gold King Mine (GKM) event sampling throughout the river system. USGS data included occasional sampling at stream gages and data collected by Church *et al.* (1997) as part of the Animas River acid mine drainage study. Samples were collected and processed with a variety of objectives. The vertical dotted line is the range of metal concentrations in western soils and sediments from Schacklette and Boerngen (1982).

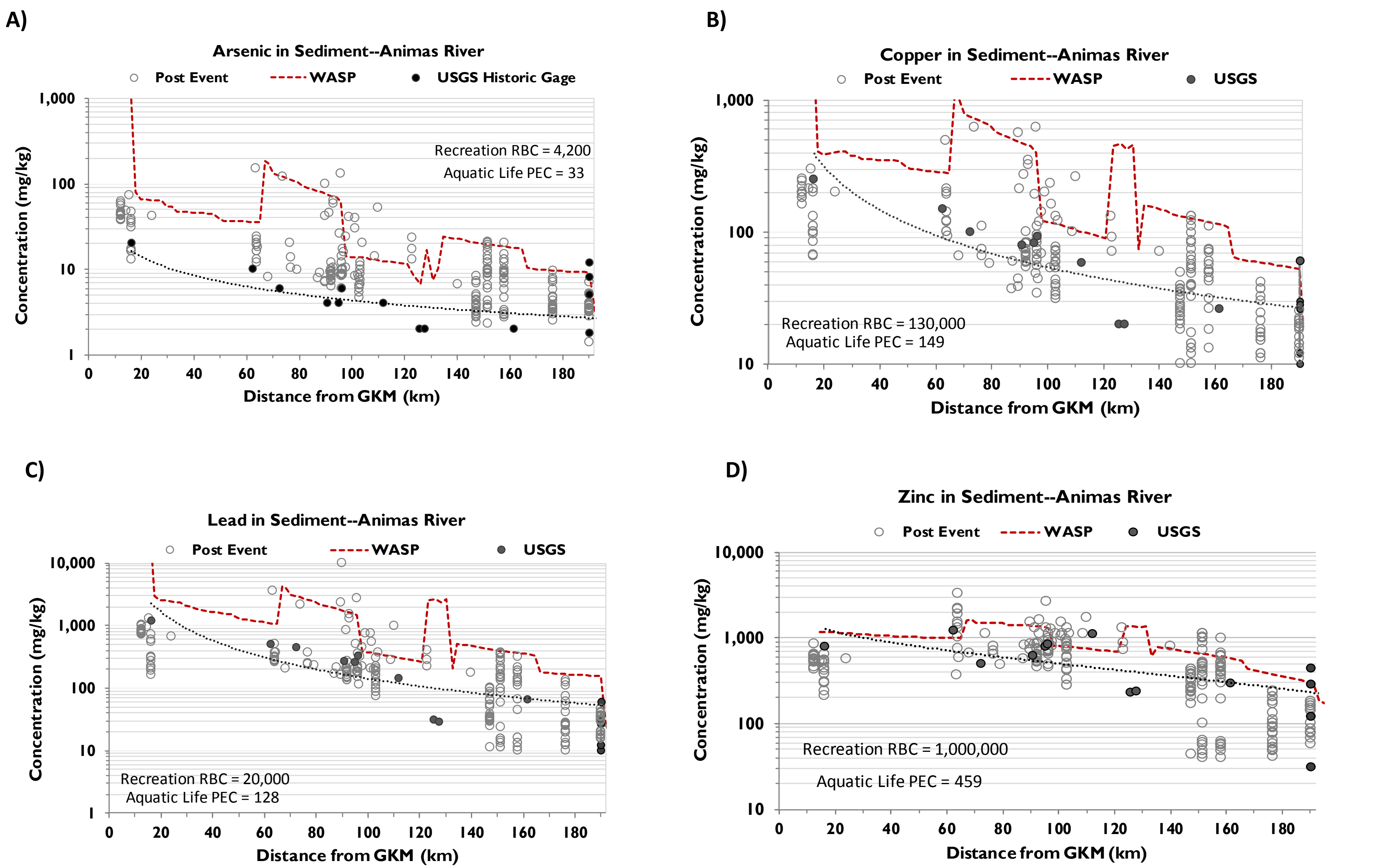


Figure 6-18. Animas River bed sediment concentrations for A) arsenic, B) copper, C) lead, and D) zinc. Metals concentrations of sample collected post-Gold King Mine (GKM) event (open circles) and historical observations (black circles) at USGS gages in the Animas River. A regression fit to the USGS gage data (dotted line) established a baseline estimate. The Water Quality Analysis Simulation Program (WASP) concentration (dashed line) is the depositional sediment concentration estimated by the model and added to the baseline established by the regression from USGS data.

Post-event concentrations of the four metals (and others not shown) generally increased in the river segments identified by WASP as likely depositional zones and generally near the predicted levels. Higher metals concentrations after the Gold King plume from RK 60–100 and RK 130–170 are of special note, as they indicate significant sediment metals deposition. WASP predictions of the location and concentrations of plume deposition were consistent with observations. Geomorphic controls on river flow were especially important in the Animas River, as the Gold King plume carried a large mass of metals in flow that alternately accelerated and decelerated with valley conditions, resulting in differential deposition. All four metals were elevated in the depositional areas.

6.3.2 San Juan River Bed Sediment

Sediment metals composition of the San Juan River is shown for four metals in Figure 6-20. Historical data collected at USGS gages and the WASP-simulated depositional sediment concentrations are included on the graph. Sediment metals concentrations show little change through the more than 360 km of the San Juan River. It should be noted, however, that sediment concentrations of lead, zinc, and to a lesser extent, copper were higher than the general river distribution in samples collected in the vicinity of RK 196, just downstream from the confluence with the Animas, indicating deposition in this immediate area. WASP-predicted bed concentrations generally exceeded observed lead concentrations, but is within the range of variation for copper and arsenic. WASP underestimated zinc concentration in the sediment bed of the San Juan River.

When compared to the Animas River samples and the regional soils concentrations reported by Shacklette and Boerngen (1984), bed sediments in the San Juan River have low concentrations of metals. Bed concentrations since the Gold King Mine release have been within historical levels relative to the few data available from USGS data gage sites. The historic range of trace metals at sites in the San Juan River reflects varying sediment levels, as discussed in Section 5.3. Elemental concentrations of the trace metals in the sediment bed of the San Juan River follow closely the composition of Mancos Shale (Figure 6-19); this explains 94% of the observed composition of trace metals in sediments and water in the San Juan.

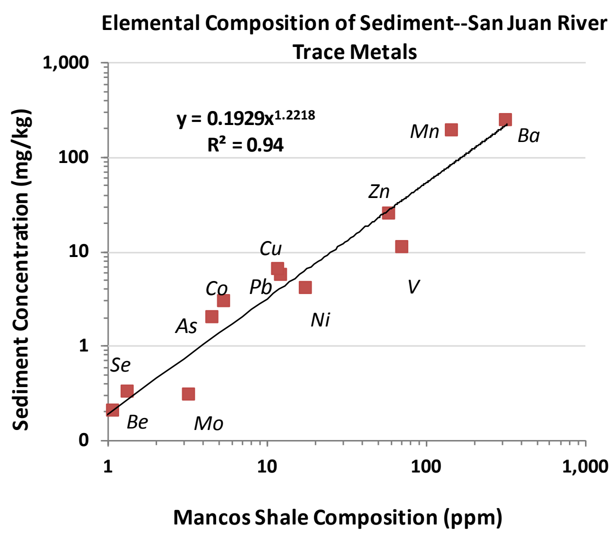


Figure 6-19. Concentrations of trace elements in the sediment of the San Juan River in relation to the elemental composition of metals in the soils and surficial deposits of Mancos Shale (from Tuttle et al. 2007).

6.3.3 Lake Powell Bed Sediment

The San Juan River flows into Lake Powell approximately 550 km from the Gold King, and 360 km downstream of the confluence with the Animas River. Lake Powell is formed by the Glen Canyon Dam, which impounds the Colorado River and its major tributary, the San Juan River. Figure 6-21 shows photographs of the San Juan River at Shiprock, New Mexico (RK 246.3) and as the San Juan begins to head into the canyon that contains Lake Powell (approximately RK 550).

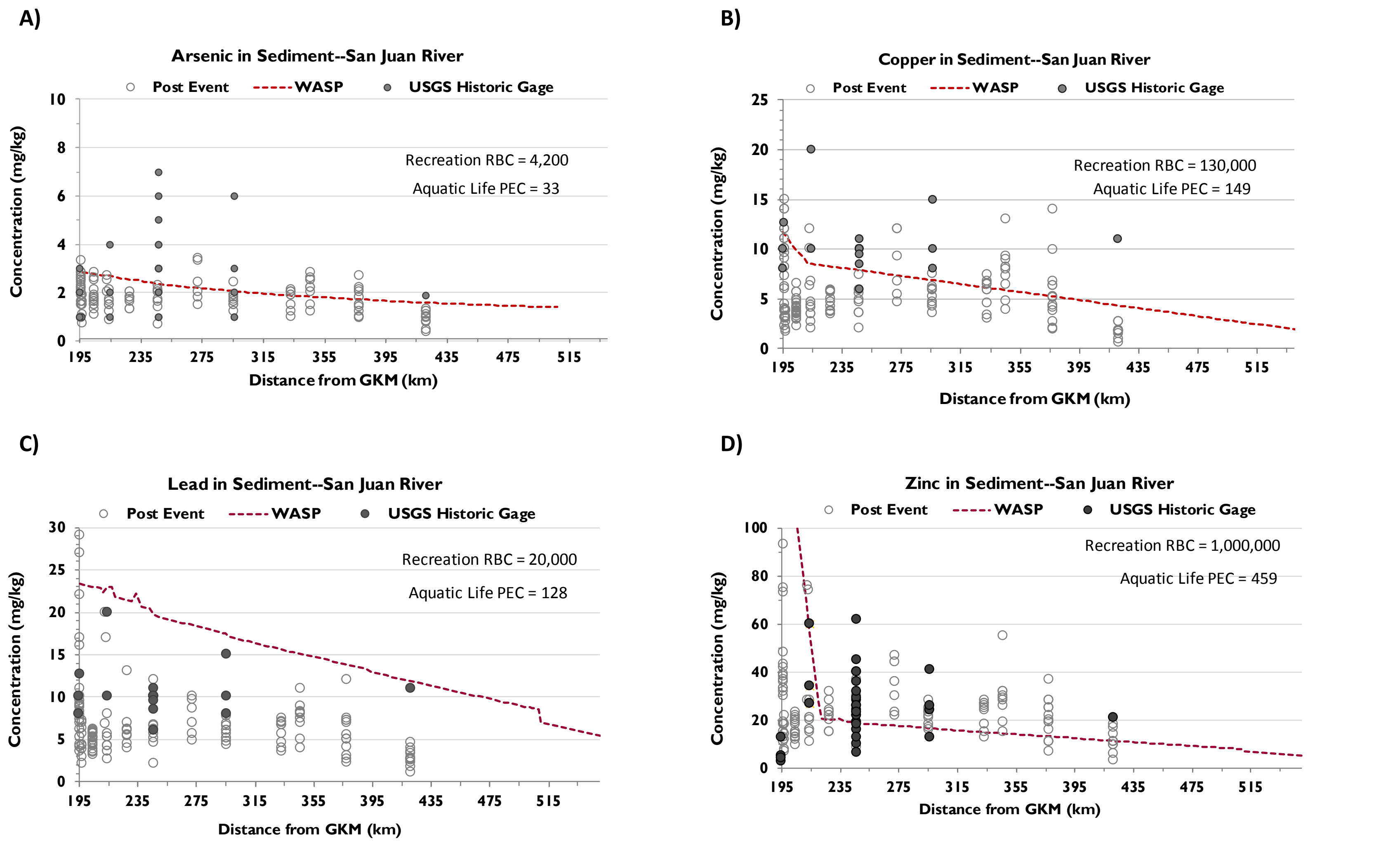


Figure 6-20. San Juan bed sediment concentrations for A) arsenic, B) copper, C) lead, and D) zinc. Metals concentrations of sample collected post-Gold King Mine (GKM) event (open circles) and historical observations (black circles) at USGS gages in the San Juan River. The Water Quality Analysis Simulation Program (WASP) concentration (dashed line) is the depositional sediment concentration estimated by the model and added to the baseline established by the regression from USGS data.

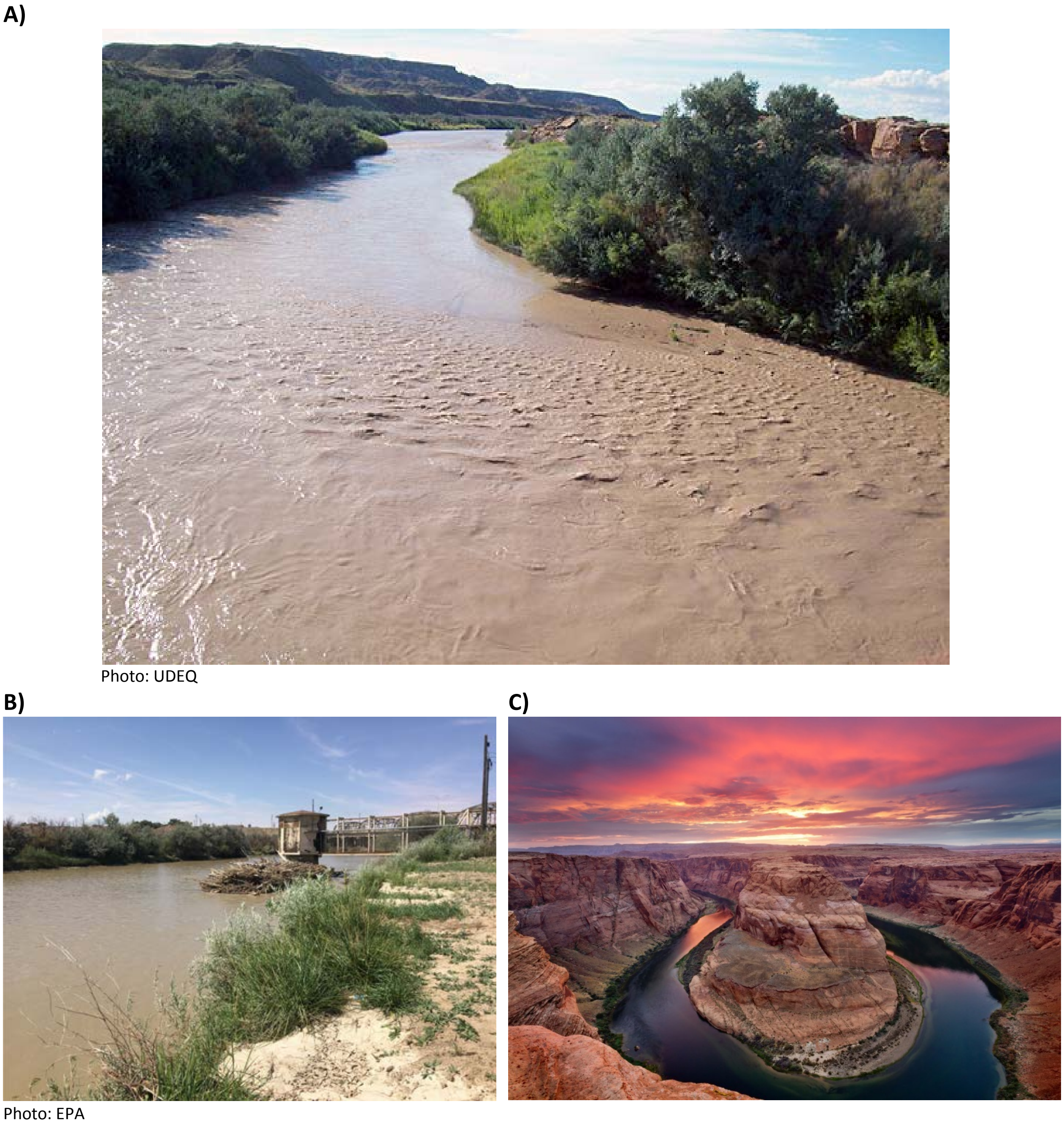


Figure 6-21. Photographs at of the San Juan River at A) Montezuma Creek (RK 346), B) Shiprock, New Mexico (RK 246) and C) as the river approaches Lake Powell in Utah at approximately RK 550.

The USGS cored the sediments of Lake Powell in 2010 and 2011 to determine metals concentrations in the lakebed (Hornerwer 2014). Figure 6-22 compares lake core metal concentrations with San Juan bed sediments after the plume. Sediment composition of the river averaged from Montezuma to Mexican Hat (RK 421.3) is low in metals concentrations relative to the 2010 to 2011 lake core samples (Figure 6-22). The lake sediments had significantly higher metal concentrations than the river sediments measured during post-release sampling.

Modeling suggests that about 450,000 kg of metals flowed into Lake Powell including background metals along with the Gold King plume, which contributed a mass of between 23,800 (empirical model) and 45,000 kg (WASP model) by the time it reached this final receiving water. Whether the plume mass will leave a signature within the larger mass in transport and higher concentrations in the lakebed is unknown. Following the spill, sediment traps were deployed by the USGS in August 2015 at the terminus of the San Juan River in Lake Powell to assess recent and ongoing deposition and sediment metal concentrations (UDEQ 2016a). The traps capture sediment as it falls to the bottom of the reservoir. Traps were retrieved in November 2015, but results have not yet been reported.

6.4 Gold King Release Mass Relative to Historic Mass in the Animas River

The Animas River has historically been contaminated with metals from mining activities in the headwaters, near the ore-rich deposits and at off-site ore processing facilities (Church *et al*. 2007). Water and sediment quality in the upper Animas and throughout downstream reaches is affected on a continual basis by these activities. Church *et al*. (1997) measured elevated metals in bed sediments from the headwaters to approximately RK 145, where their study ended. Higher flows (e.g., during snowmelt) were shown to entrain sediments and carry metals downstream with them.

The Gold King plume load was assessed in relation to annual metal loads carried by the Animas River. To do so, a simple daily metal load model was built that relies on the relationship of dissolved and total metals concentration to streamflow; this model is illustrated for dissolved and particulate lead and aluminum in Figure 6-23. Similar relationships with flow for all metals at Silverton (RK 16.4) and Durango (RK 94.2) are provided in Appendix E.

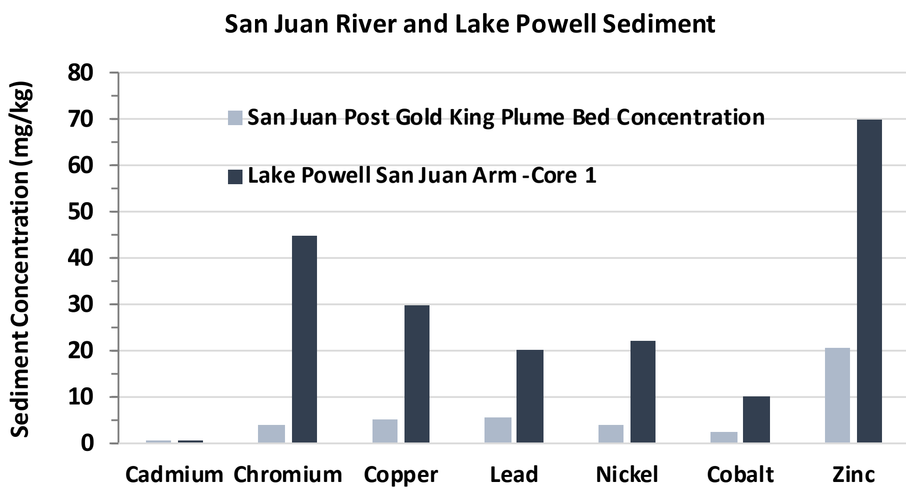


Figure 6-22. Comparison of metals concentrations in the streambed of the San Juan River averaged from sampling sites from Montezuma UT (RK 346) to Bluff (RK 421) about 50 km from Lake Powell and metal concentration in the top layers of lake core samples collected 2010-2011 reported in Hornerwer (2014).

These figures show very strong relationships for some metals and weak relationships for others. For example, like many metals, dissolved lead decreased with increasing flow (Figure 6-23A). Many metals that primarily source to surface waters through groundwater flow are more concentrated during low-flow periods. Dissolved aluminum was variable and showed a weak, but positive relationship to flow, indicating that the dissolved aluminum increased with the particulate load. Particulate metals behaved like sediment particles and tended to be low at low flows and rise significantly when flow exceeds a mobility threshold. Figure 6-23 illustrates that although many metals had a small change in concentration with either higher or lower flow, the large volume of flow that occurs over the 2-month snowmelt period transports a considerable mass of metals (Church *et al*. 1997). Increases in concentrations were not very large in many of the relationships shown in Figures 6-23, but they indicated that the influence of flow must be considered when statistically comparing pre- and post-release water concentration data.

To estimate the annual load of metals transported past Durango, these relationships were applied to daily average flow data published with each USGS gage. Figure 6-24 illustrates the daily concentration and load for zinc and copper over a one-year period modeled by this approach. The metals load was calculated by multiplying daily flow volume by concentration; this was the expected daily concentration and metals load in Durango, Colorado in an average year. Besser and Leib (2007) applied a similar approach to estimate metals concentrations and potential toxicity to aquatic life in the upper Animas near Silverton.

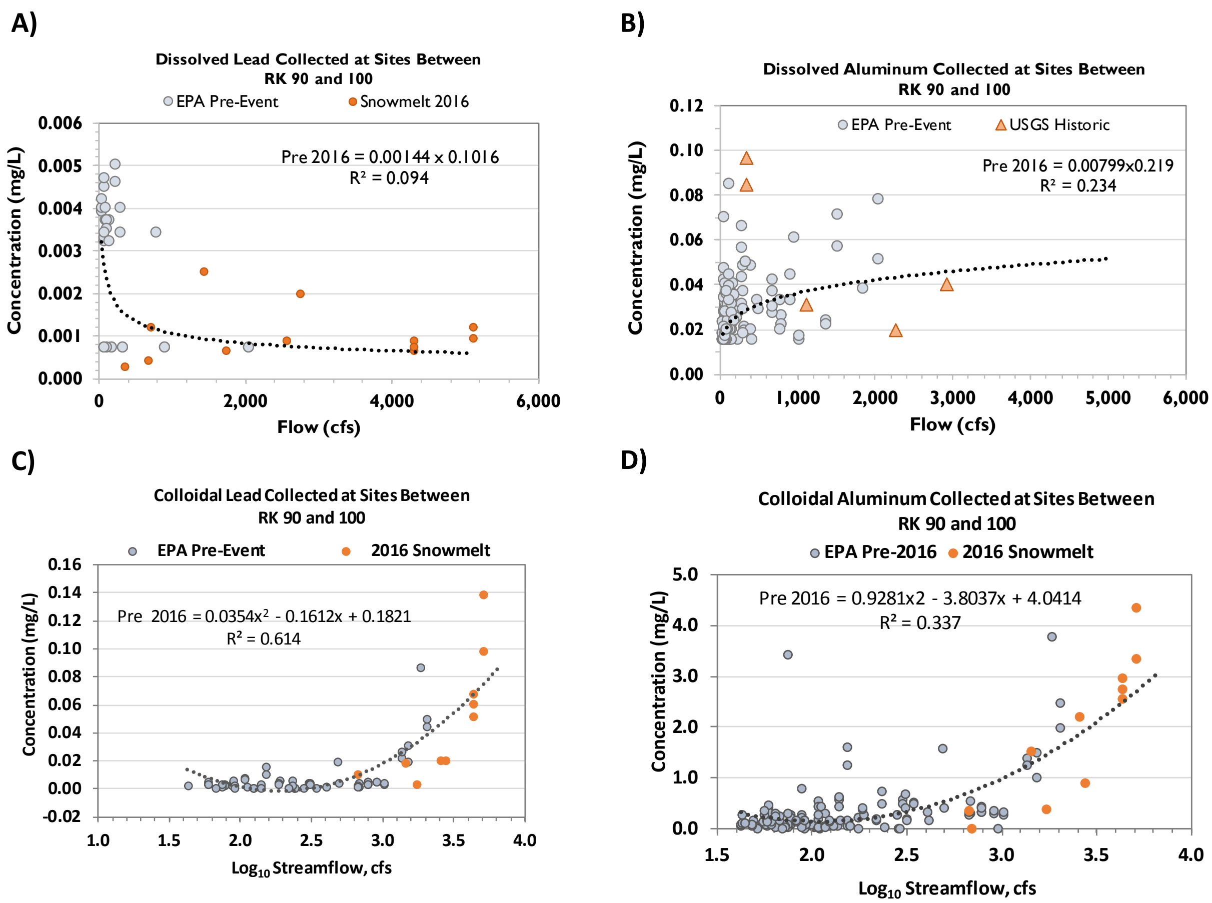


Figure 6-23. Regression relationships between flow and dissolved metal concentrations (A and B) and colloidal/particulate metal concentrations (B and C) in samples collected by EPA and USGS at Durango from 2009 to 2014. Data collected during snowmelt in 2016 are shown on the figures but not included in regressions. There was no available data for dissolved lead with historic USGS data.

These relationships and simple daily models were also used to assess post-release effects of the Gold King Mine release on water quality and sediment in Chapter 9.

Table 6-1 provides the mass of seven metals carried over the course of an average year at Durango. Each year, 20,000 kg of lead and 81,000 kg of zinc are transported in the flow of the Animas River at this location. Considering the 7 most abundant metals listed in Table 6.1, the Gold King plume mass increased the annual metals load by approximately 3%. The annual load of particulate lead and iron increased by 5.7% and 5.1%, respectively.

On a daily basis, the Gold King plume carried a particulate metals mass equal to 0.5 to 2.9 days of spring snowmelt, varying with metal; the dissolved mass was generally less than a day of snowmelt (Table 6-2). Notably greater were particulate iron and dissolved manganese. However, the Gold King plume occurred during relatively low flow conditions and concentrations and mass were significantly elevated above what would be normal for this level of flow, as discussed in detail in Chapters 4 and 5.

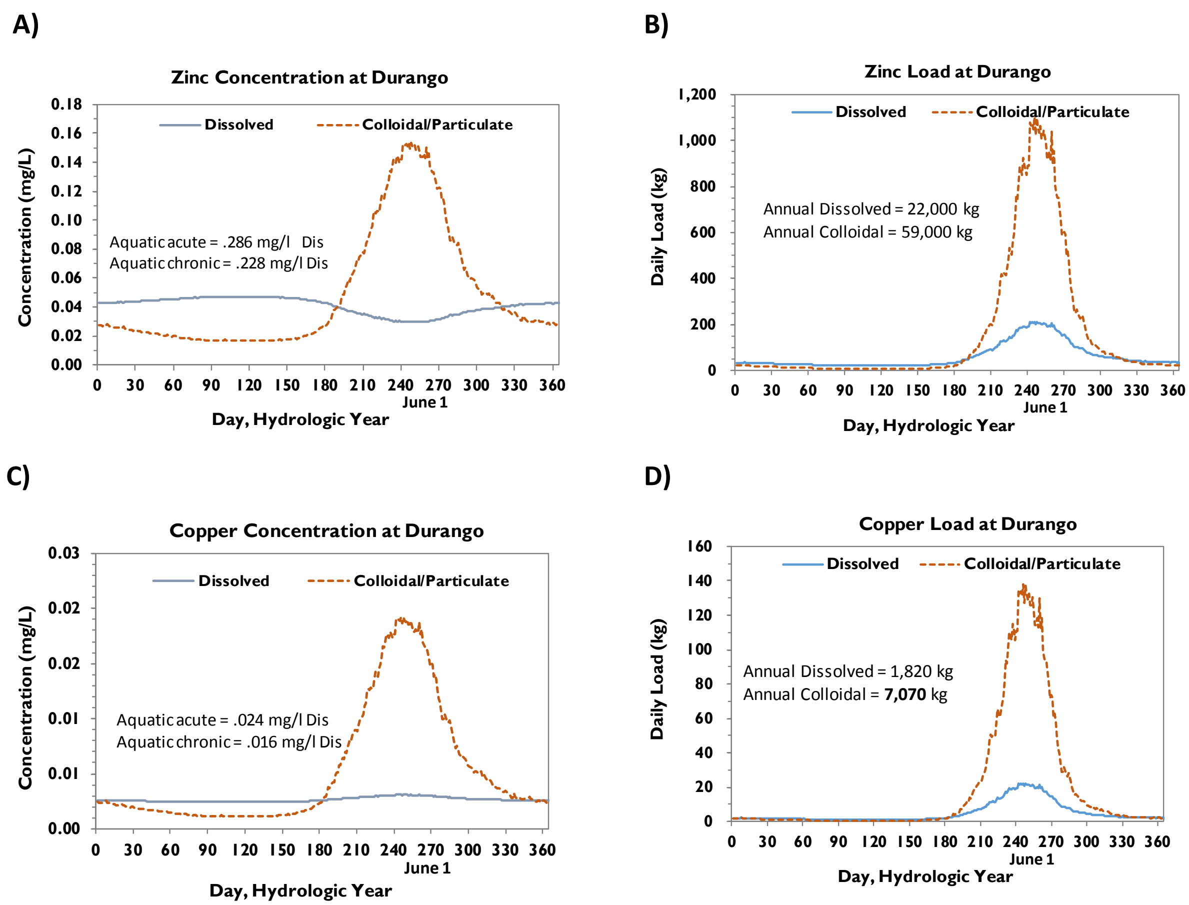


Figure 6-24. Simulated average daily concentration and load for zinc (A and B) and copper (C and D) for the Animas River in Durango, Colorado (Based on data collected between RK 90 and 100). Flow is the daily average flow for the period of record for each day published with USGS site statistics; this represents the average flow year, plotted as the hydrologic year (beginning October 1 and ending September 30). Concentration is predicted from the regression of concentration as a function of flow (e.g., Figures 6-23 and 6-24) and load is calculated by multiplying daily flow volume by concentration.

Table 6-1. Average annual metals dissolved and particulate load of the Animas River at Durango. Daily load as shown in Figure 6-25 is summed for the year. The mass of metals transported in the Gold King plume at Durango (RK 94.5) determined by the empirical model.

Animas River in Durango (RK 90-100)							
	Average Annual Metals Load Estimated Pre-2016				Gold King Plume Metals Load		
Metal	Dissolved (kg)	Particulate (kg)	Total (kg)	Metal	Dissolved (kg)	Particulate (kg)	Total (kg)
Aluminum	24,000	770,000	794,000	Aluminum	100	9,907	10,007
Iron	30,000	1,300,000	1,330,000	Iron	90	66,721	66,811
Manganese	29,000	132,000	161,000	Manganese	510	411	921
Lead	700	14,000	14,700	Lead	1.1	802	803
Copper	1,800	7,100	8,900	Copper	7.0	240	247
Zinc	22,000	59,000	81,000	Zinc	111	508	619
Cadmium	115	170	285	Cadmium	0.9	1.6	2.5
Sum 7 metals	**107,615**	**2,282,270**	**2,389,885**		**820**	**78,591**	**79,411**
				% of Annual	**0.8%**	**3.4%**	**3.3%**

6.4.1 Bed Composition Compared to Pre-Existing Sediment Mass

The Gold King Mine release resulted in significant deposition of metals mass in the Animas River, especially in the upper reaches from Silverton to Durango where approximately 83% of the 457,000 kg of metals settled as colloidal/particulates. This material was visibly evident as yellow deposits of aggregated colloids, sludge, and particulates. Streambed sediments in this reach of the river have had historic and ongoing contamination from mine waste and acid mine drainage from mining in the region for over a century. To place the Gold King Mine mass of material in context, a simple model was developed of daily metal loads at two locations where sufficient pre-event data were available.

While metals carried in the Animas River water during the passage of the Gold King plume were almost exclusively attributable to the release, the metals in the streambed after the plume also strongly reflected pre-existing contamination from mining in the watershed (e.g., Figure 6-17). Church et al. (2007) noted that millions of tons of ore and mine waste were dumped into the Animas in multiple locations and that those sediments continue to contaminate the streambed along with ongoing AMD. Headwaters geology and the history of mining impose the strong longitudinal gradient of sediment metals concentrations that was previously documented within the upper and middle Animas within Colorado by Church et al. (1997). Post-release metals concentrations generally mirrored that decline, but were locally elevated (Figure 6-18).

Table 6-2. Gold King Mine (GKM) Plume Daily Metals Load at Durango, Colorado (RK 94.2) Compared to the Mass Carried During the Peak Days of Snowmelt Runoff.

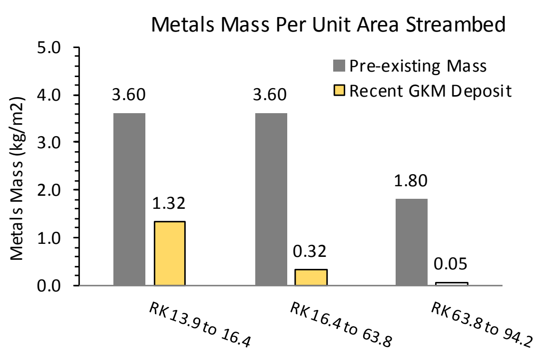
	Particulate Load		Dissolved Load	
Metal	GKM Plume (kg)	Peak Day Snowmelt (kg)	GKM Plume (kg)	Peak Day Snowmelt (kg)
Aluminum	9,907	**14,000**	100	**320**
Iron	66,721	**23,000**	90	**460**
Manganese	411	**2,500**	510	**200**
Lead	802	**425**	1.1	**5**
Copper	240	**150**	7.0	**20**
Zinc	508	**1,100**	111	**250**
Cadmium	1.6	**3.0**	0.9	**1**

Table 6-3. Estimate of Metals Mass in the Streambed of Three Segments of the Upper Animas River. Segment length and width were estimated from GoogleEarth imagery and software tools. Sediment concentrations were based on EPA remediation sampling (pre-event: 2010–2012). Plume deposits were determined from the empirical model mass estimates.

River Segment	Segment Length (m)	Segment Width (m)	Segment Area (m^2)	Sediment Bulk Density (kg/cm^3)	Segment 3-cm Depth Sediment Weight (kg)	Pre-Event Metal Conc (mg/kg)	3-cm Depth Sediment Metal Weight (kg)	Estimated Plume-Deposited Metal (kg)	Plume Metal Deposits as % of Total
RK 13.9 to 16.4	2,500	10	25,000	0.0015	1,125,000	80	90,000	33,000	36.7%
RK 16.4 to 63.8	47,400	20	948,000	0.0015	42,660,000	80	3,412,800	302,000	8.8%
RK 63.8 to 94.2	31,200	50	1,560,000	0.0015	70,200,000	40	2,808,000	75,600	2.7%

Recent deposition from the Gold King Mine release was compared to the pre-existing mass of metals in the streambed by translating sediment concentrations to mass for the segments in the upper Animas from Cement Creek to Durango. Stream area was determined from GoogleEarth measurements of channel width. A bulk density value of 1.5 g/cm^3 was applied to the top 3-cm sediment depth and multiplied by the historic metals concentration to determine pre-existing mass per unit stream area. Calculations are provided in Table 6-3 and the unit area mass comparisons are shown in Figure 6-25. The Gold King Mine release contributed a substantial mass of sediment to the Animas River in the vicinity of Silverton (RK 16.4), increasing the mass already in the streambed by approximately 37%. The plume increased mass in the top layers of sediment by an estimated 9% in the reach between RK 16.4 and 63.8 and almost 3% from RK 63.8 to RK 95.

A)



B)

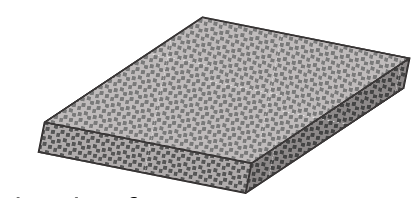


Figure 6-25. Metals mass in streambed sediments at three locations in the upper Animas expressed as mass per unit area of streambed, based on channel dimensions and sediment characteristics provided in Table 6-3. A) Conceptual diagram of unit block of bed sediment B) Mass assumes 3 cm depth.

6.5 Summary of Metals Mass

Most of the Gold King Mine plume mass was deposited in the Animas and San Juan Rivers before the plume reached the final receiving waters. Most of the mass was deposited in the Animas River (89%) while 6% was deposited in the San Juan River, and 5% was delivered to Lake Powell (based on the empirical reconstruction of the plume). The mass left behind was mostly iron and aluminum oxides, in a mix of particulate and colloidal forms bearing trace metals such as lead, copper, zinc, and arsenic. Deposits were visible for much of the Animas River and affected the metals composition of the streambed in a number of locations. These deposits would remain in place until high flows removed them or they stabilized into long-term inert minerals. Trends in sediment concentrations left as deposits in the months following passage of the plume are assessed in Chapter 9.

CHAPTER 7 POTENTIAL EXPOSURE TO METALS CONTAMINANTS DURING THE GOLD KING PLUME

Potential exposure of humans and terrestrial and aquatic life to the high metals concentrations observed during the Gold King Mine plume were short-term in nature and were characterized by an initial spike in concentrations in the water that dissipated rapidly towards return to pre-event conditions. Concentrations continued to decline over a period of days to weeks, depending on location. Emergency response efforts managed by EPA, states, and tribes limited human-related exposure by curtailing use of the Animas and San Juan Rivers for domestic water supply (e.g., drinking water and water used for other household purposes), agricultural consumption (e.g., irrigation), livestock watering, and recreation and human contact (e.g., swimming, fishing, boating, fish consumption, and ceremonial uses). Concerns remain for delayed exposures due to the potential remobilization of the deposited metals throughout the river system. This chapter addresses potential exposure to metals during passage of the Gold King plume, and Chapter 9 addresses exposure to metals in water and sediment in the year following the event.

7.1 Water Quality Criteria

State and tribal water quality standards consist of three components: designated uses of a water body (e.g., aquatic life support, contact recreation); water quality criteria to protect those uses; and an antidegradation policy (80 FR 51020, 8/21/2015). Designated use refers to a reasonable quantity of water applied to a non-wasteful use and establishes the environmental objectives for a water body. A ‘‘use’’ is a particular function of, or activity in, a particular water body that requires a specific level of water quality. In turn, water quality criteria define the minimum conditions necessary to achieve those environmental objectives. The antidegradation requirements provide a framework for maintaining and protecting water quality that has already been achieved. Water quality criteria have three components: magnitude, duration and frequency (e.g., the level of W pollutant shall not exceed X level for more than Y hours once every Z years). Numeric criteria reflect assumptions of effects mechanisms, such as ingestion or dermal contact, coupled with magnitude and duration of exposure. There are criteria to protect aquatic habitat from acute exposures (i.e., exposure to high concentrations for a short period of time), typically a concentration not to exceed for 96 hours, while chronic exposure criteria assume low concentrations for extended periods (typically, a 30-day average). Although metals concentrations in bed sediments were also affected by the plume, there are no criteria adopted for this media. EPA has recommended criteria for many of the designated uses of water.

The determination of a specific designated use depends on federal, state or tribal jurisdiction. The major designated uses generally recognized by states and tribes in the study area that are the focus of the Gold King mine release include domestic water, human contact-related, livestock watering, agriculture irrigation, fishery, wildlife maintenance and enhancement, and recreational, as they involve potential risk to human or ecosystem health. Designated uses also include industrial, commercial, and mining, but these are not addressed in this study.

States and tribes have adopted water quality criteria that establish concentrations of constituents, including metals, in water or sediments that are not expected to result in harmful effects for the designated uses of water. States and tribes in the area affected by the Gold King plume have adopted criteria for individual metals. Criteria vary according to designated use and differ among the jurisdictions. Metals criteria variously specify dissolved or total fractions for specific uses. Some criteria are a single threshold value, while others are varied by the hardness of the water. Criteria may be assigned to specific river reaches. Some criteria are similar between states and tribes for the same designated use, but many differ. A list of metals criteria relevant to the area affected by the Gold King plume are compiled in Table 7-1, categorized by water use. Note, the criteria that vary with hardness were calculated at one value for illustrative purposes.

Table 7-1. Magnitude Component of Water Criteria Applicable to Portions of the Animas and San Juan Rivers Compiled from States, Tribes, and EPA Regions. Gold-colored cells indicate the criteria is based on total recoverable metals concentration, and blue-colored cells indicate the criteria is based on dissolved metals concentrations (i.e., sample filtered through 0.45-µm mesh). Blank cells have no criteria. Hardness based criteria shown on the table are calculated at the hardness shown in the far right column. The table is a guide to differences and similarities among applied water quality criteria.

Water Quality Screening Criteria--Metals Concentrations (mg/L)

	Beneficial Use	State/Tribe	Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Calcium	Chromium[&]	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Mercury	Molybdenum	Nickel	Potassium	Selenium	Silver	Sodium	Thallium	Vanadium	Zinc	*Hardness
Domestic Water Supply	Domestic Supply	New Mexico		0.0060	0.010	2.0	0.0040	0.005		0.10		1.30		0.0150			0.0020		0.7		0.050			0.002		10.50	
	Domestic Source	Utah			0.010	1.0	0.0040	0.010		0.050				0.0150			0.0020				0.050	0.05					
	Domestic Water Supply	Navajo Nation		0.00560	0.010	1.0	0.0040	0.005		0.10		1.30		0.015			0.0020		0.6		0.050	0.04		0.0020		2.10	
	Drinking Water	Ute Mountain Ute	0.2000	0.00560	0.000	1.0		0.005		0.16		1.00		0.050			0.0001		0.1		0.050	0.10				5.00	
	Domestic Supply 1-Day	Colorado				1.0		0.005		0.050				0.050			0.0020					0.10					
Recreation and Human Contact	Primary Human Contact	Navajo Nation		0.370	0.030	98.0	1.870	0.470		0.100		9.330		0.015			0.280		18.7		4.670	4.67		0.0750		280.0	
	Secondary Human Contact	Navajo Nation		0.370	0.280	98.0	1.870	0.470		0.100		9.330		0.015			0.280		18.7		4.670	4.67		0.0750		280.0	
	Ceremonial, other uses	Ute Mountain Ute	0.2000	0.0056	0.00	1.00		0.005		0.160		1.0000		0.050			0.0001		0.1000		0.0500	0.10				5.0000	
	Fish consumption	Ute Mountain Ute		0.640	0.00001			0.084		670.0							0.000		4.6		4.200	110.00				26.0	
	Recreational	Utah	621	0.248	0.186	124.2	1.242	0.062		0.4100	7.9310	6.208	851.6	0.9100		31.0	1.242	3.104	17.5		3.104	3.64		0.0250	6.21	217.8	
	Recreational	Region 6	170	0.067	0.050	33.0	0.33	0.083		220.0	0.050	6.7	120.0	0.20		7.80	0.050	0.830	3.30		0.830			0.0020	0.83	50.0	
Agriculture	Irrigation	New Mexico	5.0		0.10			0.01		0.10	0.050	0.2		5.0				1.0			0.130				0.10	2.0	
	Irrigation (short-term)	Utah	20.0		2.0			0.05		1.0	5.0	5.0	20.0	10.0		10.0	0.010	0.050	2.0		0.020				1.0	10.0	
	Irrigation (long-term)	Utah	5.0		0.10			0.01		0.10	0.050	0.2	5.0	5.0		0.20	0.010	0.010	0.20		0.020				0.10	2.0	
	Agricultural Uses	Utah			0.10			0.01		0.10		0.2		0.10							0.050						
	Agricultural Supply	Navajo Nation	5.0		2.0			0.05		0.10	0.050	0.2		10.0				1.0			0.020				0.10	10.0	
	Agriculture	Ute Mountain Ute			0.1			0.01		0.10		0.2		0.1			0.0100		0.200		0.020					2.0	
	Agriculture	Colorado			0.10		0.10	0.01		0.10		0.2		0.10		0.20		0.30	0.20		0.020					2.0	
Livestock	Livestock	New Mexico			0.20			0.05		1.0	1.0	0.5		0.10			0.010				0.050				0.10	25.0	
	Livestock	Utah	5.0		0.20			0.05	500.0	1.0	1.0	0.5		0.10	250.0		0.010				0.050		1000.0		0.10	25.0	
	Livestock Watering	Navajo Nation			0.20			0.05		1.0	1.0	0.5		0.10							0.050				0.10	25.0	
	Wildlife Habitat	New Mexico															0.000770				0.005						
Aquatic Life Acute	Acute Agri. and Wildlife	Navajo Nation	0.750	0.088	0.340			0.0049				0.0319		0.1723			0.0024		1.0165		0.033	0.0156		0.70		0.2547	250
	Acute Warm Water	Ute Mountain Ute	0.750		0.150			0.0049		1.207		0.0319		0.1723			0.0001		1.0165		0.020	0.0167				0.2547	250
	Aquatic Acute	New Mexico	7.9432		0.340			0.002791		0.0160		0.0240		0.125		3.6647	0.0014	7.920	0.788		0.020	0.0093				0.2800	185
	Aquatic Acute	Colorado	7.9432		0.3400			0.0047		0.0160		0.0240		0.1253		3.6647			0.7879		0.018	0.00585				0.2800	185
	Warm Water Fish 1-hr	Utah	0.750		0.340			0.006		1.401		0.0378	1.0	0.2086					1.1861		0.018	0.021				0.300	300
Aquatic Life Chronic	Warm Water Fish 4-day	Utah			0.150			0.001		0.1822		0.0229	1.0	0.00813			0.000012		0.132		0.005					0.300	300
	Chronic Warm Water	Ute Mountain Ute			0.150			0.000465		0.1570		0.0196		0.00672			0.000012		0.113		0.005	0.001				0.257	250
	Chronic Agri. and Wildlife	Navajo Nation	0.0870	0.030	0.150			0.0005				0.0196		0.0067			0.000001		0.1129		0.002			0.150		0.2568	250
	Aquatic Chronic	New Mexico	3.1824		0.150			0.000705		0.0110		0.0151		0.0049		2.0247	0.00077	1.8950	0.088		0.005					0.2120	185
	Aquatic Chronic	Colorado	1.134		0.150			0.000674		0.0110		0.0151	1.0	0.00488		2.0247	0.00001		0.0875		0.00460	0.0009		0.0150		0.2120	185

[&] Chromium: State and Tribal criteria specify criteria by valence state. Criteria for CrVI were applied to CO and NM; CrIII were applied to Utah; Criteria for CAS 7440-473 were applied to Navajo Nation

Unlike for human exposure, exposure of fish and wildlife to effects of the Gold King Mine release could not be managed. Initial impacts to organisms during the plume were likely acute in nature due to the initial pulse exposure. Subsequent effects may occur from chronic exposures to metals sequestered in the streambed, which occur over longer periods. The upper Animas River has a history of such contamination (Church *et al.* 2007), to which the Gold King Mine release added fresh material.

Potential exposures to metals during passage of the Gold King plume through the Animas and San Juan Rivers was performed by screening the empirically-modeled plume to the magnitude threshold of the water quality criteria. Samples were not specifically screened, because the empirical model included all samples collected during the migration of the plume. While the analysis estimated the time period that the magnitude component of state and tribal criteria was exceeded, specific comparison to the duration and frequency components of state and tribal criteria was beyond the scope of this study.

7.2 Gold King Mine Plume Exposure Screening Methods

The Gold King plume was assessed by comparing the modeled metals concentrations for each metal in each time step to the magnitude component of the appropriate criteria, and counting the hours that the magnitude component of a criteria was exceeded. The plume passed as a rise and fall in concentration within a time period so duration of exposure would have been sequential. State or tribal criteria appropriate to the location of the site were applied. However, due to differences in criteria between states, there were abrupt changes in applied criteria along the route of the plume as it moved through three states. EPA's risk screening threshold for recreational contact following the GKM release was also applied, as EPA screened with this risk threshold during the plume, and for the extensive length of the San Juan River that flows through tribal lands. NNEPA or UMUT criteria for metals were also applied. UDEQ (2016b) documented a similar screening of water samples from the GKM release to their state criteria; those same criteria were applied at the Utah sites in this analysis.

Some designated use criteria are hardness-based. Criteria thresholds decline with the hardness of the water. Hardness measures during the passage of the plume were limited, however. Hardness increases in the lower Animas and San Juan River as it flows westward. Samples collected by NMED in the lower Animas River on August 8, 2015 ranged from 180–200 mg/L, averaging 185 mg/L. A hardness value of 185 mg/L was applied to the entire length of the Animas River during the plume passage. Hardness sampled in the San Juan River at Farmington, New Mexico during the same period ranged from 190–230 mg/L. A hardness value of 250 mg/L was used for the upper and middle San Juan River and a value of 300 mg/L was applied to the lower San Juan. Tribal criteria were applied at sites using the corresponding state's hardness value.

A specific accounting of metals concentrations at sites in the Animas and San Juan Rivers are given relative to these criteria. Assignment of criteria was also attentive to designated uses at the reach scale. This was important in the upper Animas River, where Cement Creek has no designated uses and in the Animas River near Silverton, which has very limited uses. The screening applied to the plume counts the hours that criteria were exceeded. No time duration assumptions were applied in the counting.

7.3 Gold King Plume Water Quality Screening Results

Given the relatively short temporal period of the plume, the aquatic acute criteria were the most relevant for evaluating the immediate potential impact of the plume on aquatic life. Other uses of the Animas and San Juan Rivers, including domestic supply, agricultural consumption, and recreation and human contact use were curtailed for a number of days during and after passage of the plume to minimize exposure. The number of hours that criteria were exceeded for each metal at each of the empirically-modeled locations in the Animas and San Juan Rivers, as the Gold King plume passed, are provided by water use category in Tables 7-2 through 7-6 and for tribal criteria in Tables 7-7 and 7-8:

- Table 7-2 – Recreation
- Table 7-3 – Domestic water
- Table 7-4 – Agricultural criteria (agriculture and irrigation)
- Table 7-5 – Aquatic acute criteria
- Table 7-6 – Aquatic chronic criteria
- Table 7-7 – Navajo Nation criteria
- Table 7-8 – Ute Mountain Ute Tribe criteria

Although the headwaters of the Animas River have historically been contaminated with metals from mining and acid mine drainage, concentrations in the water during the passage of the Gold King plume were orders of magnitude higher than typically occur. As the GKM plume was delivered to the Animas River and traveled downstream, the duration of the plume increased with flow drag and concentrations of dissolved and total metals declined sharply, indicating dilution and deposition of colloidal/particulates in the upper Animas reaches. This same pattern was mirrored in water quality criteria exceedances.

As expected, exceedances of the magnitude component of various water quality criteria attributable to the Gold King release were greatest in the headwaters section of the Animas River, as shown in Tables 7-2 through 7-6. (Cement Creek has no designated uses and was not screened. The Animas at Silverton also has more limited designated uses. The Animas River in the vicinity of Silverton is not designated for domestic supply; therefore, those criteria were not applied there.

Despite the high initial metals concentrations in the GKM plume, several metals did not exceed criteria for any designated uses. These included antimony, beryllium, chromium, molybdenum, and vanadium. Exceedances for most of the other metals occurred between Silverton and Bakers Bridge, Colorado (RK 16.4–64), with some extending as far as the sampling location at RK 132, downstream of Durango. Exceptions to this included aluminum and lead, and more infrequently, arsenic, barium, nickel, and silver. Hours exceeding criteria generally declined with distance for all designated uses and metals through the length of the Animas River.

Recreation criteria for several metals (cadmium, cobalt, copper, lead, manganese, and thallium) were exceeded at Silverton only (Table 7-2). Domestic supply criteria for lead were exceeded from the duration of the plume through the upper and middle Animas within Colorado (approximately RK 16.4 to 140). Cadmium had very brief excursions above criteria. Criteria related to agriculture or irrigation were exceeded for arsenic, copper, lead, and manganese for a number of hours as far downstream as RK 132 (Table 7-4).

Exceedance of aquatic acute criteria (typically a concentration not to exceed for 96 hours, except in Utah where duration is one day) was uncommon (Table 7-5).

Reflecting the strongly declining metals concentrations in the lower Animas River, aquatic acute criteria were exceeded primarily in the upper Animas above Bakers Bridge (RK 64) although aluminum criteria were exceeded in the Animas as far as Aztec, New Mexico (RK 164). Exceedances for aluminum occurred during the plume in the San Juan River.

Table 7-2. Hours Exceeding Magnitude Component of Recreational Use Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model were screened using the criteria from Table 7-1 appropriate to the site, based on state criteria (indicated at bottom of column). Only Utah has recreational criteria, so EPA Region 6 criteria were applied to other sites. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Hours At or Above Criteria During Passage of GKM Plume

Recreation	Animas River						San Juan River				
	Below Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94)	NAR06 (RK 132)	Aztec (RK 164)	Farmington (RK 190)	Farmington (RK 196)	Shiprock (RK 246)	Four Corners (RK 296)	Bluff (RK 377)	Mexican Hat (RK 421)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybdenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria Used:	EPA Region 6	EPA Region 6	EPA Region 6	EPA Region 6	EPA Region 6	EPA Region 6	EPA Region 6	EPA Region 6	UT	UT	UT
							Navajo Nation				
								Ute Mountain Ute Tribe			

Table 7-3. Hours Exceeding Magnitude Component of Domestic Use Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model were screened using the criteria from Table 7-1 appropriate to the site, based on location (indicated at bottom of column). The Animas below Silverton location was not screened for this criteria. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Domestic Water	Hours At or Above Criteria During Passage of GKM Plume										
	Animas River						San Juan River				
	Below Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94)	NAR06 (RK 132)	Aztec (RK 164)	Farmington (RK 190)	Farmington (RK 196)	Shiprock (RK 246)	Four Corners (RK 296)	Bluff (RK 377)	Mexican Hat (RK 421)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	0.00	2.75	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	0.00	38.50	34.00	32.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybdenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria Used:	CO	CO	CO	CO	NM	NM	NM	NM	UT	UT	UT
							Navajo Nation				
								Ute Mountain Ute Tribe			

Table 7-4. Hours Exceeding Magnitude Component of Agricultural Use Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model were screened using the criteria from Table 7-1 appropriate to the site, based on location (indicated at bottom of column). Definition and naming of agricultural criteria varies by state. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Agriculture / Irrigation	Hours At or Above Criteria During Passage of GKM Plume										
	Animas River						San Juan River				
	Below Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94)	NAR06 (RK 132)	Aztec (RK 164)	Farmington (RK 190)	Farmington (RK 196)	Shiprock (RK 246)	Four Corners (RK 296)	Bluff (RK 377)	Mexican Hat (RK 421)
Aluminum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	8.00	4.50	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	6.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	10.75	6.75	5.25	3.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	13.75	36.75	23.50	24.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	13.75	37.25	15.75	15.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybdenum	2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	6.75	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria Used:	CO	CO	CO	CO	NM	NM	NM	NM	UT	UT	UT
							Navajo Nation				
								Ute Mountain Ute Tribe			

Table 7-5. Hours Exceeding Magnitude Component of Aquatic Acute Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model were screened using the criteria from Table 7-1 appropriate to the site, based on location (indicated at bottom of column). Many aquatic acute criteria for individual metals vary by hardness. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Aquatic Acute	Hours At or Above Criteria During Passage of GKM Plume										
	Animas River						San Juan River				
	Below Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94)	NAR06 (RK 132)	Aztec (RK 164)	Farmington (RK 190)	Farmington (RK 196)	Shiprock (RK 246)	Four Corners (RK 296)	Bluff (RK 377)	Mexican Hat (RK 421)
Aluminum	9.50	5.25	5.00	5.75	2.50	0.00	18.00	18.00	0.00	0.00	8.00
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	7.00	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	10.50	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	5.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybdenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	13.75	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria Used:	CO	CO	CO	CO	NM	NM	NM	NM	UT	UT	UT
							Navajo Nation				
								Ute Mountain Ute Tribe			

Table 7-6. Hours Exceeding Magnitude Component of Aquatic Chronic Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model were screened using the criteria from Table 7-1 appropriate to the site, based on location (indicated at bottom of column). Many aquatic acute criteria for individual metals vary by hardness. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Aquatic Chronic	Hours At or Above Criteria During Passage of GKM Plume										
	Animas River						San Juan River				
	Below Silverton (RK 16.4)	Bakers Bridge (RK 64)	Durango (RK 94)	NAR06 (RK 132)	Aztec (RK 164)	Farmington (RK 190)	Farmington (RK 196)	Shiprock (RK 246)	Four Corners (RK 296)	Bluff (RK 377)	Mexican Hat (RK 421)
Aluminum	13.75	36.75	32.25	37.75	11.00	16.75	18.00	18.00	21.50	16.75	16.75
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beryllium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cadmium	13.75	7.50	5.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chromium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	10.50	7.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iron	13.75	40.00	37.25	44.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Manganese	7.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Molybdenum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nickel	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selenium	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silver	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thallium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc	13.75	8.25	1.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Criteria Used:	CO	CO	CO	CO	NM	NM	NM	NM	UT	UT	UT
							Navajo Nation				
								Ute Mountain Ute Tribe			

Table 7-7. Hours Exceeding Magnitude Component of Navajo Nation Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model at each site within the Navajo Nation were screened using the Navajo Nation criteria from Table 7-1. Aquatic acute and chronic criteria vary by hardness for individual metals. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

		Navajo Nation Criteria (San Juan River)--Hours At or Above Criteria During Passage of GKM Plume																		
Beneficial Use	Location	Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Iron	Lead	Manganese	Molybdenum	Nickel	Selenium	Silver	Thallium	Vanadium	Zinc
Primary Human Contact	Farmington (RK 196)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mexican Hat (RK 421)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Secondary Human Contact	Farmington (RK 196)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mexican Hat (RK 421)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Agricultural Supply	Farmington (RK 196)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mexican Hat (RK 421)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Livestock and Wildlife Watering	Farmington (RK 196)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aquatic Acute	Farmington (RK 196)	20.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mexican Hat (RK 421)	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aquatic Chronic	Farmington (RK 196)	20.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.75	0.00	0.00	0.00	0.00
	Shiprock (RK 246)	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 377)	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.75	0.00	0.00	0.00	0.00
	Mexican Hat (RK 421)	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.75	0.00	0.00	0.00	0.00

Table 7-8. Hours Exceeding Magnitude Component of Ute Mountain Ute Tribe Criteria During Passage of the Gold King Mine (GKM) Plume in the Animas and San Juan Rivers. Water concentrations estimated by the empirical model at each site within the Ute Mountain Ute reservation were screened using the Ute Mountain Ute criteria from Table 7-1. Criteria for aquatic acute and chronic criteria for individual metals vary by hardness. Table values are color coded based on relative difference within spreadsheet values to assist the reader in finding values in the table; colors are not based on importance of hours.

Ute Mountain Ute Tribe Criteria (San Juan River)--Hours At or Above Criteria During Passage of GKM Plume

Beneficial Use	Location	Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Chromium	Cobalt	Copper	Iron	Lead	Manganese	Molybdenum	Nickel	Selenium	Silver	Sodium	Thallium	Vanadium	Zinc
Drinking Water	Shiprock (RK 246)	18.00	0.00	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	21.50	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 421)	16.75	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ceremonial and other contact	Shiprock (RK 246)	18.00	0.00	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	21.50	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 421)	16.75	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Agriculture	Shiprock (RK 246)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	13.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 421)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Warmwater Aquatic Acute	Shiprock (RK 246)	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	21.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 421)	16.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Warmwater Aquatic Chronic	Shiprock (RK 246)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Four Corners (RK 296)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bluff (RK 421)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Total aluminum exceeded aquatic acute criteria through most of the length of the Animas and San Juan Rivers. Aluminum and iron oxides were among the major components of the yellowboy in the Gold King plume. Aluminum concentrations declined below criteria in the Animas River at Farmington, but then increased significantly after joining the San Juan River, which was carrying high concentrations of sediment with elevated aluminum and iron concentrations (see Chapter 5). Iron was also prevalent in the plume, but has relatively few assigned criteria, so the plume did not trigger many exceedances. It should be noted that aquatic acute criteria for aluminum mostly reference total metals (except in Utah where dissolved criteria are applied; Table 7-1). Criteria based on total concentrations were more likely to be exceeded than those based on the dissolved fraction due to the chemistry of the GKM plume.

Concentration values for aquatic chronic criteria are lower than acute criteria (Table 7-1), as these criteria reflect prolonged exposure, generally considered 30 days (with exception of Utah and the Ute Mountain Ute Tribe, which apply a 4-day criteria). Chronic criteria for Colorado and New Mexico designate dissolved concentrations for most metals, except for aluminum, which are applied as total concentrations (see Table 7-1 for specific metals). While exceedances of aquatic acute criteria were observed for copper, zinc, cadmium, lead, and manganese for brief periods as far downstream as Durango, Colorado (RK 94), aquatic chronic criteria were exceeded for a longer length of the river, and in addition to those metals, iron, nickel, selenium, and silver were in exceedance as well (Table 7-6). As with the aquatic acute criteria, aluminum exceeded aquatic chronic criteria throughout the Animas and San Juan Rivers.

The Mountain Studies Institute monitored water quality during plume passage in Durango (MSI 2016) and reported that acute aquatic criteria for aluminum were exceeded at the peak of the plume and that lead exceeded domestic water supply criteria for a period of 26 hours. They noted that fish and benthic macroinvertebrates in the Durango reach of the Animas River largely survived the Gold King Mine release based on reports from the Colorado Parks and Wildlife Department and their own studies. During the period of high lead concentrations, the City of Durango and other public water suppliers preemptively shut off their intake valves so they did not receive any drinking water from the Animas River during that time. The EPA Emergency Response Team that coordinated the local response encouraged private citizens to do so as well.

The Navajo Nation extends along the length of the San Juan River affected by the Gold King plume. NNEPA has adopted water quality criteria for water uses specific to tribal lands (See Table 7-1); these criteria were applied to all sites on the San Juan River (Table 7-7). Most notable was the exceedance of lead for primary and secondary human contact, agricultural supply, and livestock and wildlife monitoring for the length of the San Juan River. Although lead was generally higher with background sediment in the river, correlation analyses discussed in Chapter 5 showed that lead was elevated above background levels during the Gold King plume at least as far as Four Corners (RK 296). Aluminum criteria for acute and chronic aquatic life were also exceeded at the time the Gold King plume moved through the Navajo Nation lands.

The Ute Mountain Ute Tribe has reservation lands that adjoin the San Juan River beginning in Four Corners and ending between Aneth and Bluff, Utah. The tribe has adopted water quality criteria for this length of the river (Table 7-1); these criteria were applied to the two sites within that stretch of the river - Four Corners (RK 296) and Bluff (RK 377), as shown in Table 7-8. During the time that the Gold King plume passed these locations, lead, arsenic, and aluminum exceeded the criteria for drinking water and ceremonial and other contact. Aluminum criteria for acute aquatic life were also exceeded for most of the duration of the plume.

7.4 Summary of GKM Plume Exceedances

The metals that exceeded the magnitude component of criteria most frequently during the passage of the Gold King plume were lead and aluminum. A summary of those exceedances throughout the Animas and San Juan Rivers is shown in Tables 7-9 and 7-10, respectively.

Criteria for domestic supply, human contact, and agricultural criteria were exceeded for these metals; however, these uses were curtailed and the public was advised to avoid water contact throughout the length of the Animas and San Juan Rivers during the Gold King plume passage to minimize the potential for human exposure. Initial impacts to aquatic organisms during passage of the GKM plume, however, were expected to have been acute in nature due to the initial pulse exposure. For the most part, aquatic acute criteria were not exceeded during the GKM plume, with exception of aluminum criteria, which were exceeded through much of the Animas and parts of the San Juan River, and several hours of excursions above thresholds for cadmium, copper, lead, manganese, and zinc in the Animas River from Silverton to Durango (RK 94). The acute threshold values have inherent assumptions regarding duration of exposure that were generally longer than the duration of the Gold King plume. The very high concentrations that characterized the plume lasted for hours, and the full plume duration was less than 48 hours, with concentrations dropping significantly from peak highs during that time.

Most exceedances matched the period of highest concentrations in the core of the plume, but some, such as aluminum and iron, occurred for a longer duration. In the San Juan River, exceedances occurred during passage of the Gold King plume, but it should be noted that background metals concentrations in the San Juan may have also contributed. Lead, copper, zinc, and arsenic concentrations in the Gold King plume were equal to or greater than background concentrations in the San Juan River as the plume moved through the system (see Figure 5-17), although only lead and zinc had greater mass than background sediments (see Figure 6-5). Elevated levels of lead were detected at least as far as Four Corners (RK 296), before the signal was difficult to detect in the background metals load (see Figure 5-17), yet tribal criteria for Navajo and Ute Mountain Ute waters were exceeded for lead (and aluminum) beyond that location. Iron and aluminum made up a significant portion of the Gold King plume mass (Figure 3-19). As can be seen from Table 7-9, aluminum criteria were exceeded in a number of locations in the Animas and San Juan Rivers for a variety of designated uses, most notably the acute aquatic criteria. Although aluminum was a major component of the plume, total aluminum concentration increased significantly when the plume entered the San Juan River due to the aluminum content of the background sediment (Figure 6-5).

MSI (2016) provided a report on metals concentrations during and after the plume at Durango, Colorado, and UDEQ has periodically published reports on post-event water quality sampling for the San Juan River in Utah (UDEQ 2015). Post-event monitoring of fish and aquatic health is ongoing and is part of the monitoring plan for the Animas and San Juan Rivers adopted in EPA's Post-Gold King Mine Release Incident: Conceptual Monitoring Plan for Surface Water, Sediments, and Biology (2016).

Studies of fish and benthic communities have been conducted in the Animas River following the Gold King plume. Mountain Studies Institute recently released a report on studies of benthic macroinvertebrate (BMI) communities in the upper Animas River following the Gold King release through Fall 2015 (MSI 2016). This study found benthic macroinvertebrate populations in the Animas River from Silverton to Durango appear to have largely survived exposure to the high metals concentration associated with the Gold King Mine release. Colorado Parks and Wildlife data indicate that fish populations in the Animas River were not generally impacted by the Gold King Mine release either (White 2016). All species present before the plume were present after the plume, and there were no differences in BMI community health metrics from 2014–2015, although copper tissue concentrations were higher in 2015 than in 2014 at sites affected by the Gold King Mine release.

Post Gold King release effects on water quality in the fourteen months since the passage of the plume through the Animas and San Juan Rivers (from August 2015 through October 2016) will be analyzed further in Chapter 9.

Table 7-9. Summary of Estimated Magnitude Exceedances for Total (T) and Dissolved (D) Lead for All Criteria During the Gold King Plume. Water concentrations estimated by the empirical model at each site were screened using criteria from Table 7-1 appropriate to the site, based on location indicated in the water use column.

LEAD

Hours At or Above Criteria During Passage of GKM Plume

			ANIMAS RIVER						SAN JUAN RIVER				
			Silverton		Durango	SUIT	Aztec	Farmington	Farmington	Shiprock	Four Corners	Bluff	Mexican Hat
			Distance from Gold King Mine (km)										
	Water Use	Criteria Applied mg/L	16.4	64	94	132	164	190	196	246	296	377	421
Domestic Supply 1-Day	Colorado	T 0.05	--	39	34	33	--	--	--	--	22	--	--
Agriculture	Colorado	T 0.10	--	37	24	24	--	--	--	--	14	--	--
Aquatic Acute	Colorado	D 0.125	2	0	0	0	--	--	--	--	0	--	--
Aquatic Chronic	Colorado	D 0.005	7	0	0	0	--	--	--	--	0	--	--
				COLORADO							CO		
Domestic Supply	New Mexico	D 0.015	--	--	--	--	0	0	0	0	--	--	--
Irrigation	New Mexico	D 5.0	--	--	--	--	0	0	0	0	--	--	--
Livestock	New Mexico	D 0.10	--	--	--	--	0	0	0	0	--	--	--
Wildlife Habitat	New Mexico	None	--	--	--	--	--	--	--	--	--	--	--
Aquatic Acute	New Mexico	D 0.125	--	--	--	--	0	0	0	0	--	--	--
Aquatic Chronic	New Mexico	D 0.005	--	--	--	--	0	0	0	0	--	--	--
								NEW MEXICO					
Domestic Source	Utah	D 0.015	--	--	--	--	--	--	--	--	0	0	0
Recreational	Utah	T 0.91	--	--	--	--	--	--	--	--	0	0	0
Irrigation (short-term)	Utah	D 10.0	--	--	--	--	--	--	--	--	0	0	0
Irrigation (long-term)	Utah	D 5.0	--	--	--	--	--	--	--	--	0	0	0
Agricultural Uses	Utah	D 0.1	--	--	--	--	--	--	--	--	0	0	0
Livestock	Utah	D 0.1	--	--	--	--	--	--	--	--	0	0	0
Warm Water Fish 1-hr	Utah	D 0.209	--	--	--	--	--	--	--	--	0	0	0
Warm Water Fish 4-day	Utah	D 0.008	--	--	--	--	--	--	--	--	0	0	0
												UTAH	
Domestic Water Supply	Navajo Nation	T 0.015	--	--	--	--	--	--	19	18	22	17	17
Primary Human Contact	Navajo Nation	T 0.015	--	--	--	--	--	--	19	18	22	17	17
Secondary Human Contact	Navajo Nation	T 0.015	--	--	--	--	--	--	19	18	22	17	17
Agricultural Supply	Navajo Nation	T 10.0	--	--	--	--	--	--	0	0	0	0	0
Livestock Watering	Navajo Nation	T 0.10	--	--	--	--	--	--	11	11	14	2	5
Acute Ag and Wildlife	Navajo Nation	D 0.172	--	--	--	--	--	--	0	0	0	0	0
Chronic Ag and Wildlife	Navajo Nation	D 0.007	--	--	--	--	--	--	0	0	0	0	0
											NAVAJO NATION		
Drinking Water	**Ute Mountain Ute**	T 0.05	--	--	--	--	--	--	--	17	22	17	--
Cermenonial and Other	**Ute Mountain Ute**	T 0.05	--	--	--	--	--	--	--	17	22	17	--
Agriculture	**Ute Mountain Ute**	T 0.10	--	--	--	--	--	--	--	11	14	2	--
Warm Water Fish-Acute	**Ute Mountain Ute**	D 0.172	--	--	--	--	--	--	--	0	0	0	--
Warm Water Fish-Chronic	**Ute Mountain Ute**	D 0.007	--	--	--	--	--	--	--	0	0	0	--
											UTE MOUNTAIN UTE TRIBE		

Table 7-10. Summary of Estimated Magnitude Exceedances for Total (T) and Dissolved (D) Aluminum for All Criteria During the Gold King Plume. Water concentrations estimated by the empirical model at each site were screened using criteria from Table 7-1 appropriate to the site, based on location indicated in the water use column.

ALUMINUM

Hours At or Above Criteria During Passage of GKM Plume

			ANIMAS RIVER						SAN JUAN RIVER				
			Silverton		Durango	SUIT	Aztec	Farmington	Farmington	Shiprock	Four Corners	Bluff	Mexican Hat
		Criteria	Distance from Gold King Mine (km)										
	Water Use	Applied mg/L	16.4	64	94	132	164	190	196	246	296	377	421
Domestic Supply 1-Day	Colorado	T 0.05	0	0	0	0	--	--	--	--	0	--	--
Agriculture	Colorado	T 0.10	0	0	0	0	--	--	--	--	0	--	--
Aquatic Acute	Colorado	D 0.1217	10	5	5	6	--	--	--	--	22	--	--
Aquatic Chronic	Colorado	D 0.0047	14	37	32	38	--	--	--	--	22	--	--
				COLORADO							CO		
Domestic Supply	New Mexico	D 0.015	--	--	--	--	0	0	0	0	--	--	--
Irrigation	New Mexico	D 5.0	--	--	--	--	0	0	0	0	--	--	--
Livestock	New Mexico	D 0.10	--	--	--	--	0	0	0	0	--	--	--
Wildlife Habitat	New Mexico	None	--	--	--	--	--	--	--	--	--	--	--
Aquatic Acute	New Mexico	D 0.145	--	--	--	--	3	0	20	18	--	--	--
Aquatic Chronic	New Mexico	D 0.0056	--	--	--	--	11	17	20	18	--	--	--
								NEW MEXICO					
Domestic Source	Utah		--	--	--	--	--	--	--	--	0	0	0
Recreational	Utah	T 621	--	--	--	--	--	--	--	--	0	0	0
Irrigation (short-term)	Utah	D 20.0	--	--	--	--	--	--	--	--	0	0	0
Irrigation (long-term)	Utah	D 5.0	--	--	--	--	--	--	--	--	0	0	0
Agricultural Uses	Utah		--	--	--	--	--	--	--	--	0	0	0
Livestock	Utah	D 5.0	--	--	--	--	--	--	--	--	0	0	0
Warm Water Fish 1-hr	Utah	D 0.75	--	--	--	--	--	--	--	--	0	0	0
Warm Water Fish 4-day	Utah	D 0.087[1]	--	--	--	--	--	--	--	--	22	22	17
												UTAH	
Domestic Water Supply	Navajo Nation		--	--	--	--	--	--	0	0	0	0	0
Primary Human Contact	Navajo Nation		--	--	--	--	--	--	0	0	0	0	0
Secondary Human Contact	Navajo Nation		--	--	--	--	--	--	0	0	0	0	0
Agricultural Supply	Navajo Nation	D 5.0	--	--	--	--	--	--	0	0	0	0	0
Livestock Watering	Navajo Nation		--	--	--	--	--	--	0	0	0	0	0
Acute Ag and Wildlife	Navajo Nation	T 0.75	--	--	--	--	--	--	20	18	22	17	17
Chronic Ag and Wildlife	Navajo Nation	T 0.087	--	--	--	--	--	--	20	18	22	17	17
											NAVAJO NATION		
Drinking Water	Ute Mountain Ute	T 0.20	--	--	--	--	--	--	--	18	22	17	--
Cermenonial and Other	Ute Mountain Ute	T 0.20	--	--	--	--	--	--	--	18	22	17	--
Agriculture	Ute Mountain Ute		--	--	--	--	--	--	--	0	0	0	--
Warm Water Fish-Acute	Ute Mountain Ute	T 0.75	--	--	--	--	--	--	--	0	0	0	--
Warm Water Fish-Chronic	Ute Mountain Ute	T 0.087[1]	--	--	--	--	--	--	--	0	0	0	--
											UTE MOUNTAIN UTE TRIBE		

[1]out of pH and hardness range

CHAPTER 8 POTENTIAL GROUNDWATER EFFECTS

The Gold King plume passed through the Animas and San Juan Rivers over the course of about 48 hours but continued to affect water quality to some extent for weeks after the plume passed. There were hundreds of water supply wells located in the floodplain of the Animas River of Colorado and New Mexico at the time of the release, some located within meters of the river, others kilometers away. Could the metals released from the Gold King Mine and transported through the river potentially also enter the floodplain aquifer and contaminate wells?

Most of the time the rivers continuously "gain" water from the surrounding groundwater aquifer as they flow from Silverton, Colorado (RK 16) to Farmington, New Mexico (RK 192) (Timmons *et al.* 2016). Generally, water flows from the surrounding terrain into the river and there is little if any movement of water from the river into the floodplain aquifer. With no exchange of water there would be no potential for well contamination during and following the event from elevated metals in the water or sediments. For wells to take in river water, the background gradient of subsurface flow would have to reverse. This could occur at locations where the river leaks water to the alluvium (i.e., a "losing" reach). This could occur locally in high permeability deposits in combination with the stream geomorphology, and would be sensitive to river stage. High-volume pumping can also reverse the natural direction of flow and draw water from the river into the alluvium. Many wells are private domestic wells that are primarily low-volume water pumpers and some were larger volume community wells.

This chapter explores the potential for dissolved metals associated with the GKM plume water of the Animas River to have moved out of the river, into the alluvial deposits, and through subsurface transport, potentially reached the pumping wells. The analysis centers on floodplain aquifers adjacent to the Animas River. A primary objective of this analysis was to identify wells, which due to their geographic setting or pumping history, could have had the potential for drawing GKM dissolved metals from river water in sufficient quantities to pose a potential hazard.

Groundwater modeling was used to investigate the potential for water movement from river to wells at the scale of alluvial valleys containing multiple wells, and at the local scale of an individual well. This chapter includes an overview of the groundwater movement and modeling results. Details on the step-wise modeling methods and supporting data are provided in Appendix D.

Teams from EPA and the states sampled community and private well water during the GKM response to address this concern. Groundwater movement requires time to travel through the subsurface medium underscoring a challenge to sampling groundwater in order to catch a transient event. Some measurements will be discussed at the end of this chapter.

8.1 River Communication with Wells: Conceptual

The Animas River alluvial aquifer is within the floodplain deposits that fill the valley between the surrounding terraces and mountains as it winds down from the headwaters at Silverton, Colorado to its confluence with the San Juan River in Farmington, New Mexico (Figure 8-1). The alluvial valley is filled with a thick layer of sediments left by migration of the river leaving behind a layer of heterogeneous mixture of gravels, sands, silts, and clays whose surface is called a floodplain. The shallow gravel deposits contain a mixture of sands, silts and clays. The aquifer contains the water that infills in the voids between the sediment. The river is in dynamic communication with the shallow alluvial aquifer. The Animas River is a "gaining" stream on a regional basis most of the time, with groundwater draining to the river. However, there are site-specific and temporal situations where a river reach is losing water to the groundwater system.

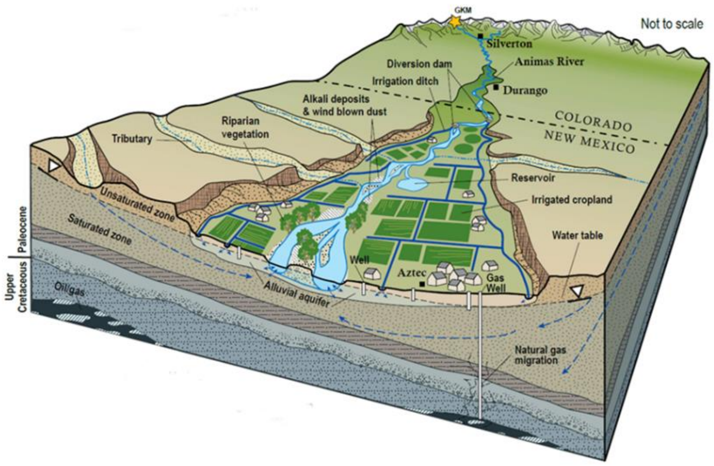


Figure 8-1. The shallow alluvial floodplain aquifer of the Animas River, with emphasis between Aztec and Farmington, New Mexico. (**Image from Timmons *et al*. 2016.)**

There are many water supply wells that tap into the aquifer, including large numbers of private households or domestic wells, community wells, and irrigation wells. Another important hydrologic feature is the use of irrigation ditches to divert the river water to satisfy agricultural fields throughout the floodplain. The wells depress the water table elevations; the irrigation ditches tend to elevate the water table elevations during the growing season. The local elevation of the river water in comparison to the local water table in the floodplain aquifer determines whether a reach is "gaining" groundwater or "losing" groundwater, assuming the sand and gravel streambed is permeable.

There is not much known about the Animas River alluvial aquifer in terms of the details of site-specific spatial heterogeneity and depth. It is aquifer heterogeneity that offers the potential for preferential pathways, or barriers, from the river to well. The USGS conducted a detailed study in the upper Animas River watershed near Eureka, Colorado, and a trench study revealed some of the complexity of the stratigraphy and gravel deposits (Vincent and Elliott 2007). The deposits include high-permeability sands and gravels and low-permeability silts (Figure 8-2).

A geophysical survey is the primary means to characterize the depth and permeability characteristics of an alluvial aquifer. The Animas Water Company invested in a geophysical/gravimetric survey of the floodplain aquifer of the mid Animas River watershed near Hermosa, Colorado, getting estimates of the base of the aquifer in five survey lines (i.e., cross-sections; Hasbrouck Geophysics 2003). The permeable deposits are suspected to be much deeper (i.e., 600–1000 feet) than the current depth of the community wells in this area (i.e., about 100 feet; Figure 8-3).

Movement of water through the aquifer can be simulated with software-based mathematical models that predict the movement of water through the deposited sediments, at rates determined by the permeability of the sediments and in directions determined by hydraulic gradient, which are largely dictated by topography. Groundwater modeling can assess how a pumping well located in the floodplain could induce dissolved solutes to enter the aquifer from the river passing by and eventually reach the well.

The effect of pumping wells can be demonstrated with the EPA Wellhead Analytic Element Model (WhAEM; https://www.epa.gov/exposure-assessment-models/whaem2000) as shown in Figure 8-4. In this figure, the hypothetical well is located about 45 m from the river. The area contributing water to the pumping well, or the well capture zone, is delineated by reverse streamline computations from the well.

The source water capture zone is defined by 64 streamlines emanating from the well. The well receives some of its water from the river, and some from water flowing toward the stream from upland areas. The degree of dilution can be inferred by the number of streamlines that come from the river compared to those that come from the upgradient aquifer. A breakthrough response to dissolved solute can be mapped by releasing forward particles from the river shoreline and recording arrival times at the well in a histogram. Nineteen particles were released from the river boundary as suggested by the capture zone streamlines. The time of arrival breakthrough, in days, at the pumping well is reported in a histogram, with five particles arriving 14 days after leaving the river. The suggested peak river concentration was diluted to about 8% (5/64). Flushing of the aquifer took place at least 65 days after plume passage. It is important to note that the model represents advective transport as steady state and does not account for dispersion, sorption, or transformation of solutes. The data do not support the inclusion of these transport processes in the well analysis. The influence of dispersion, sorption, and decay would be to reduce the concentrations arriving at the well and delay the arrival time of solute at the well. By not including these processes, the analysis is "conservative". By exploring scenarios that might be more likely to exhibit plume-to-well communication, more confidence can be placed in findings of a lack of potential for communication.

A)

B)

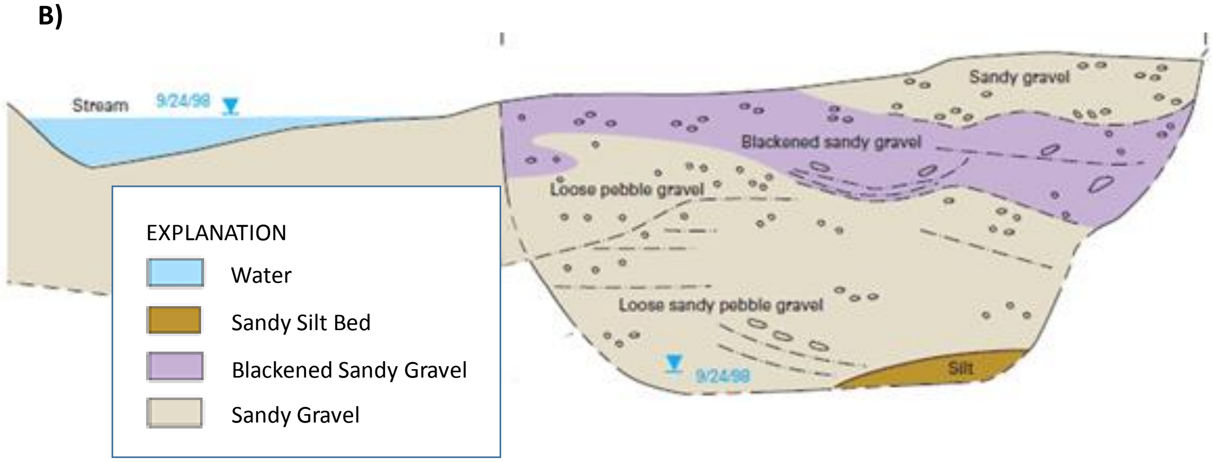


Figure 8-2. Animas River in floodplain near Eureka above Silverton, Colorado. A) GoogleEarth image showing braided dry channels and the approximate location of the geologic cross section. B) Generalized geologic cross section of the shallow floodplain deposits of the Animas River above Silverton modified from Vincent and Elliott (2007).

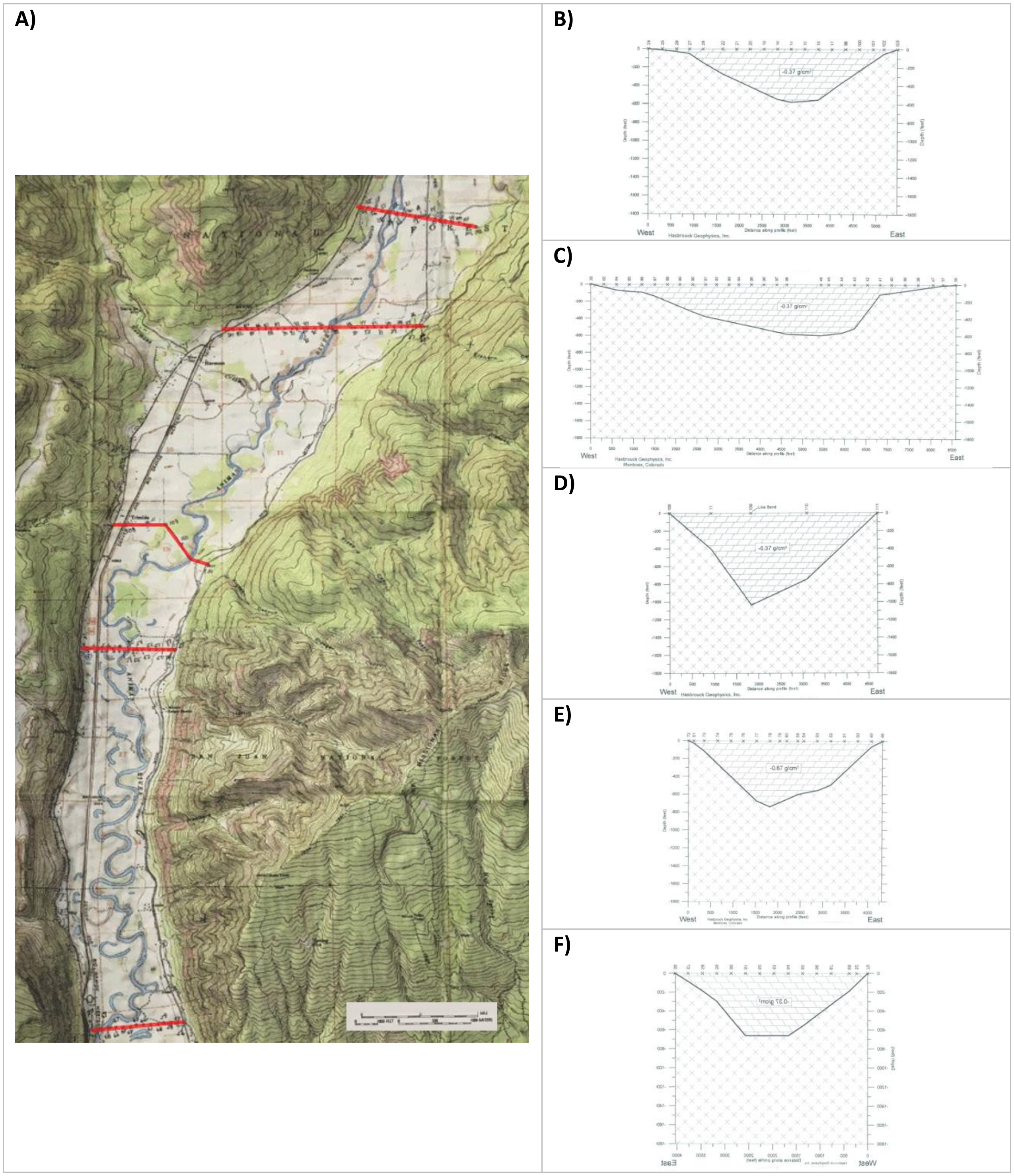


Figure 8-3. Geophysics modeling of the shallow floodplain aquifer base elevation based on a gravity survey: A) map of the five gravity survey lines; B) line 1 gravity and depth profile – 2-layer model; C) line 2; D) line 5; E) line 3; and F) line 4. Data source: Hasbrouck Geophysics (2003).

A)

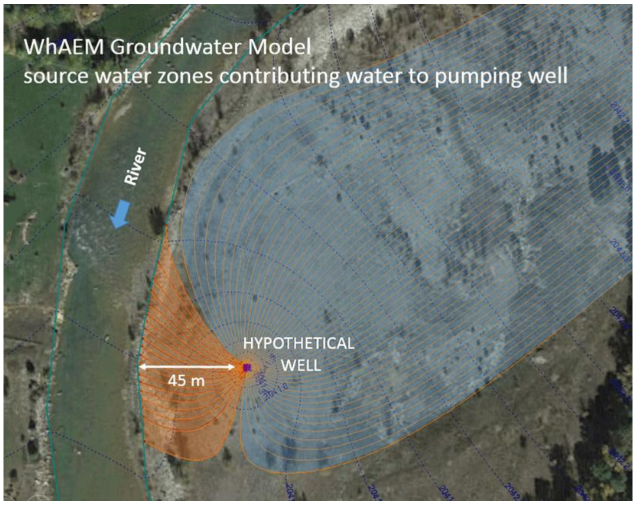


Image: GoogleEarth

B)

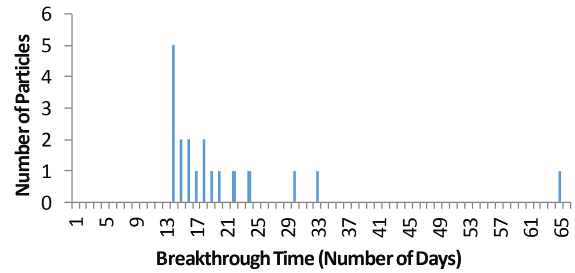


Figure 8-4. Demonstration of a pumping well capture zone and particle tracking breakthrough histogram using the Wellhead Analytic Element Model (WhAEM) of a hypothetical groundwater scenario. A) The well sources some of its water from the river (orange zone) and some from aquifer recharge and storage (blue zone). B) The breakthrough time histogram of particles released at the river shoreline and arriving at the pumping well.

This hypothetical case was under the situation where the Animas River was a gaining stream and the nearby pumping well needed to overcome the hydraulic head gradient in order to directly source river water, and with the river transporting a plume of dissolved metals, establishing a potential exposure pathway. This might be representative of a community well located in proximity to the river and continuously pumping relatively large volumes of water (i.e., hundreds gallons per minute). Under the conditions where the Animas River is a losing river, the natural hydraulic head gradient would potentially introduce dissolved solutes associated with a river plume into the groundwater aquifer, thus expanding the possible wells at risk to exposure to include nearby wells of lower pumping rates, such as domestic or household wells. A groundwater modeling investigation was chosen to further the understanding of these potential exposure pathways for two study areas where community and domestic/private wells are present: (1) the mid Animas River; and (2) the lower Animas River, as shown in Figure 8-5, and described in the next sections.

8.2 River Communication with Wells: Mid Animas River Floodplain

The mid Animas River floodplain has a known population of water supply wells, including a large number of private/domestic wells, and a limited number of community wells. It was the community well (35m66km) that had an elevated metals signal soon after the river plume passed (Figure 8-6), and this case will be investigated in more detail below.

What is the nature of groundwater/surface water interactions in this area? The long-term Animas River discharge reflects the annual cycle of late spring to early summer snowmelt runoff, with subsequent decreases in discharge, interrupted by rain events. This is demonstrated for the upper Animas River near Silverton, Colorado (Figure 8-7A). The difference between the sum of the cumulative daily stream flows and the measured daily streamflow at the USGS gage on the Animas River below Silverton is inferred to include contributing diffuse groundwater inflow (Q_{GW}) along the Animas River between the upgradient and downgradient stations. This reach of the Animas River around Silverton is understood to be a gently gaining stream most of the time, with groundwater draining toward the river, but with annual pulses of losing then gaining associated with late spring early summer snowmelt runoff, as shown in Figure 8-7B.

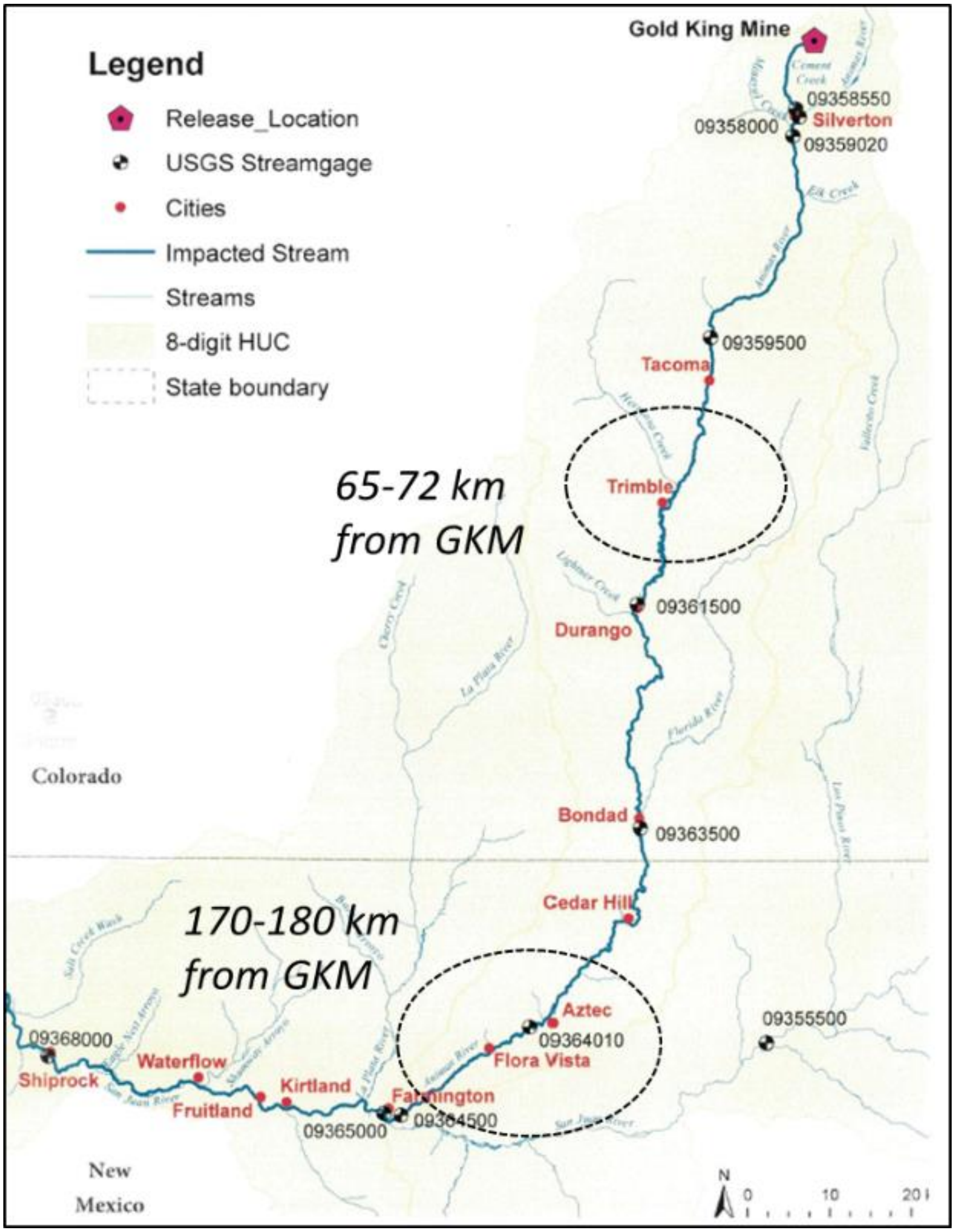


Figure 8-5. The mid Animas and lower Animas River clusters of community and private wells selected for groundwater modeling analyses. The mid Animas River groundwater study area is between Tacoma and Durango, Colorado, 65-72 km downstream of the Gold King Mine (GKM) release site. The lower Animas River groundwater study area is between Aztec and Farmington, New Mexico, 170-180 km downstream of GKM.

The goal of the computational modeling approach undertaken was to capture the essence of the regional groundwater flow system and explore the understanding of groundwater-surface water interactions under the influence of pumping wells. The step-wise and progressive modeling approach and calibration strategy (i.e., start simple, then add complexity) is described in detail in Appendix D.

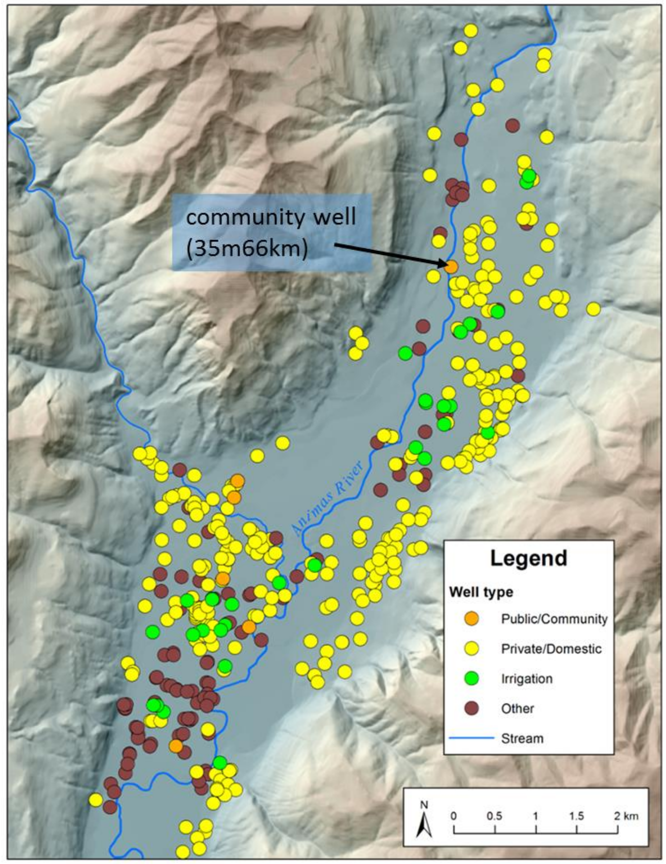


Figure 8-6. Water supply wells of the floodplain of the mid Animas River of Colorado (RK 65-72). The background is the topographic digital elevation model (DEM) and the hydrography of the USGS Hermosa Quad. Well data available from the Colorado Division of Water Resources (DWR) well permit search database. The community wells are represented by the orange circles, the private wells by the yellow circles.

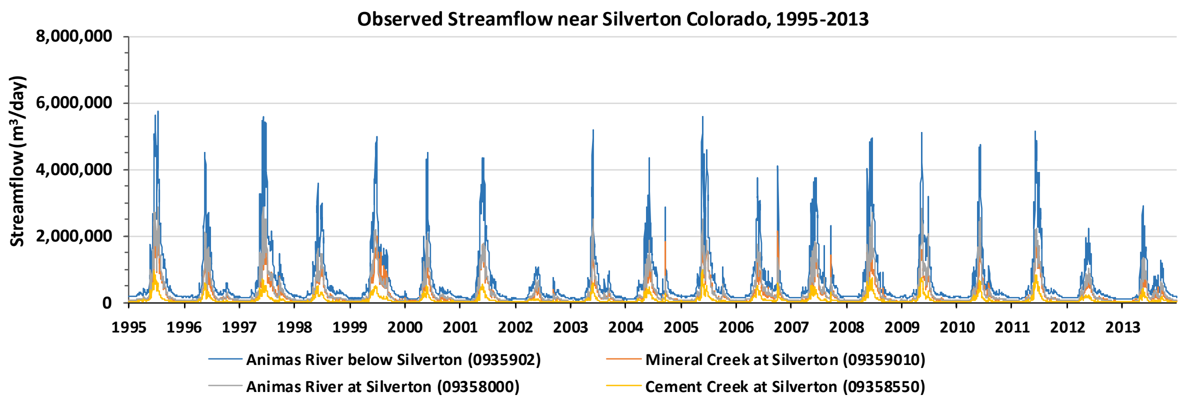
The analytic element computer program GFLOW (v.2.2.2; www.haitjema.com) was used to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). The GFLOW program is well documented and accepted within the groundwater modeling community (Hunt 2006; Yager and Neville 2002), particularly when applied to shallow groundwater flow systems involving groundwater/surface water interactions (Johnson and Mifflin 2006; Juckem 2009) and for recharge estimation (Dripps *et al*. 2006). The mathematical foundation of the semi-analytic model includes equations that express the physics of steady advective groundwater flow within a continuum; continuity of flow and Darcy's law are satisfied at the mathematical elementary volume.

Sometimes, conceptual complexity, particularly at the local scale, suggests numerical modeling techniques. For this project, the USGS MODFLOW-NWT and MODPATH (particle tracking) solvers were used within the Groundwater Modeling System (www.aquaveo.com, GMS v 10.1) to investigate the influences of fully three-dimensional flow, and transient pumping. The MODFLOW solver uses the finite difference numerical solution technique, with grid-based rows and columns defining three-dimensional cells, allowing simulations of multi-layer aquifers, non-horizontal base elevations, and opportunities to vary hydraulic conductivity, porosity, and storativity cell by cell (Harbaugh 2005). The MODFLOW solver has undergone 30 years of development and quality testing by USGS.

The Analytic Aquifer Simulation (AnAqSim) model (v.3, release 29 Sept 2016; www.fittsgeosolutions.com) was used for local scale modeling under the influence of aquifer heterogeneity and anisotropy of hydraulic conductivity. The AnAqSim model uses a hybridization of the analytic element method and finite difference method that divides the modeled region into subdomains, each with its own definition of aquifer parameters and its own separate analytical element model (Fitts 2010). This gives it strong capabilities with respect to heterogeneity and anisotropy. It also employs high-order line elements, spatially variable area sinks, and finite-difference time steps to allow multi-level aquifer systems and wide-ranging transient flow simulations.

The GFLOW model was used for the initial regional scale modeling of steady state flow. The regional models provide initial boundary conditions for local scale transient and full three-dimensional modeling using MODFLOW. The regional model also provided the boundary conditions for the local scale AnAqSim modeling of the influences of aquifer heterogeneities, such as buried river channels, and aquifer anisotropy caused by vertical stratification of sands and clay layers. The progression in conceptual complexity and the application of the GFLOW, MODFLOW, and AnAqSim models are mapped in Table 8-1.

A)



B)

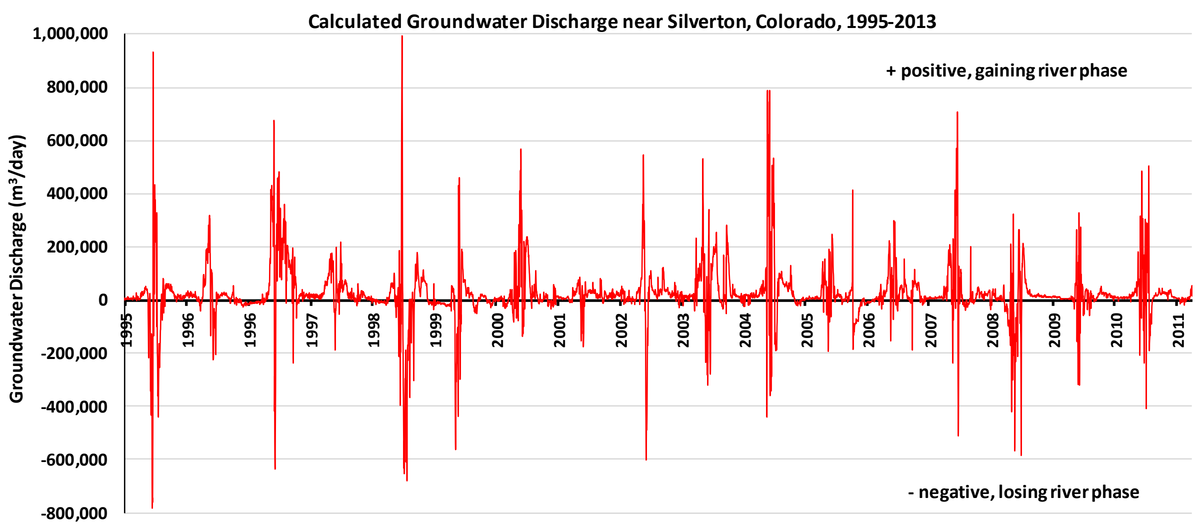


Figure 8-7. Streamflow analysis of the upper Animas River near Silverton, Colorado. A) Streamflow hydrographs of measured discharge (Q) in cubic meters per day of the Animas River and tributaries near Silverton, Colorado. B) Inferred groundwater inflows along the section of the Animas River near Silverton, CO, 1995-2013.

Table 8-1 Modeling Approach and Computer Codes.

	Spatial Scale	Conceptual Complexity	GFLOW	MODFLOW	AnAqSim
simple	Regional	Single layer infinite aquifer (piecewise homogeneous properties, horizontal base elevations, point sinks for wells, line-sinks for rivers, area elements for zoned recharge and aquifer properties), Dupuit Forchheimer assumption (neglect resistance to vertical flow; hydraulic heads constant with depth, horizontal 2D flow), Non-time variant (steady state) stress and flow	☑		
	Local	Extracted constant head outer boundary condition from regional model, time-variant (transient) stress and flow		☑	
	Local	Extracted constant head outer boundary condition from regional model, three dimensional flow		☑	
	Local	Extracted constant head outer boundary condition from regional model heterogeneous internal domains, anisotropy of hydraulic conductivity			☑
more complex	Both	Particle tracking (reverse – capture zones; forward – breakthrough response)	☑	☑	☑

The regional GFLOW model construction and calibration for the mid Animas River floodplain wells is described in Appendix D (Figure 8-8). Line-sinks are used to represent the rivers and creeks. A no-flow boundary is maintained at the catchment boundary or drainage area between the USGS gage on the Animas River at Tall Timbers resort, and the USGS gage on the Animas River near Durango. The flat alluvial floodplain is clearly revealed by the USGS digital elevation map and represented by area elements in the GFLOW model. The gravimetric estimate of aquifer thickness occurred at each of the scan lines previously described. These elevations were used to parameterize a stepping base representation in the GFLOW model, where each area element had a horizontal and impermable base.

The GFLOW model solved for the regional water balance for the August 2015 to October 2015 period, and was compared to observations based on USGS gaged water flows at Tall Timber Resort and Durango, Colorado. The GFLOW model output of hydraulic heads was compared to the static water levels reported at the time each of the wells was drilled. Model calibration is discussed in detail in Appendix D.

The GFLOW model predicted that only a small number of wells would source from the Animas River, and that all of them were located in the upper section between Bakers' Bridge and Hermosa. In Figure 8-9, hydraulic head contours are shown as dotted lines and the river flow is top to bottom (i.e., north to south). The gaining sections of the river are colored black; the losing sections are shown in green. Forward particle traces are shown in red, with residence time limited to 90 days' time-of-travel. Note there are three private domestic pumping wells located inside the hyporheic zone colored light red. In the regional mid Animas GFLOW model, well distances from the river ranged from 10 m to over 2000 m. The GFLOW model suggested that only three wells in the mid Animas River area sourced water from the river, and distances of these wells from the river ranged from 10–123 m. There were many wells within 123 m of the river that the model suggested do not source river water. Therefore, it could be that distance from the river alone is not predictive of well sourcing from the river.

The GFLOW model suggests a possible explanation. The model shows the river in the Baker's Bridge area would be losing water to the aquifer creating a hyporheic zone as shown in pink in Figure 8-9A. The three wells within this area would source water from the river and be potentially vulnerable to a river plume. Perhaps the geomorphology in this region is such that the Animas River flow spills into the floodplain aquifer deposits after traveling through the impervious metamorphic mountain geology. This is worthy of follow up field investigation.

The GFLOW regional model predicts that community well 35m66km would source from the Animas River under a variety of conditions (Figure 8-10). The GFLOW simulated breakthrough times with high-volume pumping and low porosity (n=0.25) was 25 days. Note that under the same high-volume pumping but with higher porosity (n=0.35), particle arrival was 44 days. The analysis suggests peak river concentration would be diluted to about 17% (2/12) and flushing of the aquifer occurs in about 160 days. A full sensitivity analysis on area recharge, hydraulic conductivity of aquifer material, and pumping rate of the well is described in Appendix D. The combination of parameters (i.e., low recharge, high alluvium hydraulic conductivity, high well pumping rate, low alluvium porosity) that creates the earliest breakthrough of 25 days is shown in Figure 8-10. As previously stated, the model represents steady averaged conditions (i.e., time invariant pumping and hydrology) and advective transport that does not account for dispersion, sorption, or decay of solute.

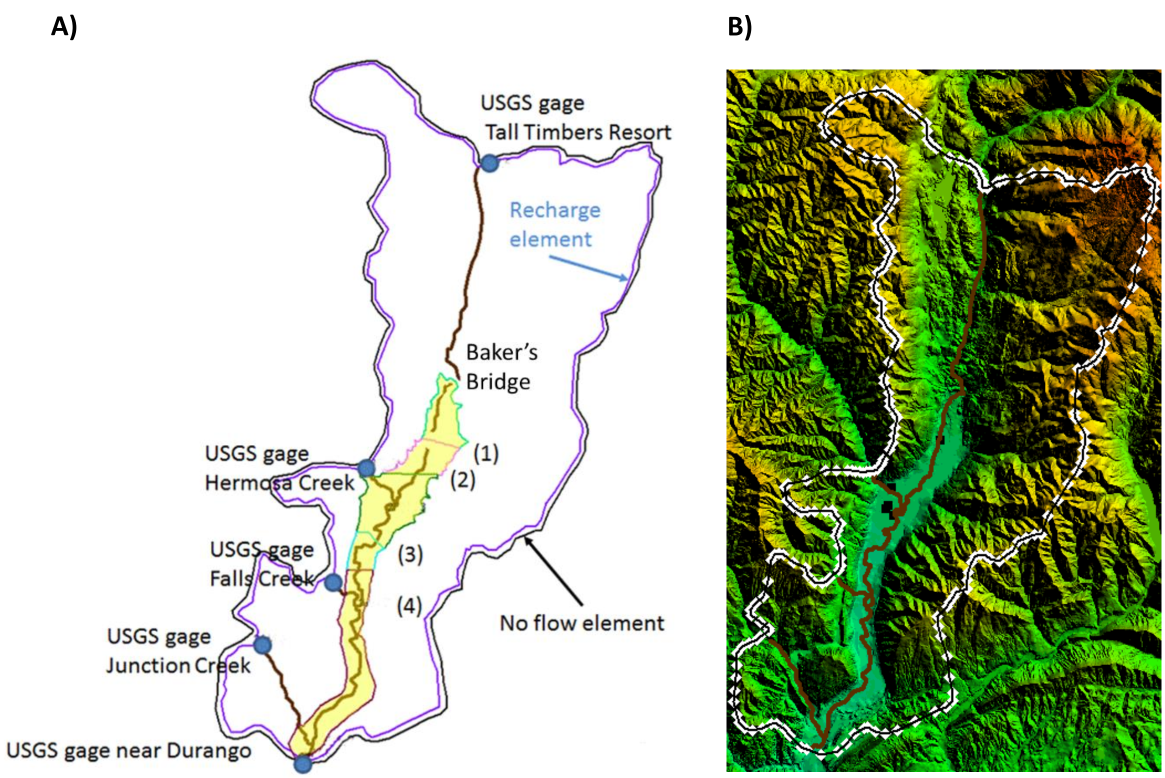


Figure 8-8. GFLOW analytic element groundwater model for the mid Animas River floodplain. A) Layout of analytic elements. B) The USGS digital elevation model (National Elevation Dataset 10m resolution) was used to define the catchment between USGS gages.

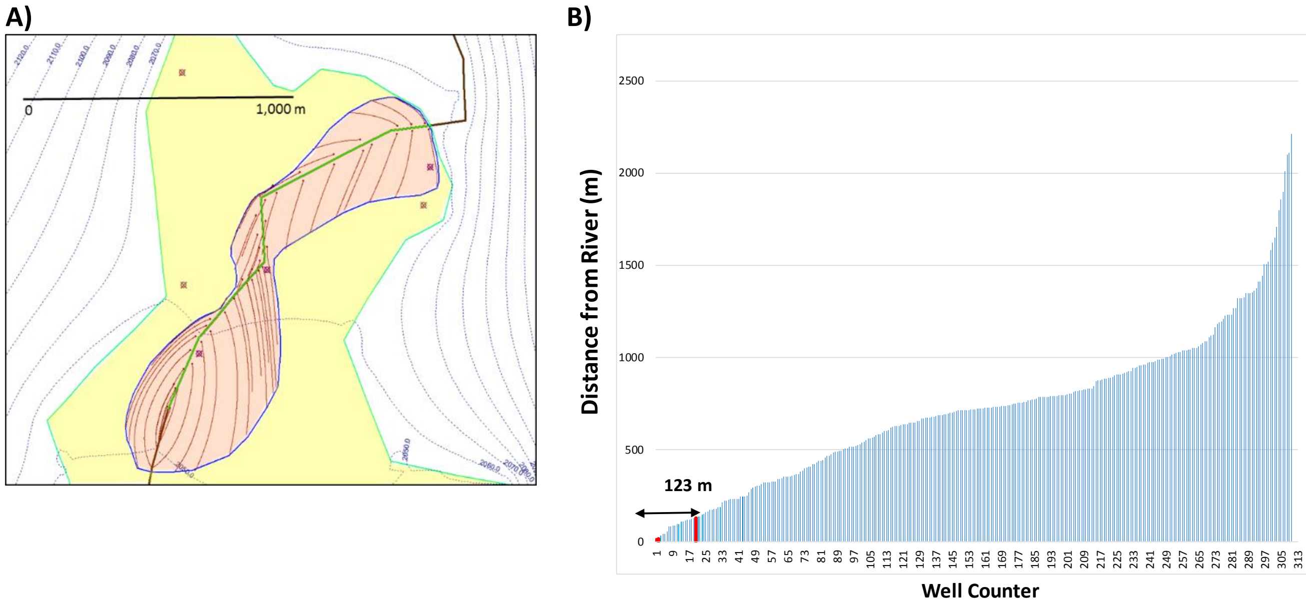


Figure 8-9. GFLOW model of the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015. A) Solution showing hydraulic head contours (m) and forward streamlines with respect to pumping wells (points). B) The histogram graph shows the distances of wells from the river (over 300 wells) with highlighted wells that the model suggested would source from the river (3 wells).

There are a number of detailed local-scale factors that would be expected to influence groundwater-surface water interactions, well capture of river water, breakthrough times of conservative river solute in the well, and anticipated dilution. A series of local-scale modeling scenarios were explored and these are described in Appendix D. These included an investigation of the influence of transient pumping using the MODFLOW model and the data from community well 1000m70km. The influence of transient or pulsed pumping at the well was shown to be localized and effectively represented by the time averaged GFLOW model. An investigation of three-dimensional flow using MODFLOW/MODATH was conducted with the data associated with the 35m66km community well. The MODFLOW/MODPATH offered more complex capture zones than the Dupuit-Forcheimer (DF) simulations using the GFLOW model, and the MODFLOW/MODPATH breakthrough times of river solute at the well were earlier than the GFLOW model, given steeper gradients represented for similar well discharge. Finally, an investigation of local scale aquifer heterogeneity was conducted using the AnAqSim model and the data associated with the 75m71km community well. While the model suggested pumping rate was critical to the determination of the well sourcing from the Animas River, the nature and distribution of buried stream channels in the floodplain would have significant influence on solute breakthrough times and dilution.

8.3 River Communication with Wells: Lower Animas River Floodplain

The lower Animas River of New Mexico also supports a number of community wells and domestic/ household wells, along with a highly active system of diversions of river water to irrigation ditches (Figure 8-11). The GKM release of dissolved metals was observed to be more dispersed and diluted by the time it reached the lower Animas River area.

A) **B)**

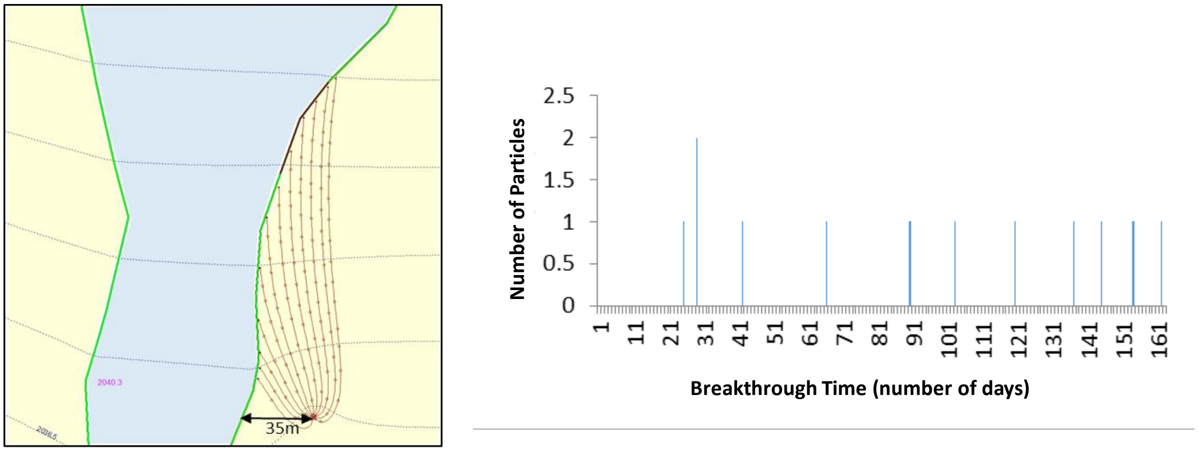


Figure 8-10. GFLOW capture zone and solute breakthrough histogram for a mid-Animas River community well. GFLOW analysis of mid Animas River community well (35m-66km), high pumping (Qw= 2,616.5 m^3/d) and low porosity (n=0.2). A) Particle tracking with 12 forward pathlines, and B) predicted time of arrival breakthrough (days) reported in a histogram with a particle arriving in 25 days.

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has embarked on a survey of synoptic water levels in the lower Animas River between Riverside and Farmington and private water levels after the GKM release of August 5, 2015 (Timmons *et al.* 2016). The water levels after the GKM release provide empirical evidence of segments of the Animas River that might be losing water to the aquifer. The surveys released have included observations in August 2015, January 2016, and March 2016. The January 2016 data represent the water table under “baseflow” conditions and not under the influence of mountain snowmelt runoff or irrigation ditches (Figure 8-12). There are a number of wells indicating a negative gradient in this section of the lower Animas River between Riverside and Farmington, New Mexico. The negative hydraulic head gradient suggests that in these sections and at this time (i.e., January 2016), the Animas River was losing water to the aquifer. Most of the potential losing reaches are in the northern half of the study region for this time period. The sporadic spatial distribution of the potential losing reaches underscores the site-specific nature of the phenomenon.

The NMBRMR also monitored continuous precipitation and Animas River and irrigation ditch stages at select locations (Figure 8-13). As would be expected, the Animas River stage elevation responds very quickly to precipitation events. The alluvial well in this location has a more muted and delayed response to the precipitation/river stage signal. About a five-day delay in the signal from river stage to well response was recorded based on observations at an alluvial well. Also, the influence of the irrigation ditches is apparent. Once the irrigation ditch was shut down for the winter, the water levels in the alluvial well dropped to the baseflow levels.

The NMBGMR synoptic water level data were an important constraint on the GFLOW model and calibration for the lower Animas River study area is described in Appendix D. The model was used to perform capture zone estimation for the water supply wells, both community and private, and where there was evidence of sourcing from the river, evaluate breakthrough curves at the well. An average pumping rate for the private domestic water wells was assumed to be 400 gallons per day, a high estimate because it does not account for expected return flow to the aquifer via septic leach fields. The community wells were assumed to pump at the driller’s log rated yield (also a maximum pumping rate).

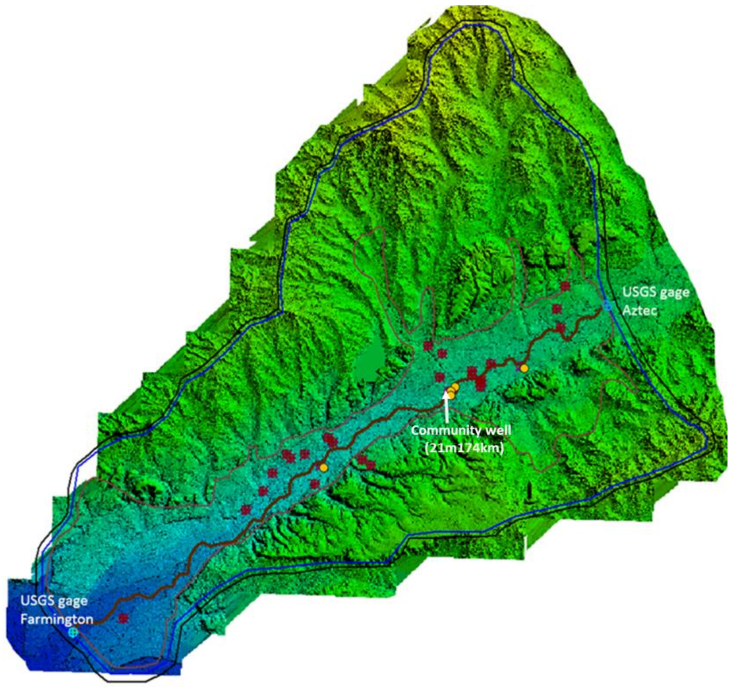


Figure 8-11. Community wells (orange) and select private wells (red) for the Lower Animas River floodplain study area. The catchment draining between the USGS gages at Aztec and Farmington was delineated as guided by the light detection and ranging (LiDAR) digital elevation model (DEM). Note the 21m174km community well. Data source: New Mexico Resource Geographic Information System (http://rgis.unm.edu/)

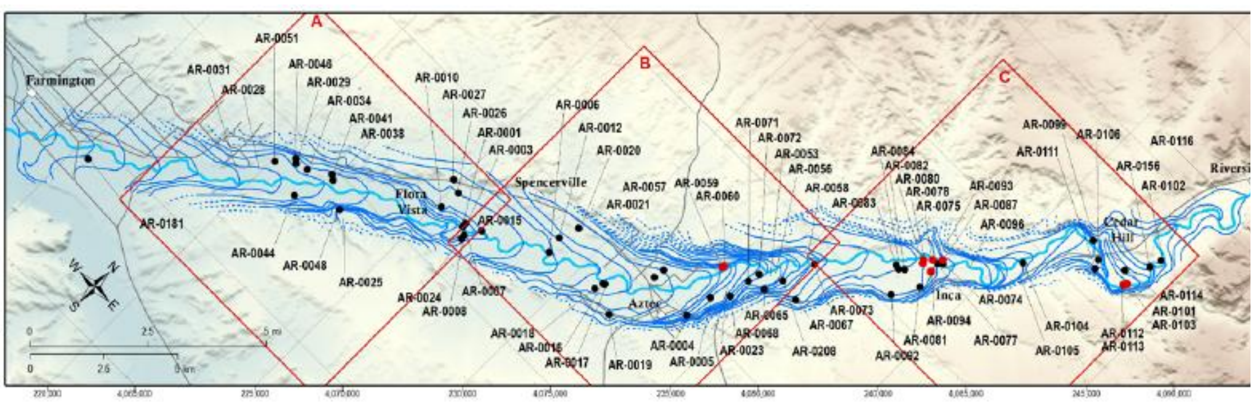


Figure 8-12. High-resolution synoptic survey of the river water levels and well water levels in the lower Animas River floodplain, January 2016, between Riverside and Farmington, New Mexico. The wells were geospatially located using hand-held global positioning system (GPS). A high-resolution light detection and ranging (LiDAR) digital elevation model (DEM) was used to estimate land surface elevations. Data collection supports the New Mexico Bureau of Geology and Mineral Resources Aquifer Mapping Program (Timmons *et al.*, 2016). The wells with negative gradient (shown as red dots) indicated segments of the Animas River that were losing river water to the aquifer.

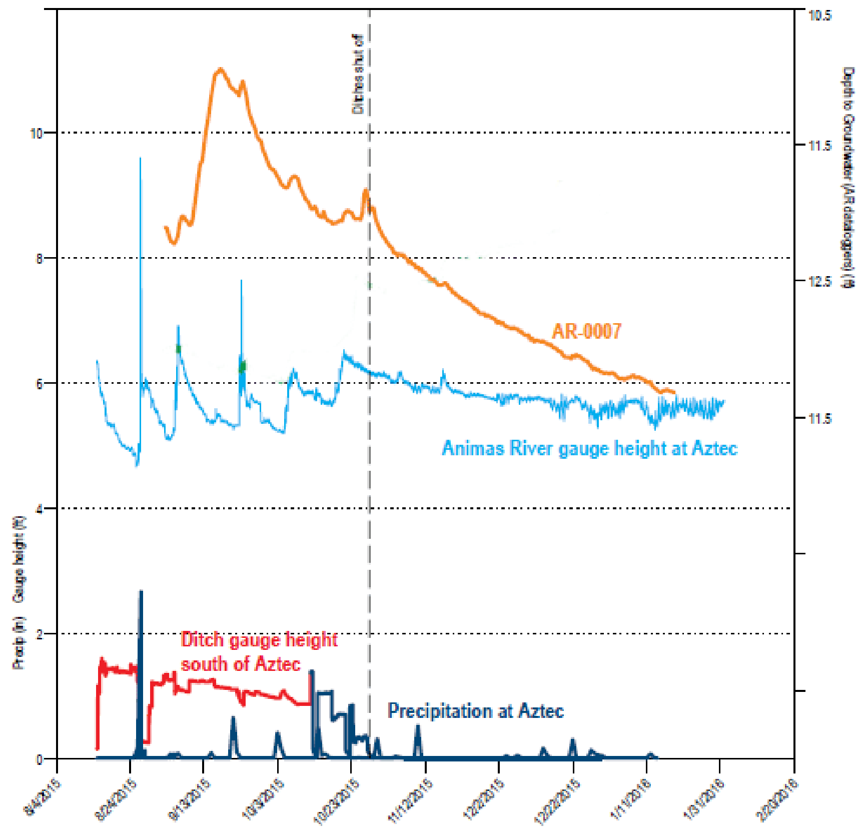


Figure 8-13. Hydrographs from the Aztec, New Mexico area including a well with continuous data recorder plotted with influences from precipitation, Animas River stage, and ditch gage height. Well AR-0007 is located on the south side of Aztec, is 32 feet deep, and is located on the east side of the river. (Modified from Timmons *et al.*, 2016).

The river and irrigation ditches are represented in the GFLOW model as line-sinks. The private and community wells are represented as point sinks. The regional water balance was calculated for August to October 2015 based on USGS gaged river flows at Aztec and Farmington. The GFLOW model calibration is described in Appendix D. The resulting regional model is shown in Figure 8-14. The 90-day capture zones of the wells are too small to be seen at this scale. The model suggests only the 21m174km community well, pumping at a maximum rate of 817.6 m^3/d, sources from the river.

While the GFLOW model predicted the 21m174km community well might source from the Animas River, the first arrival of the plume took over 90 days, and dilution was dominant (Figure 8-15). Flushing of the aquifer occurs in about two years under these conditions. Breakthrough time with same pumping but higher porosity (n=0.35) has a particle arriving in 131 days. The model suggests that peak river concentration is diluted to about 2% (1/48). Again, note that the analysis is steady (i.e., time invariant pumping and hydrology) and advective transport does not account for dispersion, sorption, or transformation of solutes. Lack of data prevents meaningful uncertainty analysis.

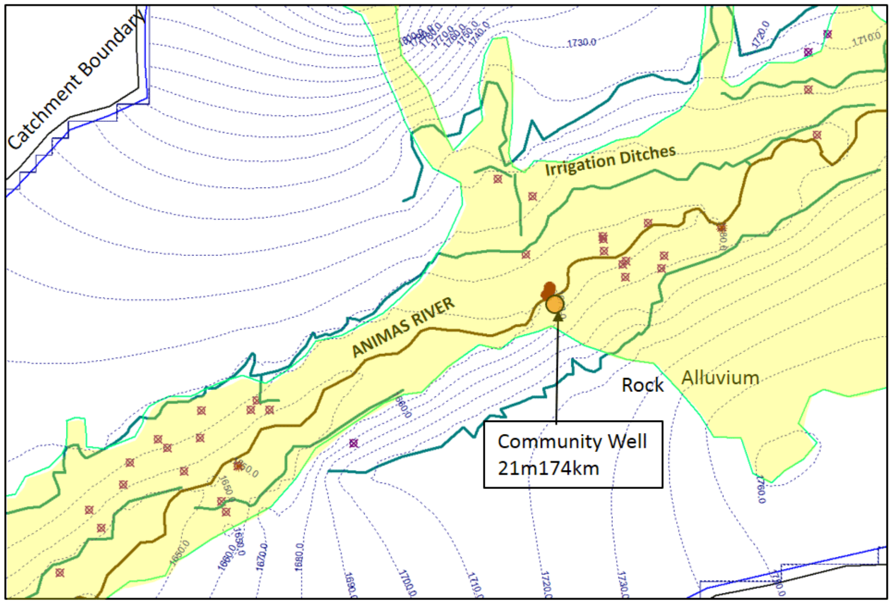


Figure 8-14. GFLOW model of groundwater-surface water interactions in the lower Animas River floodplain between Aztec and Farmington, New Mexico (RK 170-180) for the averaging period August to October 2015.

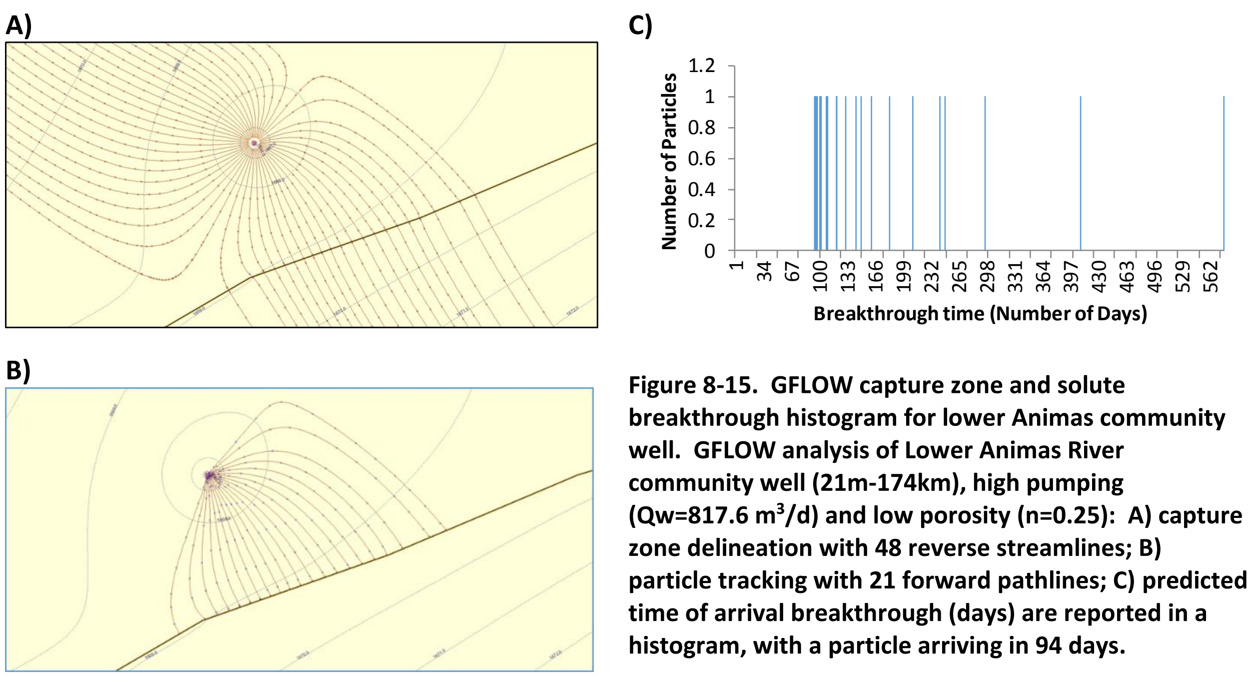


Figure 8-15. GFLOW capture zone and solute breakthrough histogram for lower Animas community well. GFLOW analysis of Lower Animas River community well (21m-174km), high pumping (Q_w=817.6 m^3/d) and low porosity (n=0.25): A) capture zone delineation with 48 reverse streamlines; B) particle tracking with 21 forward pathlines; C) predicted time of arrival breakthrough (days) are reported in a histogram, with a particle arriving in 94 days.

8.4 Empirical Data of Dissolved Metals Concentrations in Wells

Dissolved metals that were most useful as tracers associated with the GKM plume include primarily aluminum and iron, and also manganese, zinc, and cobalt. Together, these metals represent about 95% of potentially toxic metals released to the rivers (Utah DEQ 2015). This section will visit the hypothesis that dissolved metals in the GKM river plume could have impacted floodplain wells through examination of empirical data (i.e., well water quality sampling).

8.4.1 Mid Animas River Floodplain Community Wells

Elevated zinc concentrations were observed at community well 35m66km on August 14, 2015 (Figure 8-16D). The secondary drinking water standard for zinc, based on taste, is 5 mg/L (5,000 µg/L), and the observed peak well concentration is an order of magnitude below the taste standard.

Dissolved background zinc concentrations in the upper Animas River near Elk Creek are expected to be around 0.08–0.20 mg/L as reported in Church *et al.* (2007, Chapter E9 Quantification of metal loading by tracer injection and synoptic sampling, 1996-2000, Figure 17). The distinction between dissolved phase zinc and colloidal phase zinc in the Animas River is extensively discussed in Church *et al.* (1997). The observed concentration of dissolved zinc in the GKM plume in Cement Creek was about 172 mg/L.

The observed Animas River surface water quality observations by the Colorado Department of Public Health (CDPH) at the Baker's Bridge area after the passage of the GKM plume (August 12–18) showed evidence that the dissolved zinc concentrations in the river had returned to background levels of 0.09–0.13 mg/L. The maximum observed dissolved zinc concentrations in the Animas River associated with the GKM plume near Baker's Bridge (approximately RK 64) was about 1.9 mg/L.

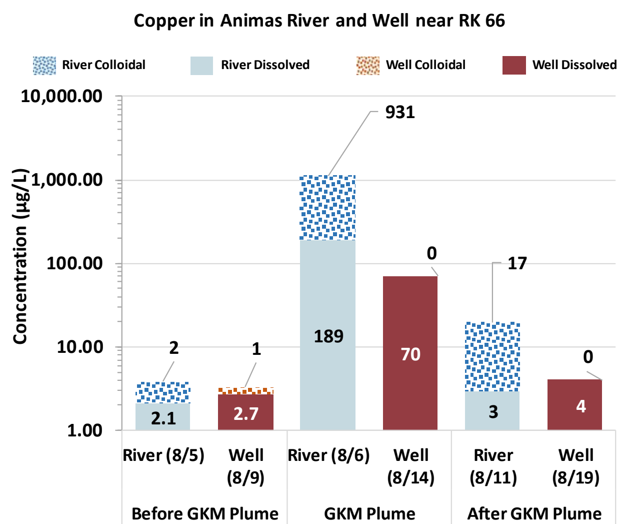
The dissolved zinc plume associated with the Gold King release would be expected to arrive in the mid Animas River area (RK 65–75) early in the day of June 6 and take less than 24 hours for the majority of the metals to pass, based on water quality observations and empirical and process modeling. The CDPH groundwater quality data at the 35m66km well indicated an elevated dissolved zinc concentration of 0.58 mg/L on August 14, with lower levels observed on August 9 and August 19. Assuming a potential eight-day delay in arrival of zinc from river to well allows a segregation of the data into suspected before-plume, plume, and after-plume categories.

Other metals showing an elevated response on August 14 based on the before-plume, plume, and after-plume presentation included dissolved copper, lead, and nickel (Figure 8-16A-C). Metals not indicating an elevated response on August 14 were aluminum, manganese, arsenic, beryllium, cobalt, and selenium. The pH and iron values were not reported.

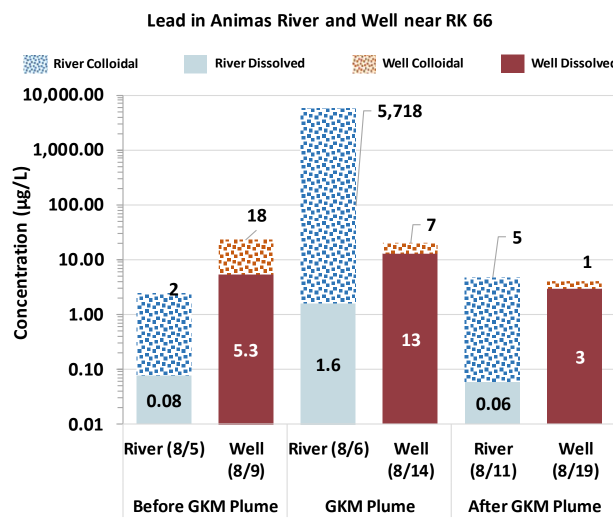
The CDPHE water quality measurements available in the other mid Animas community wells (i.e., 75m71km, 650m71km, and 575m71km) did not have noteworthy changes suggesting impact by the GKM release.

The groundwater modeling associated with the 35m66km community well, as described above, included insights into the possible communication of the well with the river plume. The modeling did satisfy fundamental continuity of flow and fundamental physical laws of groundwater mechanics, and included the primary process of advective transport of dissolved solute. The sensitivity modeling using GFLOW of solute breakthrough times ranged from 25 days to 187 days, based on choice of high or low recharge, hydraulic conductivity of the alluvium, pumping rate of the well, and aquifer porosity. The observed arrival of the dissolved zinc plume at the 35m66km community well was perhaps less than eight days. Fully three-dimensional flow modeling might explain the possible earlier arrival time of solutes at the well, as described in Appendix D.

A)



B)



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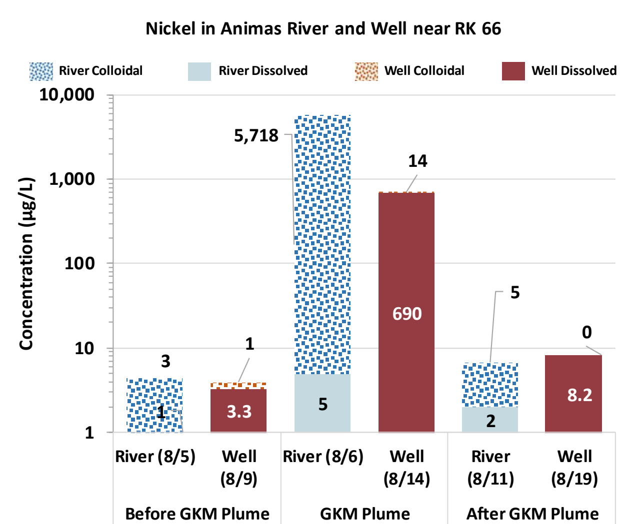


D)

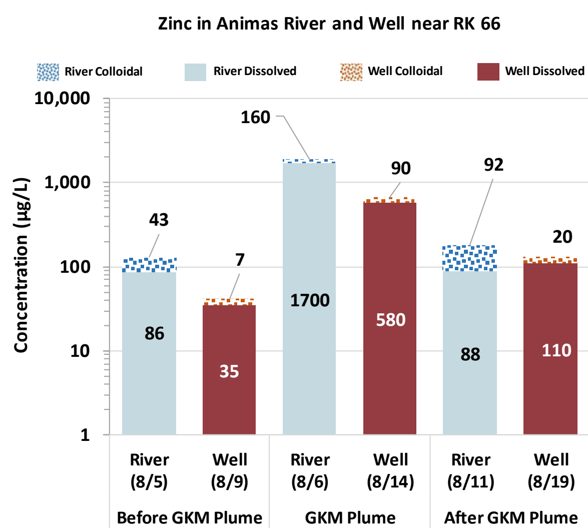


Figure 8-16. River and well dissolved and colloidal metals concentrations of A) copper, B) lead, C) nickel, and D) zinc around RK 66 of the mid-Animas River. The data are organized into before, during, and after plume time windows assuming the peak river plume passed the location on August 6 and a potential eight-day lag in transport in the groundwater system before arrival at the well.

Given the limitations on site-specific data, the groundwater modeling analysis of the 35m66km community well did not include local aquifer heterogeneities such as buried braided stream channels, which can facilitate and accelerate river-to-well communication.

The modeling did not represent reactive transport that would affect metals conversions between dissolved and colloidal forms. The groundwater modeling did not include the potential for clogging of the river bed sediments by algae or precipitated chemicals. These processes would retard river-to-well communication.

The groundwater modeling analysis of the 35m66km community well did not include complications such as transient pumping and transient river flows, and potential pumping interference from nearby private wells, or the influence of irrigation ditches, which could complicate a geochemical signal at the well.

In the end, the results of the modeling and the analysis of the empirical evidence could not rule out the hypothesis that the 35m66km well did pump Animas River water impacted by the GKM release of August 5, 2015.

8.4.2 Lower Animas River Floodplain Community Wells

There was no clear evidence for water quality impact of the GKM plume on the community wells sampled in the lower Animas River floodplain, between Aztec and Farmington near RK 163 (Figure 8-17). The dissolved metals concentrations in the lower Animas River associated with the GKM release were much lower than was observed in the mid Animas River, somewhat due to dilution and dispersion, but more likely influenced by geochemistry as segregation into colloidal form occurred. The community wells seem to indicate a fairly consistent groundwater quality concentration for copper, lead, nickel, and zinc, perhaps indicating the aquifer waters were in a state of equilibrium or long-term mixing. The active spreading of river water via irrigation ditches and field application could be a factor.

The ongoing study by the NMBGMR (Timmons *et al*. 2016) that includes identification of wells located in proximity to seasonal losing reaches of the lower Animas River and associated measurement of well water quality, including conservative constituents like sulfate, will strengthen the understanding of the dynamic system.

8.5 Summary

Given the hidden nature of the subsurface, and the lack of definitive field observations, the GKM groundwater exposure assessment is based on hypothesis testing using multiple lines of evidence, including physics-based groundwater flow models, and publically available field observations. The potential vulnerability of water supply wells to receive river source waters (e.g., capture zones) was modeled; movement of a conservative solute to the wells expected to source from the river was simulated (e.g., breakthrough analysis); and based on the breakthrough analysis, models were used to anticipate mixing of conservative river plume source water with other source waters (e.g., rainfall recharge, other aquifer waters) resulting in estimates of dilution at the pumping well.

From the empirical information, the hypothesis that certain pumping wells could be vulnerable to impact from the GKM river plume could not be rejected. Perhaps more useful was the use of the modeling approach to explore the site-specific factors that might influence vulnerability.

There are hundreds of water supply wells in the floodplain aquifers of the Animas River, ranging from continuous larger volume pumping wells (i.e., the community wells) to the small pumpers (i.e., the domestic/household wells). There are also intermittent intermediate pumpers (i.e., the irrigation wells).

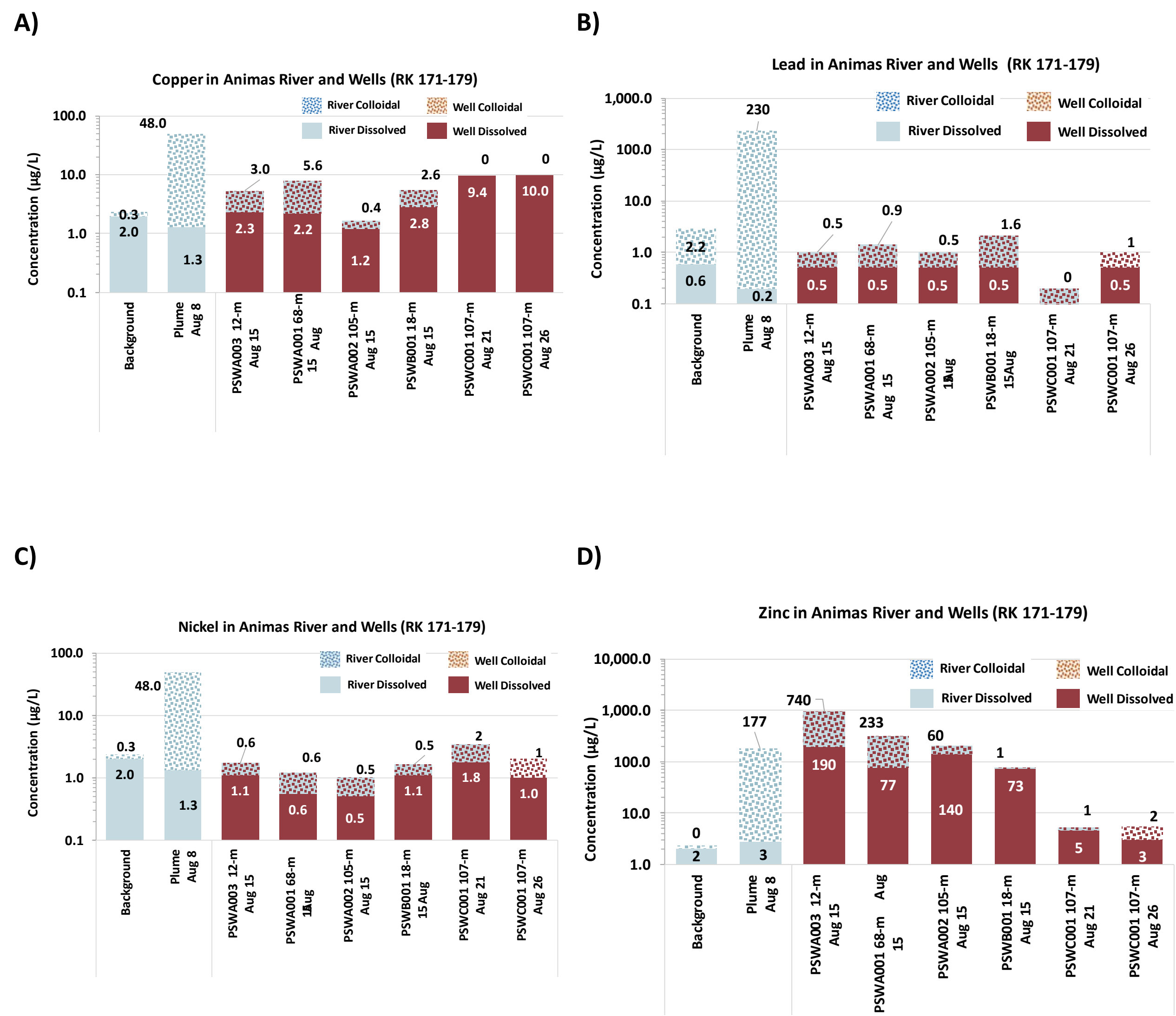


Figure 8-17. River and well dissolved and colloidal metals concentrations of A) copper, B) lead, C) nickel, and D) zinc around RK 171-179 of the lower Animas River in New Mexico.

Of the hundreds of domestic/household wells investigated, the groundwater capture zone modeling suggests only a handful of these wells potentially source from the Animas River and were potentially vulnerable to exposure to the GKM river plume. Given their low pumping rates, the domestic/household wells would most likely need to be located in proximity to a losing reach of the river to be vulnerable to sourcing river plume water. The complication as to whether any given stretch of the Animas River is either gaining or losing is site specific and temporally changing. Water balance methods were too coarse to capture the dynamism; a high resolution synoptic field survey of water levels during the period of plume passage would be required. The operation of nearby irrigation ditches in the weeks prior to the GKM release could have played a role in elevating water levels in the flood plain aquifers, and the elevated aquifer water levels would have supported subsurface drainage toward the river, not seepage from the river to the aquifer.

For the community wells, because of their higher pumping rates, vulnerability to directly pumping Animas River source water would be mostly controlled by their proximity to the river. The computer modeling suggests that for the community wells investigated (i.e., five in the mid Animas River floodplain of Colorado; five in the lower Animas River floodplain of New Mexico), a mid-Animas community well located less than 35 m from the river received a percentage of water directly from the river under expected pumping, another mid-Animas River community well located 75 m from the river would source river water if pumping at a maximum rate, as did a lower Animas community well located 21m from the river did. The modeling suggested the breakthrough time of river plume showing up at the wells closest to the river would be days to weeks.

More detailed local-scale modeling suggested breakthrough times of conservative river solutes at the pumping swell could be shown to be very sensitive to the presence of aquifer heterogeneities and to three-dimensional flow analysis. Transient pulsed pumping is expected to be a less important influence.

The community well located within 35 m of the Animas River had an observed chemical signal of some dissolved metals. The team could not reject the hypothesis that this signal could have been associated with the GKM plume. The observed breakthrough time was earlier than suggested by the computer simulations. This is not completely unexpected since the computer modeling did not account for local aquifer heterogeneities and dispersion. There is a lot of dynamism in the local exchanging of river water to the alluvium as observed episodically in the river hydrograph records (e.g. Figure 8-7). It is possible that the timing of the Gold King plume relative to the receding hydrograph from the storm several days earlier could have coincided with a short-lived shift in that reach into a losing phase contributing to this well response. The observed peak raw water concentrations at the 35-m well were below federal drinking water action levels. Of the community wells investigated, this was the only one to exhibit a potential chemical signal that could be associated with the passage of the GKM plume in the Animas River.

CHAPTER 9 WATER AND SEDIMENT QUALITY POST GKM EVENT

This chapter will discuss the water and sediment quality after the Gold King Mine event. Metals concentrations were elevated during passage of the Gold King Mine plume throughout the Animas and San Juan Rivers (Chapter 4) and receded back towards pre-event conditions within days after plume passage. The summed metals concentrations in the Animas River at Durango, Colorado during the plume, and for several weeks afterward, illustrate the pattern of concentrations at many locations in the weeks after the release (Figure 9-1). Typically, dissolved major cations (calcium, magnesium, potassium and sodium) are the dominant constituents in water during August while concentrations of other metals are quite low.

Most of the metals released from the Gold King mine and entrained between the mine and Cement Creek were deposited in the Animas River and to a lesser extent, in the San Juan River. The deposits were particulates, aggregated colloids and precipitates that likely had a variety of particle characteristics and mineralogy, such as gypsum, gibbsite, and ferrihydrite. Gold King Mine materials were deposited in a similar longitudinal pattern as pre-existing mining impacts, where concentrations lessened with distance from the Animas headwaters. The challenge for post-event analysis was to determine the longevity of the deposited material and subsequent fate within the natural temporal variability of processes that control the water chemistry of these diverse rivers.

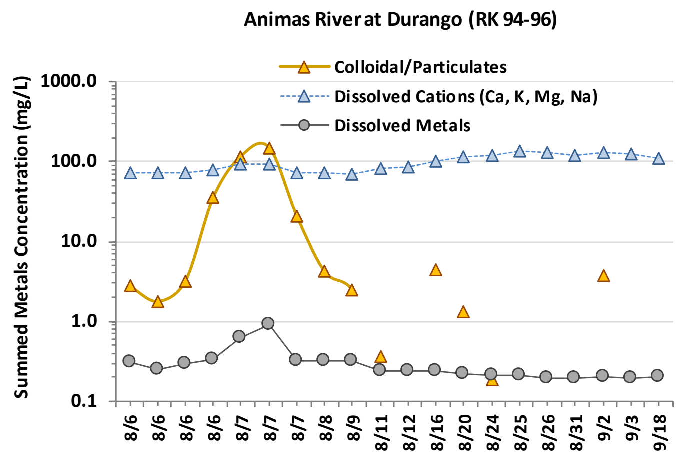


Figure 9-1. Summed total metals concentrations shown in sample sequence for 43 days during and after the Gold King plume in the Animas River at Durango, Colorado (from August 6 to Sept 18, 2015). The background dissolved metals concentration is dominated by the major cations (calcium, magnesium, potassium, and sodium).

Several phenomena could determine how these deposits continue to influence water and sediments over time. Deposited minerals had varying chemical and physical stability in the short term, as water returned to background pH and chemical composition. Incipient minerals could have dissolved, while those that remained continued to undergo “aging” towards increased internal crystalline stability. Some geochemical reactions would be expected to continue within deposits for some time (Nordstrom 2011) and could affect water chemistry and sediment metals, thus influencing water chemistry during the low-flow fall months when there is less water to dilute (Spruill 1987). Of particular concern was the physical remobilization of deposits during high flows, such as prolonged spring snowmelt or storms. Following the GKM release, some locations within the area were subjected to significant “monsoonal” storms from August through October 2015, and the Animas and San Juan Rivers experienced spring snowmelt from April through June 2016.

This chapter examines trends in water and sediment metals concentrations, focusing on determining detectable impacts on post-event water and bed sediment concentrations as a result of GKM material deposits in the river system. EPA initiated a follow up monitoring effort to monitor physical, chemical and biological characteristics of the rivers and evaluate impacts from the release. The details of the Conceptual Monitoring Plan (2016a) are available on EPA’s GKM webpage. A supplemental report will provide analyses of other data collected under the Conceptual Monitoring Plan, including tissue contaminants and biological integrity. This report summarizes water and sediment chemistry and streamflow observations provided by multiple organizations in the 14 months since the release, looking at where, how long, and to what level metal concentrations were changed in the Animas and San Juan Rivers immediately after the GKM release and within the 14 months following and what those post-event patterns imply about the fate of the Gold King Mine metals.

The primary questions following the Gold King Mine release and the passage of the metals-contaminated plume through the Animas and San Juan Rivers were:

- Did the concentrations of metals in the water and sediment return to and persist at pre-event levels?
- Did plume deposits impact post-event water quality relative to pre-event conditions?
- Was there a second wave of contamination in later high flows from the re-suspension of deposited material?

9.1 Overall Patterns in Metals Concentrations

9.1.1 Spatial Patterns

There is significant spatial and temporal variability in water conditions and metal concentrations in the large geographic area contributing to the Animas and San Juan Rivers, due to differences in geology and climate and the historic impacts of land use and mining. Analysis of the Gold King Mine plume movement through 550 km of the river system, as discussed in earlier chapters, identified some of this pre-existing spatial and temporal variability in water and sediment metal concentrations. The GKM plume added a veneer of metals to existing deposits in the Animas and San Juan.

The longitudinal patterns of metals concentrations in water and sediment are illustrated in Figures 9-2 and 9-3, respectively. These figures concisely present the more than 1,400 water samples and 700 sediment samples collected during and after the GKM release. Longitudinal patterns follow pre-existing patterns shown by the USGS basin-wide AMD studies. These studies identified water quality impacts arising from geologic processes and historic mining in the Animas River headwaters and offsite ore processing (Church *et al.* 1997, 2007). Longitudinal patterns were strongly evident in the Gold King Mine plume (Chapter 4), in surface water quality during the plume (Chapter 5), and in historic data for bed sediment metals (Chapter 6). There is a steep longitudinal gradient along the Animas River emanating from the ore-rich and AMD-contaminated headwaters.

Repeated measurement after the GKM release showed that metals concentrations varied temporally at individual locations. Some variability in metals post-release also followed general annual and storm-related flow patterns. Streamflow is an important driver of metals concentrations in the water and perhaps in the streambed (Spruill 1987; Church *et al*. 1997; Leib *et al.* 2007). After the release, most sites showed patterns of change from the high concentration values observed during and immediately after the plume for a period of days to weeks. These patterns will be evaluated throughout this chapter.

Figure 9-4 illustrates some of the temporal change in concentrations immediately following the release using lead as an example. Lead in colloidal/particulate form was one of the metals present in high concentrations in the Gold King Mine plume. Plume deposits were high in lead in the upper Animas, as evidenced by samples collected at multiple locations within this reach after plume passage (Figure 9-4). Data points are colored reflecting time since the plume passage (i.e., red immediately after and moving to cooler colors over time). Over the next several weeks after the plume, lead in some of the locations had already begun to decline towards the segment average, but the sampling also demonstrates the spatial variability of deposits. Sediment concentrations of many metals, including lead, were also high in the upper Animas River (see Figure 6-18).

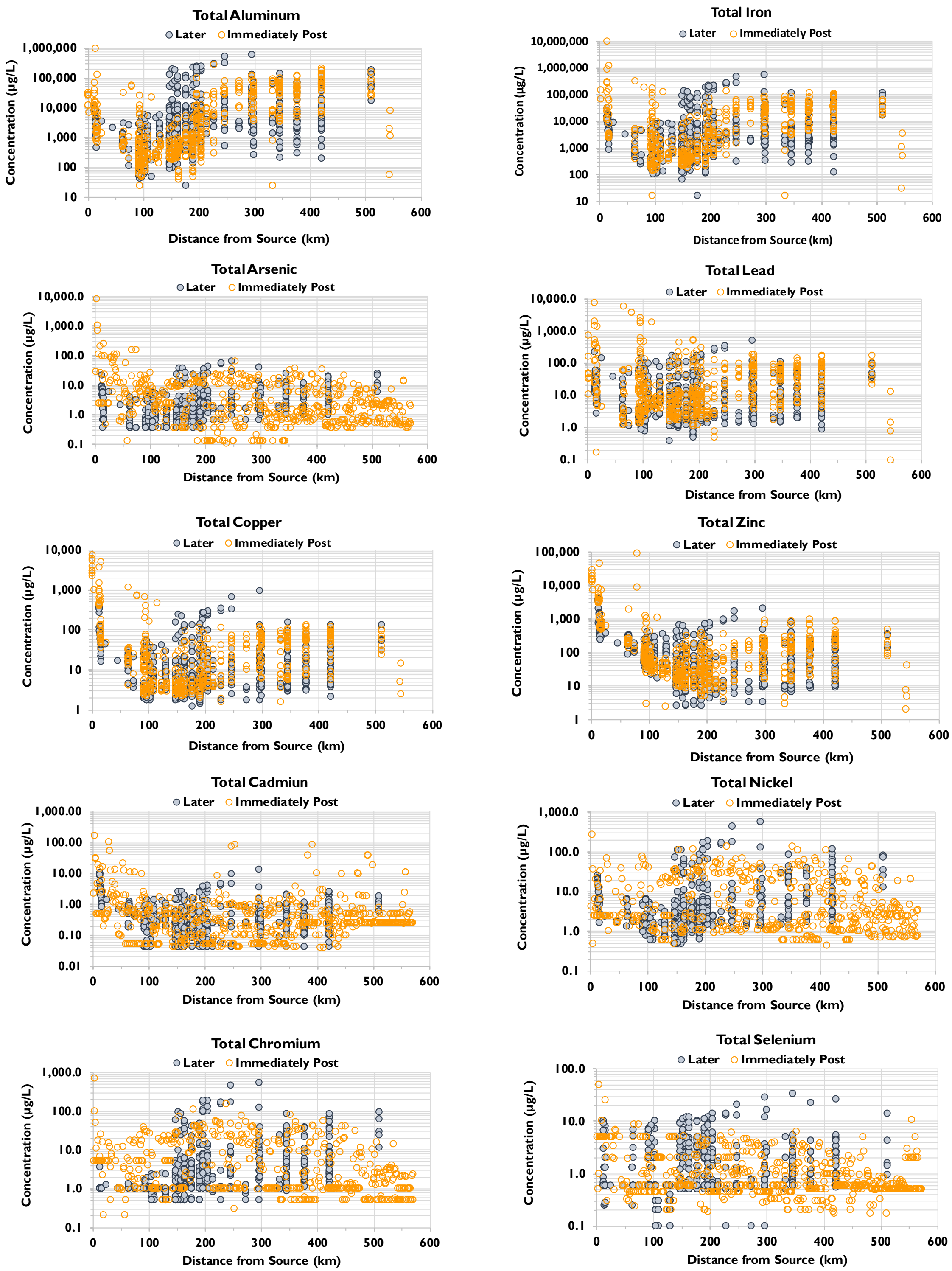


Figure 9-2. Total water concentration for ten metals in all samples collected in the Animas and San Juan Rivers from August 2015 to June 2016. Immediately post data (orange circles) are from August 5 to August 21. Later refers to samples collected from August 22 to July 2016 (gray circles).

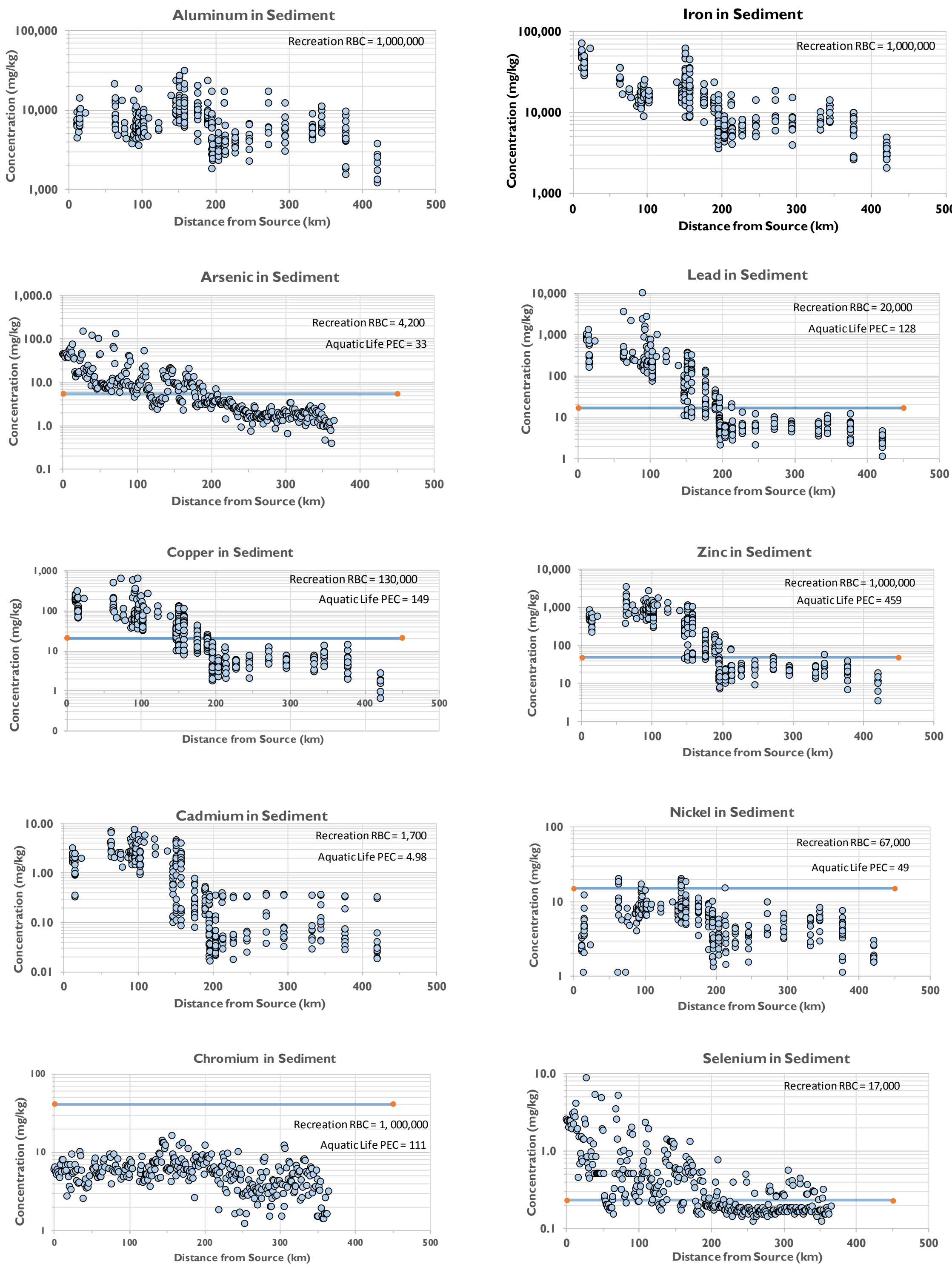


Figure 9-3. Sediment concentration of all samples collected in the Animas and San Juan Rivers from August 2015 to June 2016. Blue lines shown for some metals indicate the mean concentration of that metal in surficial deposits and natural soils in the western United States as determined in a synoptic survey by Shacklette *et al*. (1984).

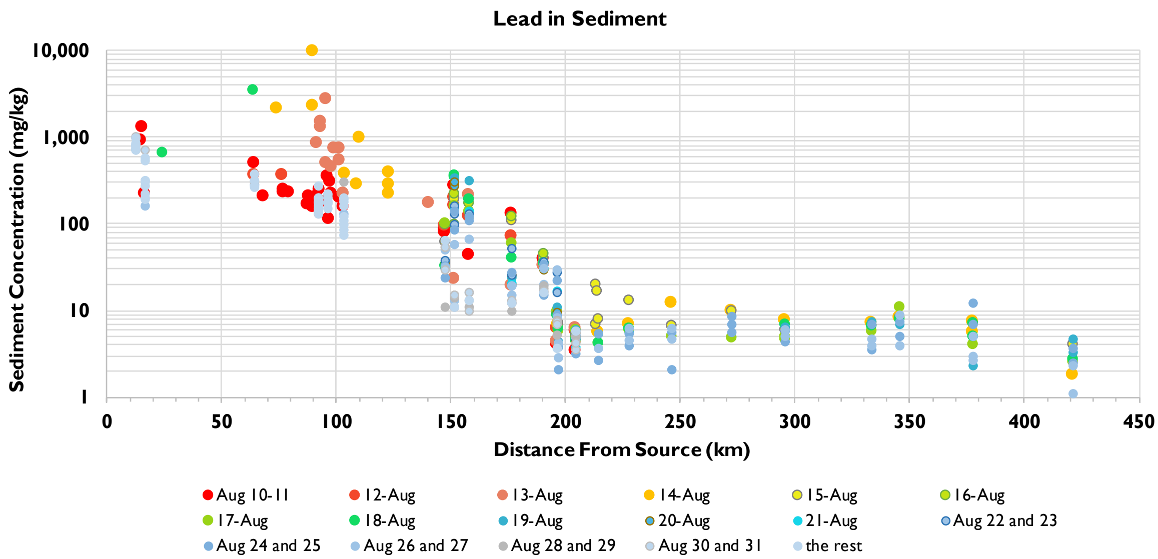


Figure 9-4. Sediment lead concentrations in all samples collected during August 2015 in the Animas and San Juan Rivers. Data are color-coded by sampling date to identify any patterns within the immediate period after the Gold King Mine release.

9.1.2 Streamflow and Metal Concentrations

Site-specific variability evident in metals concentrations in Figures 9-2 is at least partially determined by streamflow in each location. The importance of streamflow in determining concentrations of metals in water was introduced in Chapter 6, where it was shown that metal concentrations correlate either positively or negatively to streamflow, depending on whether they are in the dissolved or particulate/total fraction. The general patterns of streamflow in various locations in a geographic area are important for interpreting patterns of metals concentrations over time in those locations (Church *et al*. 1997). This is especially the case for analyzing potential mobilization of Gold King Mine deposits, a main concern for post-release water quality.

The hydrographs at an upper Animas River location between Silverton and Baker’s Bridge and at a lower Animas River gage in Farmington from the time of the GKM release through spring snowmelt 2016 are shown in Figure 9-5. Although there were several freshets in the upper Animas, flow generally declined during the 9-month period after the release, following seasonal patterns. The upper and middle Animas River to approximately RK 140 did not experience the level of flow observed during the Gold King Mine plume until the rising limb of snowmelt in April 2016.

Flow patterns were very different in the lower Animas and San Juan Rivers. There were significant storms where flows during plume movement were exceeded. The first occurred within three weeks of the plume, on August 27, 2015, and additional storms occurred through September and October. Thus, trends in metals and processes that control them varied spatially within different segments of the Animas and San Juan Rivers in the post-plume period due to these weather patterns.

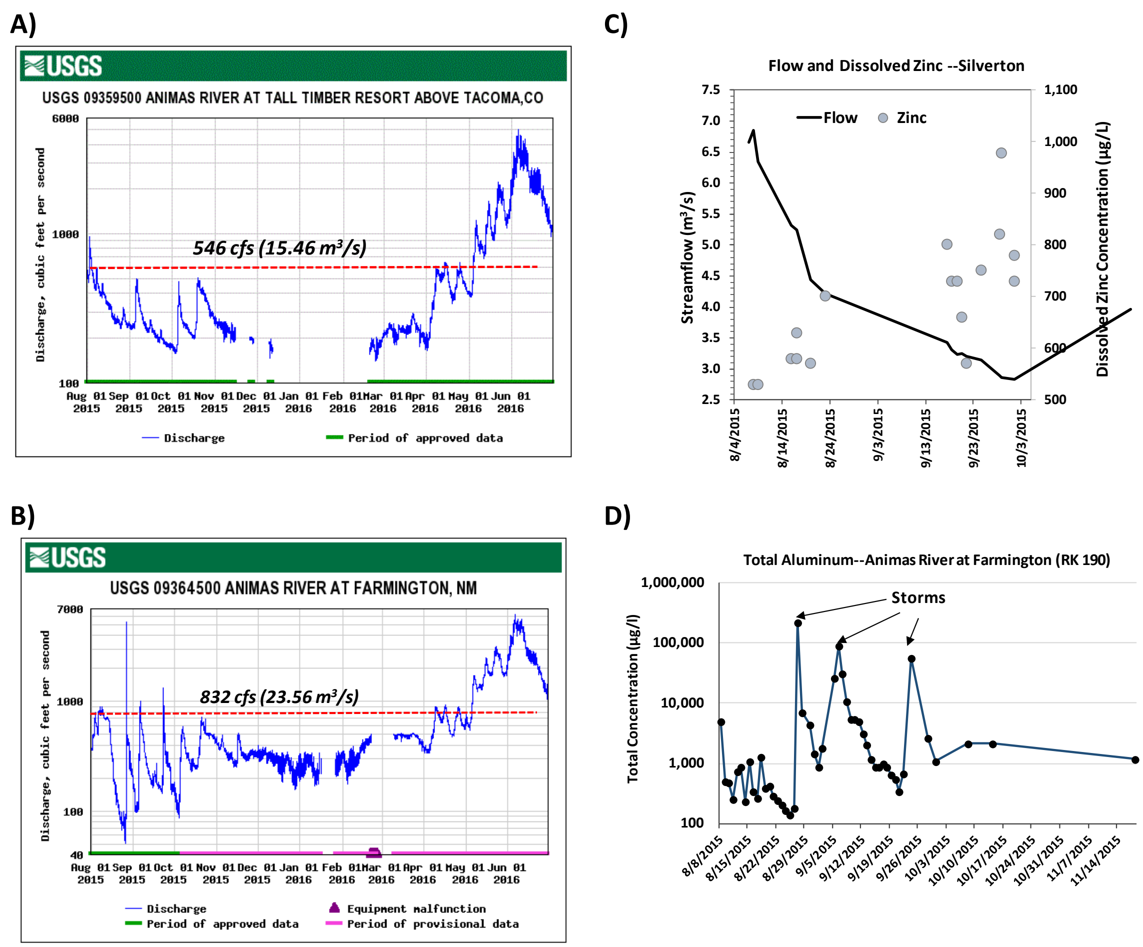


Figure 9-5. Hydrographs of the Animas River at USGS stations at A) Tall Timber in the upper Animas at RK 48.8 and B) Farmington in the lower Animas at RK 190.2 from August 1, 2015 to June 15, 2016. C) Example of relationship between flow during a low flow period in the hydrograph and dissolved metal (zinc) concentrations. D) Example of high flow effects on total metals concentrations (aluminum) during three storms at the Animas Farmington gage in the fall of 2015.

The relationship of metal concentrations to flow was evident in the post-event fall 2015 and snowmelt 2016 sampling. In the weeks following the release, receding streamflow increased concentrations of dissolved metals, as illustrated in Figure 9-5C. Figure 9-5D shows examples of elevated aluminum concentrations that coincided with three high flow events evident in the hydrograph. The relationship between metals and streamflow influenced patterns of metal concentrations and was important to control for in statistical analyses and interpretation of temporal patterns of metals in water.

9.2 Analysis of Temporal Trends in Metals Concentrations

This analysis focused on temporal trends in metal concentrations in water and sediment throughout the Animas and San Juan Rivers after the passage of the GKM release, using water and sediment data collected primarily since the release. The objective of this analysis was to connect the post-event response of water and sediment metals to the initial plume effects described in Chapters 4 through 6.

Observational data are presented graphically for the 14 months following the event, including the spring snowmelt in June 2016. The analysis in each geographic area focused on the most salient observations and patterns that emerged for that area. Potential differences in metals concentrations prior to and following the Gold King Mine event were statistically tested at the locations where sufficient historic data were available. This analysis began with the Animas headwaters and moved downstream, emphasizing the most important and dominant trends following the release in each of the broadly defined segment of the river system that had reasonably uniform behavior and response to the Gold King Mine release.

Discussion of this analysis varies geographically, depending on availability of data and the nature of trends that became evident. Analysis grouped sampling locations into three regions for the Animas River and three for the San Juan River, as follows:

- Upper Animas River (RK 12.5 to RK 16.4) includes sampling sites in Cement Creek and the Animas River below Silverton.
- Middle Animas River (RK 16.4 to RK 140) includes major sampling locations at Baker's Bridge (RK 63.8) and multiple sites in Durango and in the Southern Ute Indian Tribe Reservation.
- Lower Animas River (RK 140 to RK 193) includes the river segment from RK 140 to the confluence with the San Juan at RK 193 in Farmington, New Mexico.
- Upper San Juan River (RK 193 to RK 214) includes Farmington to Fruitland, New Mexico.
- Middle San Juan River (RK 214 to RK 296) includes major sampling locations in the area of Shiprock and Four Corners.
- Lower San Juan River (RK296 to RK 550) includes major sampling locations at Montezuma Creek; Bluff, Utah; and Mexican Hat, Utah to Lake Powell

9.2.1 Post-Gold King Mine Release Data Sources

Water and sediment monitoring has continued in the year following the GKM release to understand the long-term impacts of the release and post-event changes to incipient minerals in deposited sediment. Almost 1,400 water quality samples were collected from the Animas and San Juan Rivers during and following the Gold King Mine release. Samples were collected by EPA, states, tribes, municipalities, and NGOs, as described in Chapter 2 and Appendix A. Most of the post-event samples were collected in August through October 2015. Since the fall, data providers have scaled back frequency of sampling and applied a longer-term monitoring strategy at key locations. Monitoring during 2016 snowmelt was a major emphasis, with sampling intensifying from April through June 2016. As with plume analysis, observed data were compiled from multiple sources and presented collectively with all the inherent variability associated with differences in methods.

Availability of post-event data allowed evaluation of trends after the release. Establishing whether water quality returned to pre-event levels required comparison to samples collected prior to the release. Various studies, monitoring programs, and routine sampling at USGS gages have generated historic data for metals concentrations in water and sediment in the Animas and San Juan Rivers prior to the Gold King Mine release. Pre-event data were distributed longitudinally along the Animas and San Juan Rivers, allowing some comparisons throughout the length of the river system affected by the release. However, pre- to post-release comparisons were dependent on the availability of data. Although historic data added insight on expected metals concentrations, their use for statistical testing was more limited due to inconsistencies in coverage of water and/or sediment, total versus dissolved fractioning of water samples, and coverage of specific metals among locations. Sources of historic data are listed in Table 9-1.

Care was taken to ensure comparable data in statistical testing. There was greater uncertainty associated with differences in sampling and testing methods within the historic data than in the post-event data, although important laboratory and metadata was available for the samples used. Analysis was restricted to data collected in the last 15–20 years, especially in the upper Animas river segments. Although more historic data exists for some locations, long-term watershed changes could make very old data less reasonable for comparison to post-event samples.

Table 9-1. Data Sources and Number of Samples (D=dissolved, T=total) for Pre-event Metal Concentrations in Surface Water Samples. Only samples from 2009 to 2014 were used for statistical tests in the Animas River because of potential changes to water quality with operation of a treatment facility during this time.

Data Source	Cement Creek (12.5)	Animas River					San Juan River (RK 193-510)
		Silverton (RK 16.4)	Baker's Bridge (RK 64)	Durango (RK 94)	Southern Ute Indian Reservation (RK 104-132)	Farmington (RK 190)	
EPA Superfund (2012-2015)	13 D, 13 T	130 D, 40 T	5 D				
EPA STORET (2009-2014)				165 D, 148 T			120 D
Southern Ute Indian Tribe (2002-2014)					25 D, 23 T		
USGS (1995-2010)						12 D	116 D
Navajo Nation (2011-2015)							30 D

9.2.2 Statistical Methods and Presentation

The importance of addressing the effect of flow on metal concentrations in water and sediment is illustrated for historic and post-event data collected in the Animas River at Silverton and Durango in Figure 9-6. Post-event concentrations followed the same pattern in relation to flow as the pre-event data.

Statistical comparisons of pre- and post-event data included only data within comparable flow ranges to account for the relationship between flow and concentration. This restriction reduced available data at most sites and eliminated the opportunity for statistical comparison at sites with limited data. An example of a statistical comparison of pre- and post-event concentrations of dissolved arsenic and cadmium in a narrowed-range of flow is illustrated at Durango, Colorado in Figure 9-7.

Statistical analyses were performed on aluminum, cadmium, copper, iron, lead, manganese, and zinc. Major cations (calcium, potassium, magnesium and sodium) that were the predominant background dissolved metals were not evaluated. The majority of samples for a number of trace metals were near detection limits, and metadata suggested that detection limits varied among datasets. The impact on statistical testing could be large when the majority of samples are reported at the detection level, so statistical comparisons were not performed with populations with a large proportion of non-detects. These considerations led us to focus on the seven listed metals. Where non-detects occurred (rare for these seven metals), the concentration was set equal to the detection limit for statistical tests. Pre-event data is limited to the years 2009 to 2014 in the Animas River as changes in treatment facilities could have impacted water quality.

All measured concentrations were log-transformed. Two statistical tests were performed for each metal a parametric t-test assuming unequal variance in the two samples, and a non-parametric Wilcoxon test. Reported p-values are for two-tailed tests, which were used when either result may be of interest, (e.g., Sample A significantly higher or significantly lower than Sample B)

Some sites were only sampled a single time in the snowmelt 2016 period or in the pre-event period, which hampered formal statistical testing for pre-event versus post-event differences in water quality. For these instances, z-scores were used to quantify the magnitude of the deviation of the single observation from a group of observations taken at a specific location and time. The z-score for the single observation (Equation 1) was calculated as:

$$(SO\text{-}GM)/GSD \qquad \text{Equation 9.1}$$

where SO is the single observation measurement, GM is the mean of the group of observations, and GSD is the standard deviation of the group of observations.

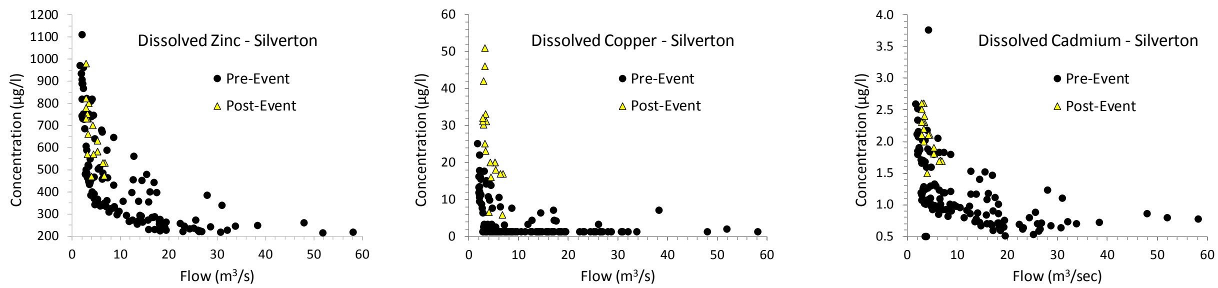


Figure 9-6. The relationship between some dissolved metals and flow is illustrated showing observations at RK 16.4 (Silverton). Some post-event dissolved metal concentrations (yellow triangles) appear elevated relative to pre-event samples (black circles) within some flow ranges.

For data sampled from any distribution (normality need not apply), Chebyshev's Inequality (Kvanli *et al.* 2006) suggests that at least 89% of sampled values will fall between +/-3 standard deviations of the mean. Given this result, the single observation was considered to be markedly different from the group of data if the absolute value of its z-score was ≥3.

Statistical results are summarized in tabular format by location in Sections 9.3–9.6. Tables provide the pre-event mean concentration, post-event mean concentration, and significance levels (p-values) for both statistical tests. To facilitate visual interpretation, results in the tables are color coded according to the scheme shown in Figure 9-8. Yellow indicates statistically significant increases in post-event concentrations compared to pre-event concentrations; other colors grade relative to the strength and direction of change of post-event samples.

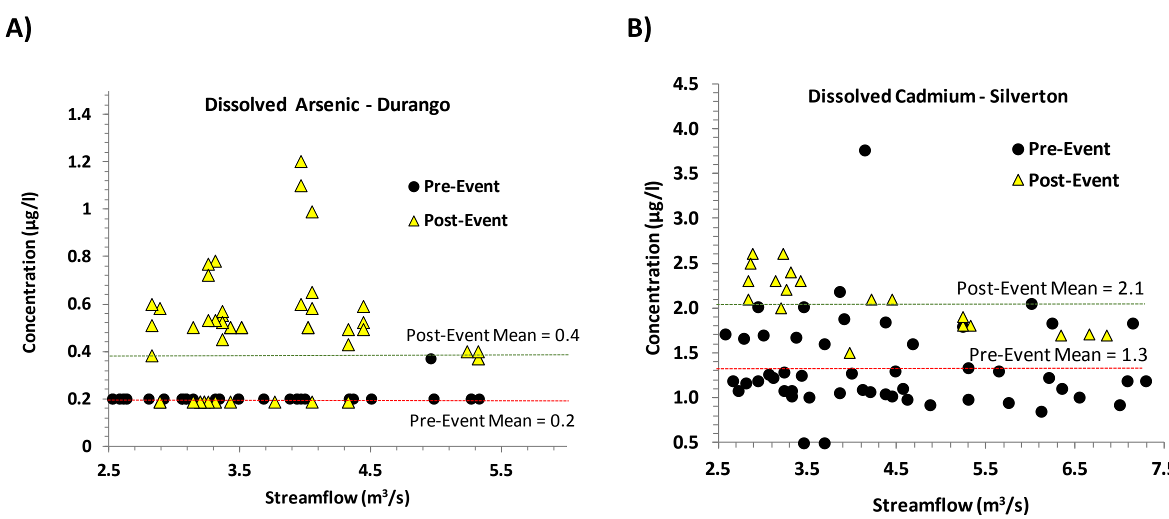


Figure 9-7. Illustration of flow-restricted statistical comparisons between pre-event (black circles) and post-event (yellow triangles) metal concentrations: A) dissolved arsenic at Durango (RK 94) and B) dissolved cadmium at Silverton (RK 16.4). Mean values for the pre-event and post-event samples are shown. Pre-event samples were screened according to flow and all post-event samples within the same range were selected for testing. Pre-event and post-event concentration data were statistically compared using a parametric Student's t-test (assuming unequal variance in the two samples) and a non-parametric Wilcoxon rank sum test. Concentrations were logged (base 10) prior to testing, which produced normal or near-normal data.

9.3 Upper Animas River Post-Event Metals Concentrations

9.3.1 Cement Creek (RK 12.5)

Cement Creek has historically high concentrations of dissolved and total metals relative to other areas, due both to geology and mine discharge. Cement Creek experienced the highest concentrations of metals during the Gold King Mine release and also received some sediments eroded from the mine waste pile. Since the release, EPA contractors have constructed a treatment facility at Gladstone, near the junction of the North Fork and Cement Creek, that receives all of the effluent from Gold King Mine. They have also recovered eroded material from the stream and stabilized the recovered sediment, the waste pile, and the interior of the mine (Figure. 9-8).

The treatment facility tracks effluent rate of flow and samples metals on a frequent basis (Figure 9-10). Flow rate from the mine varies over the year, sharply increasing during the peak of snowmelt. Metal concentrations average somewhat lower than the estimates used in Chapter 3 to determine the mass of material spilled from the mine. The facility received approximately 733,000 kg of metals from the Gold King Mine from October 2015 through July 2016 and removed about 79% of the mass from the effluent; Cement Creek received approximately 150,000 kg of metals that passed by the facility during this period (Figure 9-10B). Treatment statistics are provided on a monthly basis in Table 9-2. As can be seen from the table and Figure 9-10B, the facility was effective in removing metals during a large spike in inflow experienced during snowmelt.

Post > Pre	Both p-values < 0.05
Post > Pre	One p-value < 0.05
Post = Pre	Neither p-value < 0.05
Post < Pre	One p-value < 0.05
Post < Pre	Both p-values < 0.05

Figure 9-8. Color coding of statistical test results in tables presenting comparisons of pre- and post Gold King Mine release metals concentrations. Statistical test comparison p-values are coded according to the scheme shown. Post-event means can increase or decrease relative to pre-event samples.

Although treatment has removed a large mass of metals from the Gold King Mine effluent, there are numerous other mines in the watershed that also impact Cement Creek. Cement Creek continues to have prominent yellowboy coloring due to ongoing AMD leakage from numerous mines in the watershed.

The time trace of all samples collected since August 5, 2015 show some trends in metals since the release. Time series of post-event concentrations of eight total metals in Cement Creek water samples since August 2015 are shown in Figure 9-11. All metals have declined since the release. Concentrations tended to increase slightly during the late summer months, following expected low-flow patterns (Spruill 1987). Total concentrations did not increase during the spring snowmelt as might be expected with particle mobility, given that peak flow in 2016 was the fourth highest observed in 20 years of record at the USGS gage (provisional). The ratio of lead to aluminum used as a signature of the GKM release shown in Figure 9-11 was initially high after the release and has decreased over time. This indicates that the effects of the release on water quality have diminished relative to the chronic background water quality resulting from ongoing acid mine drainage.

Despite observed trends toward lower concentrations evident in post-event water samples (Figure 9-11), many dissolved and total metals water concentrations were statistically increased in Cement Creek relative to pre-event observations (Table 9-3); recent snowmelt data are not included in these comparisons. The majority of the change was made up of particulates, especially iron, and some additional aluminum and manganese. Increased particulates could reflect treatment effects on water chemistry and/or materials left behind in the stream during the release.

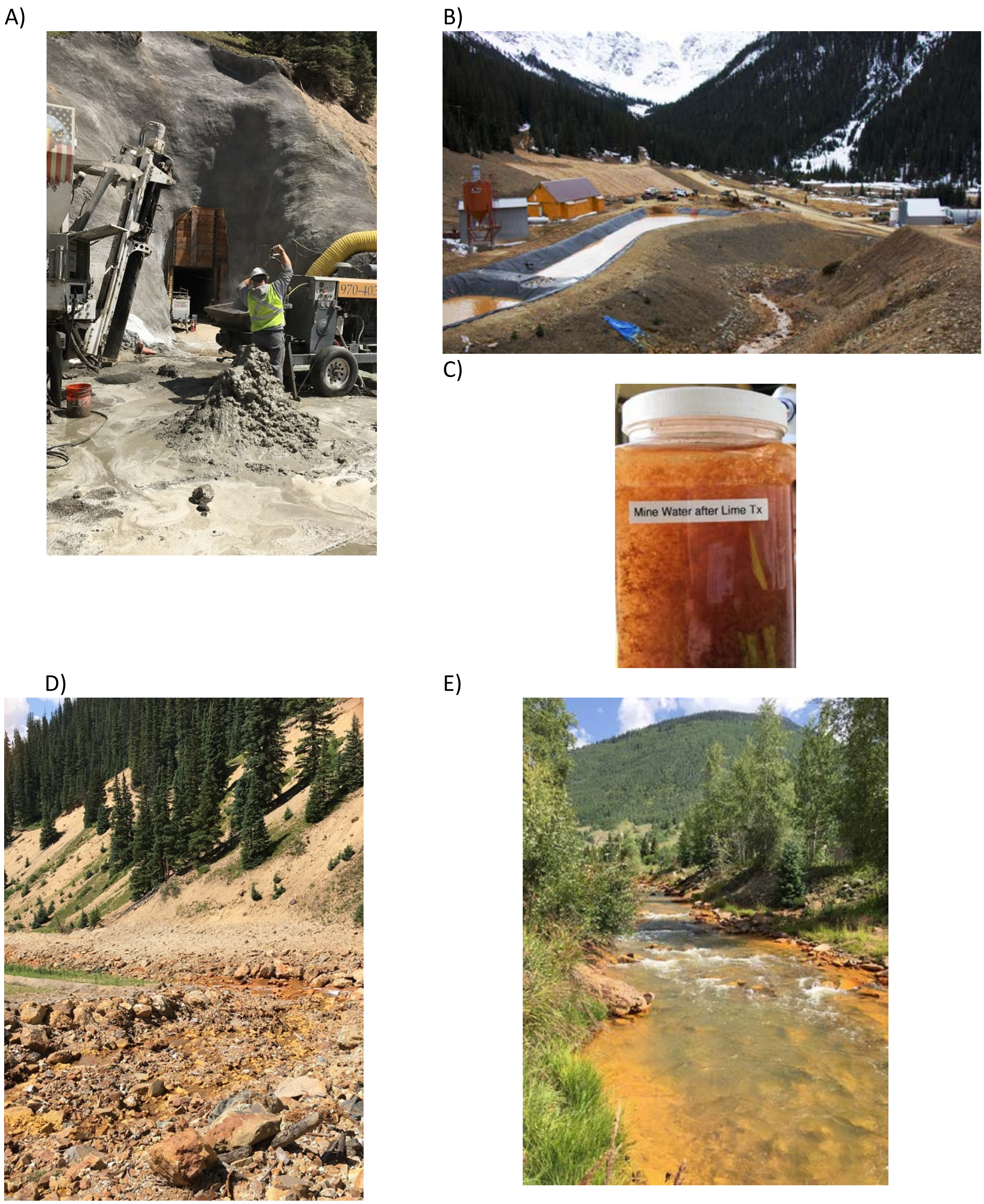
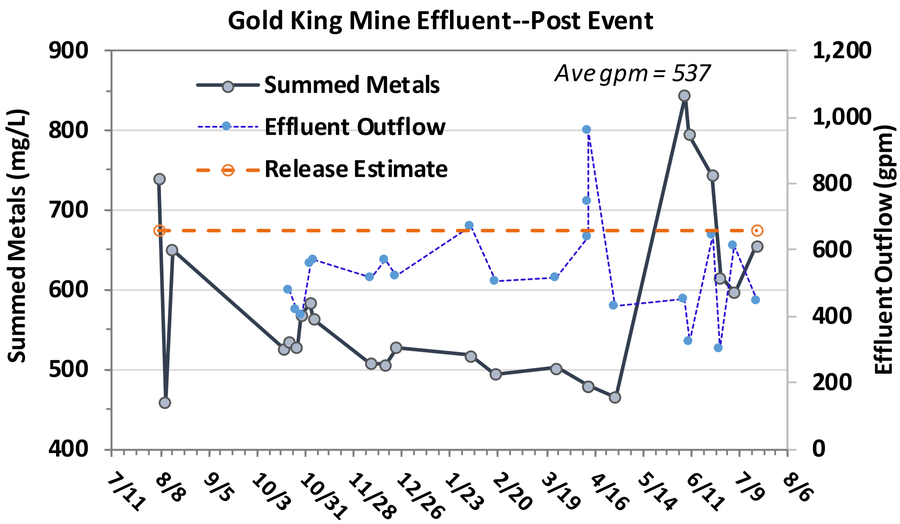


Figure 9-9. A) Gold King Mine (GKM) entrance August 2016; B) GKM setting ponds and Gladstone Water Treatment Plant (from EPA 2016); C) Treated GKM effluent; D) stabilized North Fork Cement Creek below mine; E) Cement Creek in Silverton.

A)



B)

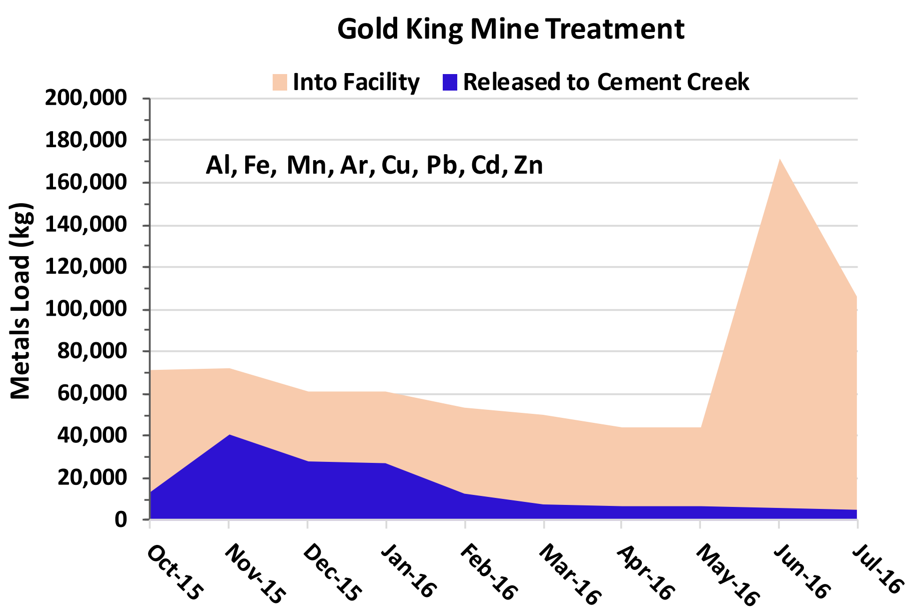


Figure 9-10. A) Weekly statistics on rate of inflow of effluent and total metals concentrations received at the Gladstone treatment facility from the Gold King Mine. B) Treatment efficiency of Gold King Mine effluent shown as inflow of metals to mass of metals released to Cement Creek.

Table 9-2. Gold King Mine Treatment Facility Efficacy in Removing Metals from Mine Influent Before Release to Cement Creek. Data compiled monthly by EPA contractors at the facility.

		Metals Mass (kg)									
		Oct-15	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16
Aluminum	Into Facility	9,185	9,526	7,862	8,165	6,577	6,350	5,897	5,897	26,422	17,010
	Released to Cement Creek	1,826	5,443	2,759	2,875	530	91	88	88	425	531
Iron	Into Facility	38,556	38,556	32,961	33,566	28,577	25,855	22,907	22,907	115,667	65,772
	Released to Cement Creek	4,956	18,597	11,959	11,014	1,991	181	209	209	877	435
Manganese	Into Facility	12,701	13,381	11,491	10,886	10,433	10,433	8,845	8,845	8,278	10,660
	Released to Cement Creek	5,273	11,113	8,892	8,779	9,866	7,258	6,237	6,237	4,037	3,810
Arsenic	Into Facility	13	13	11	10	10	9	8	8	82	31
	Released to Cement Creek	1	4	3	3	1	0	0	0	1	0
Copper	Into Facility	2,064	2,019	1,663	1,633	1,542	1,452	1,293	1,293	4,366	2,994
	Released to Cement Creek	332	1,157	654	973	105	12	13	13	33	23
Lead	Into Facility	14	13	12	12	12	10	9	9	11	13
	Released to Cement Creek	2	10	3	3	1	0	0	0	0	0
Cadmium	Into Facility	23	25	21	21	19	18	16	16	62	37
	Released to Cement Creek	5	15	12	9	3	2	2	2	2	2
Zinc	Into Facility	8,392	8,165	6,653	6,350	6,124	5,897	4,990	4,990	16,670	9,979
	Released to Cement Creek	1,344	4,513	3,461	3,395	491	118	156	156	181	159
Summed	Into Facility	70,947	71,697	60,674	60,644	53,292	50,024	43,964	43,964	171,559	106,495
	Released to Cement Creek	13,738	40,853	27,743	27,051	12,988	7,662	6,706	6,706	5,557	4,961

Total Water Concentration- Cement Creek (RK 12.5)

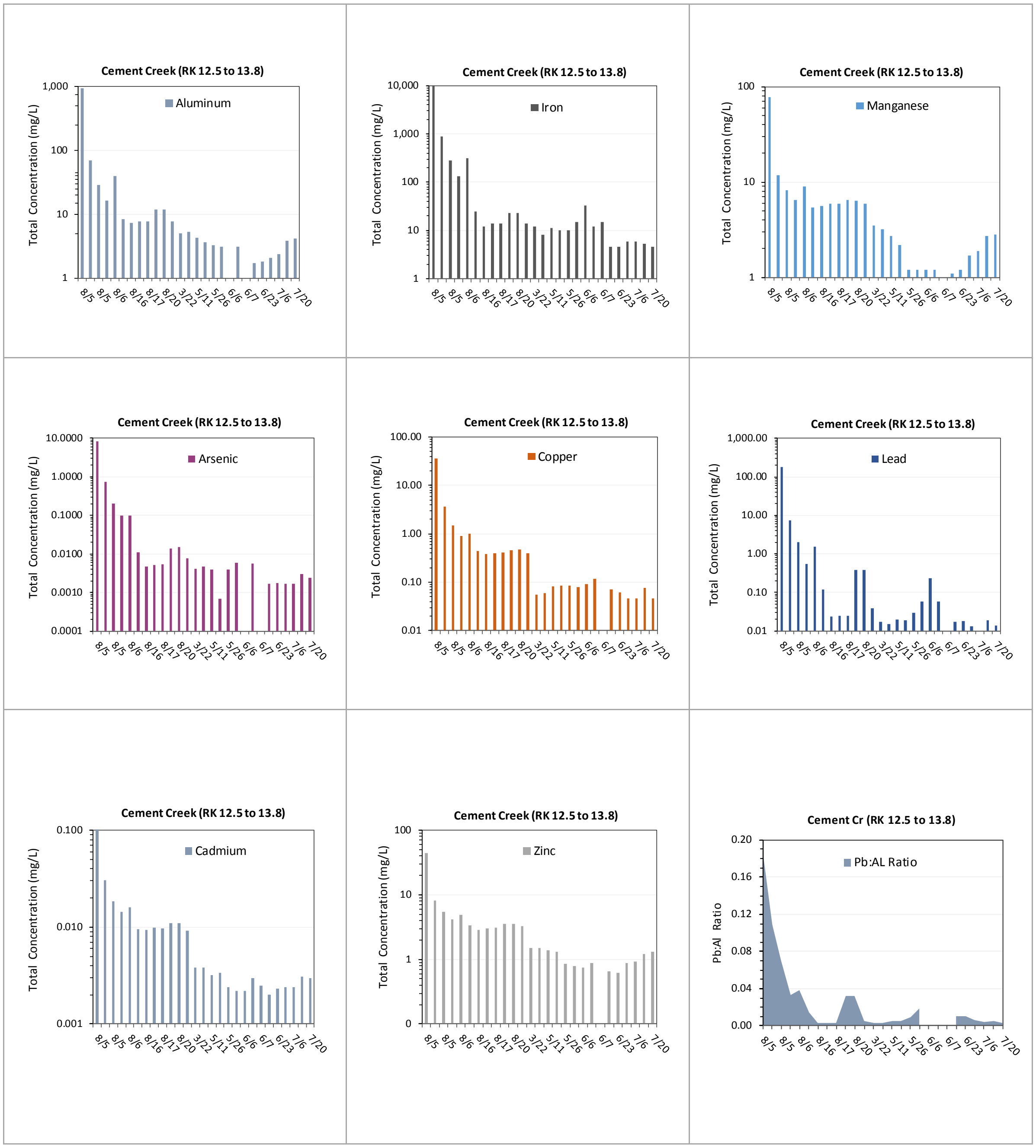


Figure 9-11. Total water concentration of samples collected from Cement Creek at RK 12.5 to 13.8 from August 5, 2015 to June 30, 2016 sequenced in time. Data were collected between August 5, 2015 and August 26, 2016. Note that dates are not uniform among sites; two samples could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple samples provided in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. 2016 snowmelt data are included, where available. The last date sampled was July 20, 2016. The Gold King Mine plume was clearly evident at this location, but sampling began after the plume. The data presentation is intended to emphasize post-release trends.

Table 9-3. Results of Statistical Analyses Comparing Pre-event and Post-event samples for Cement Creek (RK 12.5). Data include samples that were collected at flow between 2.8-7.1 m^3/s. Pre-event includes data from 2009 to 2014. Concentrations were logged (base 10) prior to testing. Mean concentrations are shown, SE=standard error of the mean.

Cement Creek (RK 12.5)

Dissolved Concentration

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	7,050	291	7,600	76	0.15	0.016
Cadmium	6	0	10	0.2	0.00036	0.0001
Copper	106	15	388	14	0.0018	0.0001
Iron	8,700	990	7,900	588	0.54	0.31
Lead	15	2	18	4.7	0.52	0.97
Manganese	4,700	221	6,300	111	0.0037	0.0001
Zinc	2,400	79	3,500	68	0.0002	0.0001
n=	6		17			

Total Concentation

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	6,600	389	8,000	323	0.03	0.003
Cadmium	6	0	10	0.2	0.0001	0.0001
Copper	100	13	370	13	0.00015	0.0001
Iron	9,300	854	15,200	999	0.012	0.0001
Lead	16	2	25	26	0.21	0.42
Manganese	4,500	239	6,300	127	0.0013	0.0001
Zinc	2,300	92	3,400	70	0.00015	0.0001
n=	7		14			

Bed Sediment Concentration

Metal	Pre-Event Sample (mg/kg)	Fall 2015 Average (mg/kg)	SE	z-score
Aluminum	5310	6626	216	-1.4
Cadmium	0.595	2.1	0.07	-4.4
Copper	55.6	193	4.6	-6.4
Iron	143000	50970	1637	11.9
Lead	282	803	21	-5.3
Manganese	478	581	16	-1.4
Zinc	666	557	19	1.2
n=	1	22		

Bed Sediment Concentration

Metal	Pre-Event Sample (mg/kg)	Snowmelt 2016 Average (mg/kg)	SE	z-score
Aluminum	5310	7627	281	-3.0
Cadmium	0.595	1.6	0.32	-1.4
Copper	55.6	101	7.2	-2.3
Iron	143000	74940	5846	4.0
Lead	282	380	25	-1.5
Manganese	478	633	53	-1.1
Zinc	666	540	83	0.4
n=	1	8		

Bed sediment concentrations in Cement Creek are compared in Table 9-3, as well. Note that there was only one pre-event sample, so the previously described z-score approach was used to give this sample context relative to post-event samples. The post-event streambed was elevated in lead, copper, and cadmium relative to the historic sample, while iron decreased significantly.

9.3.2 Animas River Below Silverton (RK 16.4).

The Animas River below Silverton is measured at a location known as A72. This site receives AMD-contaminated water from the entire upper Animas watershed. Cement Creek makes up approximately 20% of that flow. Post-event concentrations of eight total metals sampled at A72 since August 2015 are shown in Figure 9-12. Metals declined after the plume and remained steady or slightly elevated during the low-flow fall period. Lead increased somewhat during spring snowmelt, while other metals declined.

Statistical comparisons of pre- and post-event water and bed sediment concentrations are provided in Table 9-4. Dissolved metals concentrations were generally increased in the post-event period relative to pre-event for most metals and were statistically significant for several metals. Total concentrations of iron and copper were also elevated. Sediment metal concentrations decreased or remained the same relative to pre-event conditions. Most notable was a large decline in aluminum and iron in the bed sediment at this location.

Metals concentrations of bed sediments from August 2015 through snowmelt in 2016 are shown in Figure 9-13. Concentrations of aluminum, iron, and trace metals remained relatively constant during the fall period in the Animas River below Silverton at RK 16.4 (Figure 9-13B and D). During snowmelt (Figure 9-13A and C), aluminum concentration remained the same, iron spiked in May, then receded, and trace metals, such as lead and copper, increased.

The Animas River below Silverton is impaired from historic mining and ongoing AMD and does not have many designated uses. Average historic metals concentrations during the fall exceed many of Colorado's aquatic chronic criteria, but do not exceed acute aquatic criteria on average. The status of the Animas River below Silverton (RK 16.4) did not change relative to chronic and acute water quality criteria for most metals after the Gold King Mine release, except copper, which increased above the chronic threshold on average. Potential toxicity of copper for fish and zinc for benthic communities has previously been identified in risk assessments for AMD in this area by USGS (Besser and Leib 1999) and EPA.

9.4 Middle Animas River Post-Event Metals Concentrations

The middle Animas River includes sampling sites from Baker's Bridge (RK 63.8) to approximately RK 140 near Bondad, Colorado, close to the border between Colorado and New Mexico. There are many sampling locations within this segment that were monitored by a variety of agencies, tribes, and NGOs during and after the GKM plume, and historic samples were available at several locations. Samples in nearby proximity were combined for graphical presentation; statistical comparisons only included data from the same location.

The river segment between Baker's Bridge and the Durango area was an important depositional zone during passage of the Gold King Mine plume. Depositional patterns estimated by the WASP model are shown in Figure 9-14. Modeling estimated that between 103,000 to 75,000 kg of metal mass (up to 30% of plume total) settled between Bakers Bridge and Durango (Chapter 6). Another 262,000 to 335,000 likely deposited upstream of Baker's Bridge.

Total Water Concentration--Animas River Below Silverton (RK 16.4)

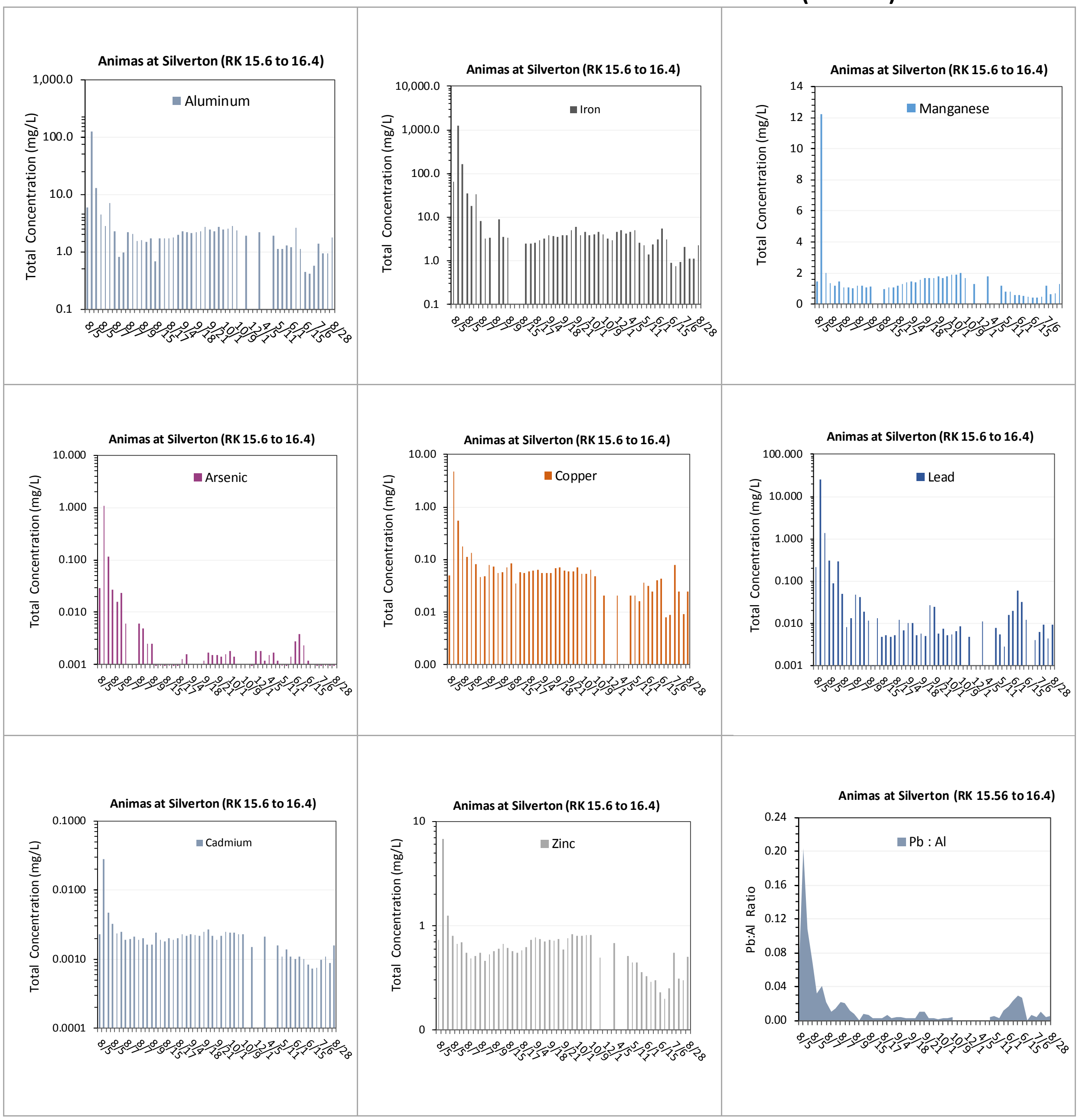


Figure 9-12. Total water concentration of samples collected from the Animas River at RK 16.4 (below Silverton) from August 5, 2015 to June 30, 2016 sequenced in time. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. 2016 snowmelt data are included, where available. The Gold King Mine plume was clearly evident at this location but sampling began after the plume. The data presentation is intended to emphasize post-release trends.

Table 9-4. Results of Statistical Analyses Comparing Pre-event and Post-event samples in the Animas River at RK 16.4 (below Silverton, Colorado). Data include samples that were collected at flow between 2.8-7.1 m^3/s. Concentrations were logged (base 10) prior to testing. Mean concentrations are shown, SE=standard error of the mean.

Animas River Below Silverton (RK 16.4)

Dissolved Concentration

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	46	22	160	107	0.0016	0.0014
Cadmium	1.3	0.09	2.1	0.08	<0.0001	<0.0001
Copper	2.7	0.75	22.3	2.8	<0.0001	<0.0001
Iron	1406	75	1509	220	0.7	0.75
Lead	0.29	0.04	0.37	0.85	Non-Detection Bias*	
Manganese	1419	69	1471	69	0.7	0.79
Zinc	490	23	651	31	<0.0001	<0.0001
n=	**41**		**19**			

Total Concentration

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	2,207	660	2,053	88	0.68	0.11
Cadmium	2	0	2	0.08	0.27	0.24
Copper	26	3	57	2.6	0.0001	0.00005
Iron	3,038	303	3,746	354	0.05	0.04
Lead	10	29	9	2.4	0.70	0.80
Manganese	1,440	129	1,449	71	0.53	0.63
Zinc	654	40	645	27	0.43	0.60
n=	**11 (9 for Fe, Mn; 10 for Cu)**		**18**			

Bed Sediment Concentration Fall 2015

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	SE	t-test p-value	Wilcoxon p-value
Aluminum	14783	2246	8022	474	0.05	0.002
Cadmium	1.8	0.35	1.1	0.15	0.07	0.11
Copper	128	17	121	15	0.83	0.69
Iron	53455	5688	37866	1471	0.06	0.008
Lead	442	49	310	35	0.08	0.33
Manganese	1793	413	1240	100	0.24	0.18
Zinc	603	79	392	28	0.07	0.03
n=	**5**		**22 (21 for Fe)**			

Bed Sediment Concentration 2016 Snowmelt

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	SE	t-test p-value	Wilcoxon p-value
Aluminum	14,783	2,246	11,100	1284	0.29	0.51
Cadmium	1.8	0.4	1.2	0.58	0.27	0.53
Copper	128	17	100	65	0.5	0.65
Iron	53,455	5,688	56,600	9478	0.74	0.92
Lead	442	49	408	759	0.78	0.64
Manganese	1,793	413	1,670	484	0.74	0.92
Zinc	603	79	455	116	0.27	0.53
n=	**5**		**8**			

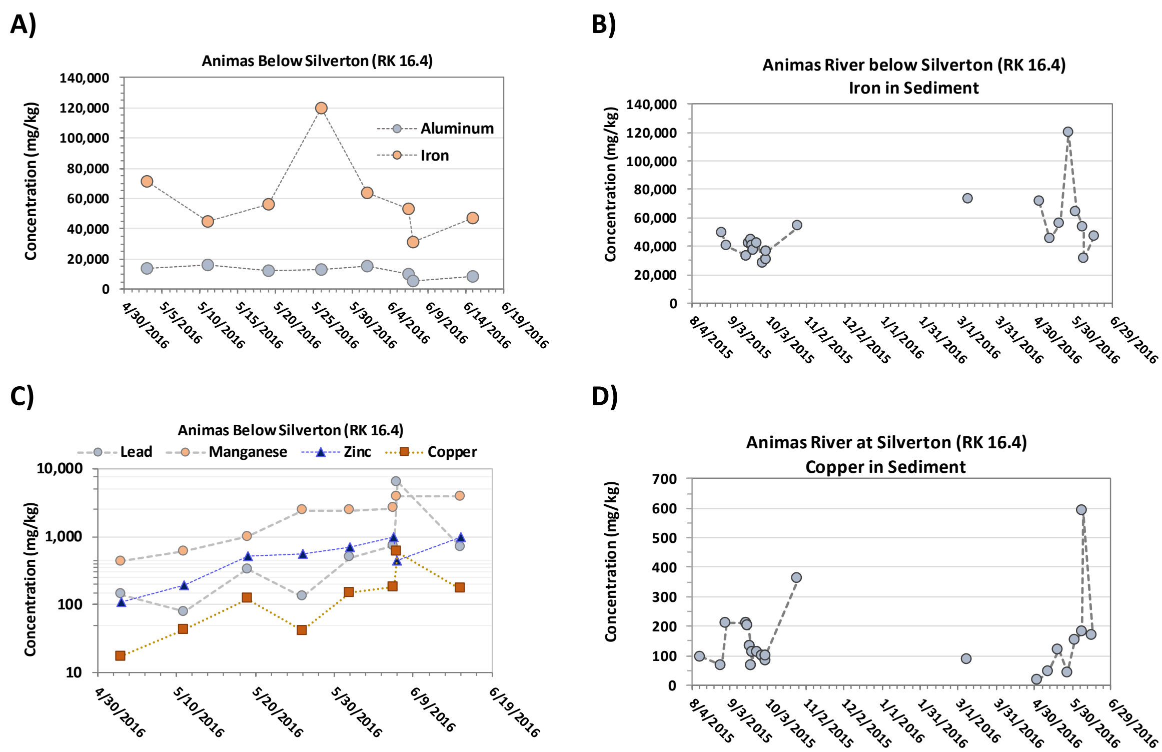


Figure 9-13. Time sequence of sediment concentrations in the Animas River at RK 16.4 (below Silverton). A) Aluminum and iron during snowmelt from April through June 2016; B) Iron from August 5, 2015 through June 2016. Iron is shown because it was the major component of the Gold King Mine Mass; C) Trace metals during during snowmelt from April through June 2016; and D) Copper from August 5, 2015 through June 2016.

9.4.1 Baker's Bridge (RK 64)

The time series of post-event total concentrations of eight metals in the Animas River water samples collected in the vicinity of Baker's Bridge (RK 63.8) from August 2015 through June 2016 is shown in Figure 9-15. There are no pre-event water samples for statistical comparison at this location. The plume was sampled very near peak, and two samples were collected before arrival of the plume as the only representation of pre-event conditions.

After a sharp peak during the plume, water concentrations of most metals declined over the next 2–4 weeks. Some reached levels observed prior to the arrival of the plume (e.g., Pb, As, and Mn); others did not reach the lowest levels previously observed during the summer lower flow period (e.g., Al, Fe, Cu, and Zn) (data not shown). Small increases in zinc, copper, and cadmium during the fall were consistent with expected low flow patterns (e.g., Figure 9-15).

Lead in both the water and sediment showed the most remarkable patterns at this area. The plume was high in particulate lead. Total water concentrations of lead within this reach exceeded the Colorado 1-day domestic supply criteria of 0.05 mg/L for several days during the plume period (Figure. 9-15) and during a portion of the spring snowmelt period. Rapid decline was evident at the long-term monitoring site shown in Figure 9-15. Arsenic and copper also showed the same pattern as lead at this site, but elevated concentrations did not persist in the sediments; baseline concentrations were also high. Other metals fluctuated through the fall months (e.g., arsenic and iron) or increased following the surface water concentration (e.g., zinc; Figure 9-15).

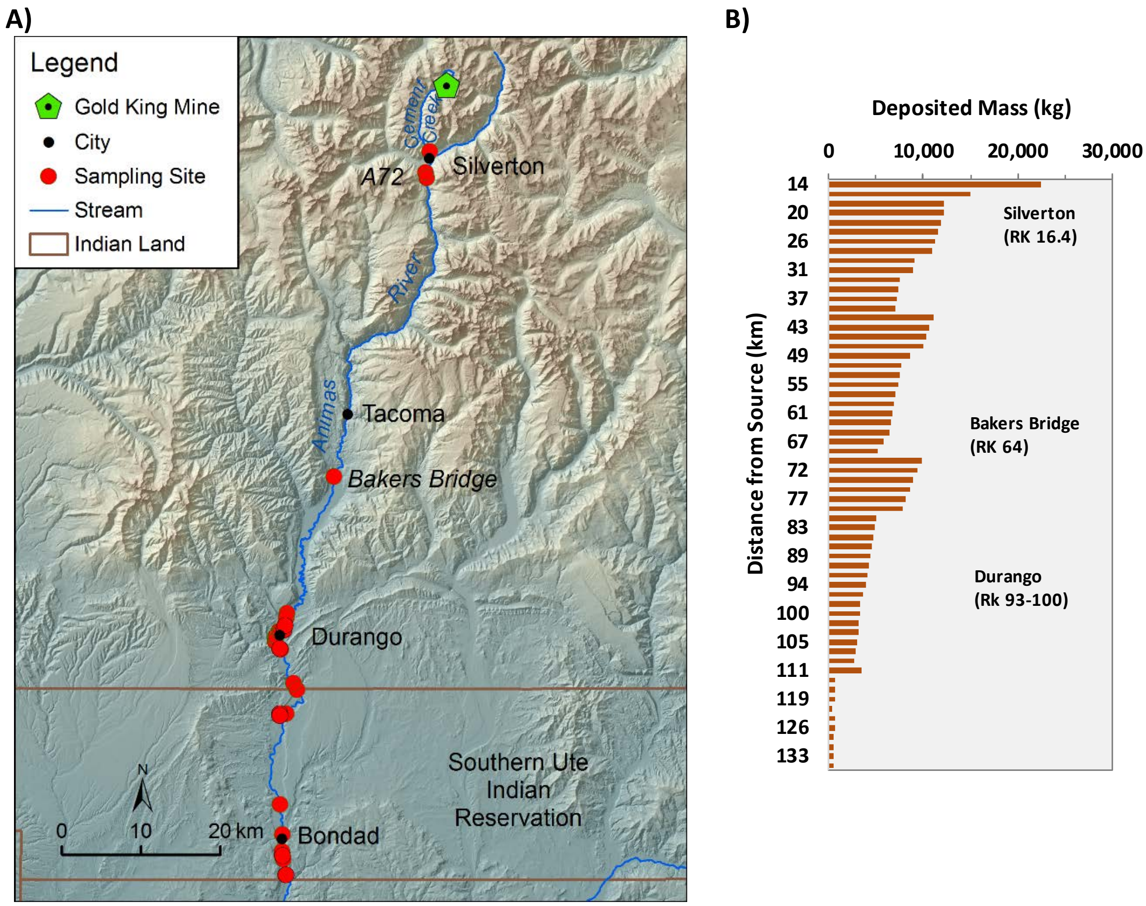


Figure 9-14. Location map of the upper and mid Animas River segment. A) Middle reach of the Animas River from the headwaters including Cement Creek to approximately RK 140 near the Colorado-New Mexico border. Sampling locations are shown as red dots. B) Mass deposits estimated with Water Quality Analysis Simulation Program (WASP) modeling in approximately 2-km segments throughout the middle Animas reach as an indicator of localized deposition zones.

The time sequence of metals in sediment at RK 64.0 are shown for four metals in Figure 9-16. Sediment metals fluctuated widely in the period immediately after the event and during snowmelt. There were differences among metals, and there were no clear patterns during the fall months. Metals in the bed were higher at the time spring sampling began, when streamflow was already responding to snowmelt.

Despite deposition in this reach, metals in the sediment were not elevated relative to pre-event conditions as paired t-tests show in Table 9-5. Concentrations of all metals, with exception of lead, were actually decreased during the fall months following the Gold King Mine release relative to a limited number of historic samples. Concentrations and sample variability were high in both pre- and post-event datasets (there were no pre-event water samples for comparison). In Chapter 6, it was shown that the GKM mass deposited in the bed in this reach of the Animas River was not large relative to the pre-existing sediment mass. This appears to be reflected in the lack of difference between post-event concentrations relative to historic samples.

Total Water Concentration--Animas River RK 63.8 (Bakers Bridge)

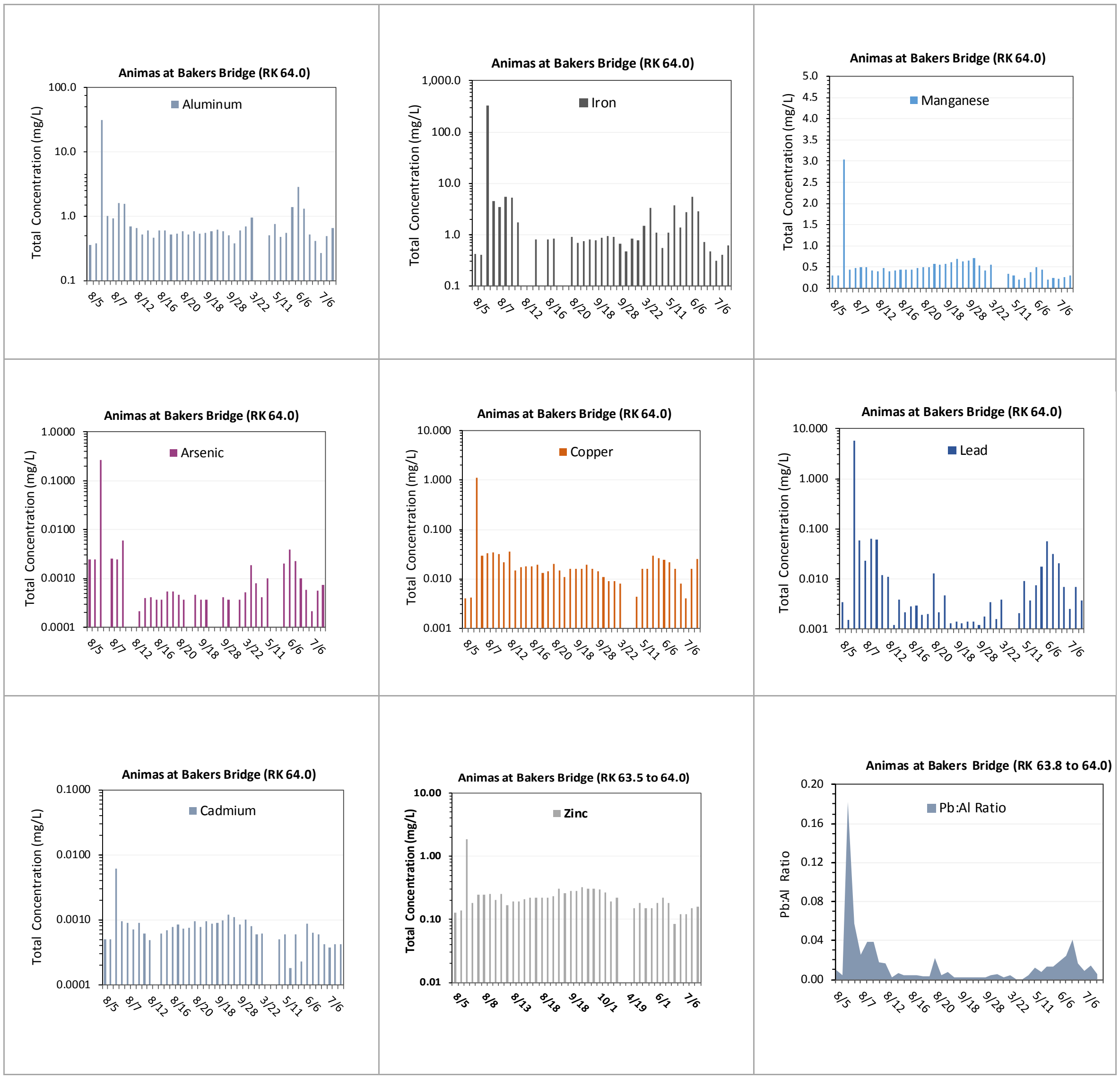


Figure 9-15. Total water concentration of samples collected from the Animas River at RK 63.8 (Baker's Bridge) from August 5, 2015 to June 30, 2016 sequenced in time. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. 2016 snowmelt data are included, where available. The data presentation is intended to emphasize post-release trends.

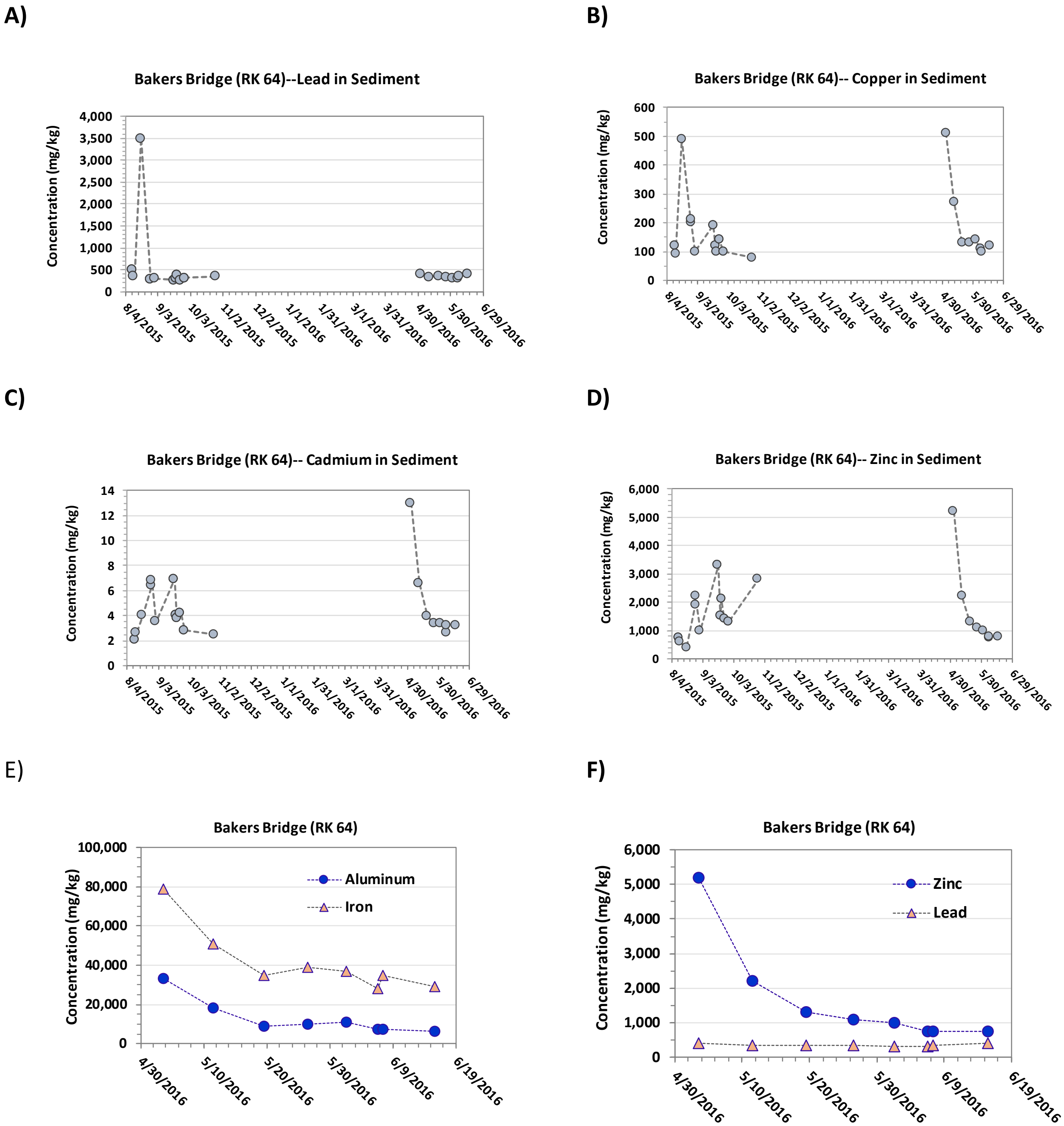


Figure 9-16. Sediment concentration of samples sequenced in time in the Animas River at RK 64 (Bakers Bridge) in mg/kg. All samples from August 8, 2015 to June 30, 2016 for A) lead, B) copper, C) cadmium, and D) zinc are shown. The time series during snowmelt 2016 for E) aluminum and iron, and F) zinc and lead.

Table 9-5. Results of Statistical Tests on Streambed Sediment Metal Concentrations on the Animas River at RK 64.0 (Baker's Bridge) for Pre-event and Fall 2015 Samples. Concentrations were logged (base 10) prior to testing. Mean concentrations are shown, SE=standard error of the mean. Pre-event samples were collected from 2009 to 2014.

Bed Sediment Concentration Fall 2015

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	SE	t-test p-value	Wilcoxon p-value
Aluminum	15,700	7,410	9,500	921	0.70	0.99
Cadmium	7.5	3.9	4	0.38	0.59	0.62
Copper	170	60	135	22	0.85	0.77
Iron	42,500	10,918	28,500	1,316	0.45	0.16
Lead	300	33	370	177	0.12	0.15
Manganese	5,800	2,608	3,600	415	0.67	0.77
Zinc	3,700	1,668	1,400	205	0.22	0.22
n=	**4**		**18 (16 for Fe)**			

Bed Sediment Concentration 2016 Snowmelt

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	SE	t-test p-value	Wilcoxon p-value
Aluminum	15,700	7,410	10,800	3,179	0.64	0.83
Cadmium	8	3.9	4	1.2	0.51	0.67
Copper	170	60	160	50	0.85	0.67
Iron	42,500	10,918	39,400	5,895	0.96	0.67
Lead	300	33	350	11	0.13	0.07
Manganese	5,800	2,608	4,200	1,144	0.64	0.67
Zinc	3,700	1,668	1,300	537	0.10	0.07
n=	**4**		**8**			

Water and sediment sampling of 2016 spring runoff began April 30 after snowmelt had already begun to ramp up for several weeks (Figure 9-16E and F). Mobilization-level flows greater than those at the time of the plume began on April 15 (not shown). Metals concentrations in the water (Figure 9-15) and sediment (Figure 9-16) responded to higher flow. Water samples showed a relatively small increase in concentrations of the typically particulate metals (Al, Fe, Pb, and As) that were consistent with previously documented levels (Church *et al.* 1997). Concentration relationships to flow for many of the metals are provided in Appendix E. Water concentrations rose and fell with flow over the 6-week snowmelt period.

Sediment concentrations were initially high relative to the fall months and declined steadily during the snowmelt through the rising and falling limb of the hydrograph (Figure 9-16E and F). This indicates that Gold King Mine deposits, along with other sediments, were mobilized during this period. Sampling ended around June 15, before spring runoff was fully complete. At the end of sampling, mean bed concentrations were closer to historic conditions than in the fall (Table 9-5).

Estimated mobilization of GKM deposits was discussed in Chapter 6. The WASP water quality model ran resuspension scenarios, estimating that GKM deposits would remobilize, producing small incremental increases in water concentrations relative to the flow volume. Part of the observed increase in metals concentrations was due to flow alone, as peaks in the upper Animas watershed were higher in 2016 than in recent years and flow levels were higher than in pre-event samples. After integrating the 2016 samples into the empirical daily concentration models, it was shown that the small increase in concentrations was sufficient to transport the estimated mass deposited in the headwaters. See Chapter 6 for that analysis.

9.4.2 Durango Area to RK 140

Water and sediment sampling were intensive during and following the Gold King Mine plume in the reach of the Animas River between RK 89 and 99, which includes the city of Durango. Numerous data providers, including CDPHE, EPAR8, and NGOs contributed the 113 data points shown in Figure 9-17, which is a time series of post-event water samples collected from RK 89.9 to 97.9. This compilation of multiple sites in Durango was visually informative for post-event trends and plume characteristics. Note that sites were not combines for statistical tests.

The plume front traversed through the reach in approximately 3 hours and was sampled at a number of locations. Note that half of the samples shown on Figure 9-17 were collected from August 5–20, 2015. Spring 2016 samples are the most recent. Few samples were collected from November 2015 through March 2016. Collectively, the samples taken during the plume defined its maximum concentrations. The plume arrived abruptly on the evening of August 6 with the peak at RK 94.2 (Rotary Park) occurring on August 7 at 1:15. After the core passed through in the first few hours, concentrations declined more slowly through August 10. Some of these data were used for the empirical modeling of the plume (Chapters 4 and 5), which closely follows the pattern shown in Figure 9-17. Several samples taken prior to plume arrival indicated pre-existing conditions. MSI (2016) provided detailed reports of trends in water quality and aquatic life following the Gold King Mine release at this location.

An interesting aspect of the data presentation in Figure 9-17 is the opportunity to generally compare data among providers. Data gaps result when a provider did not test for all metals in the TAL panel (e.g., iron). Differences in laboratory detection limits stair step concentrations (e.g., arsenic). Unexplained variability creates a “comb-like” or fuzzy effect (e.g. manganese or zinc), revealing the magnitude of differences among closely timed or spaced samples due to random or systematic differences in methods among providers. Despite the variability, a coherent picture of water quality emerges. Water quality data are presented in this way at a number of locations in this report as an efficient way to present a considerable amount of data. Potential data issues, such as those mentioned, are not resolved, but merely presented. Readers should examine each figure closely in that there is no set time scale (i.e., samples are merely presented in order; x-axis is not fixed) and concentration scales vary among locations (y-axis scales are not uniform).

A notable aspect of total metals at Durango was declining concentrations following the Gold King Mine plume through the fall months until spring snowmelt began in 2016 (Figure 9-17). Copper, zinc, and aluminum increased for a brief period between August 12 and August 15, then continued the pattern of decline. Concentrations of many metals declined below pre-existing concentrations by October, despite decreasing flow during the period that should have stimulated small increases in some of the metals (due to lower dilution).

There were historic data for total and dissolved metals concentrations in water available for pre- and post-event statistical comparisons at several locations in the middle Animas reach, including Durango (Table 9-6) and the Southern Ute Indian Tribe Reservation at RK 103 to approximately RK 140 (Table 9-7). Concentrations of both dissolved and total metals in the Animas River at Durango were either the same or lower in the post-event period relative to pre-event data, confirming the apparent trends in the time trace plots. The decline in concentration relative to pre-event observations was most notable for total aluminum, and lead. Total aluminum decreased by 48 and 30%, respectively. Given the small change in the dissolved fraction, this change must have been in particulate concentrations. Total iron increased post event.

Pre-event data were also available for the Animas River where it flows through the SUIT reservation, with samples collected from RK 103 to RK 132 km. Dissolved concentrations of several metals declined post-event (i.e., cadmium, copper, lead, manganese) while aluminum and iron did not change.

Total Water Concentration--Animas River Durango Area (RK 89 to 98)

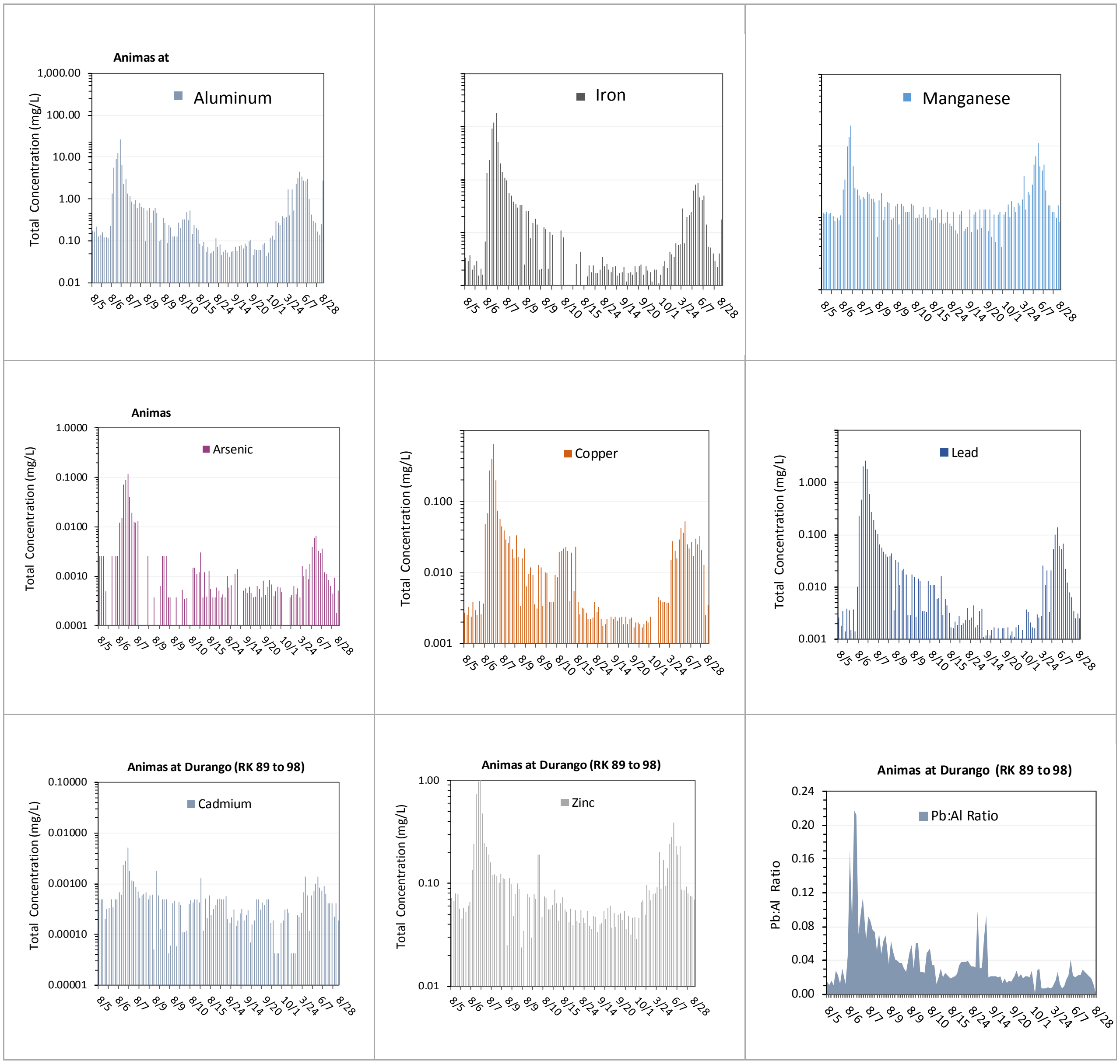


Figure 9-17. Total water concentration of samples collected from the Animas River from RK 89 to 98 from August 5, 2015 to June 30, 2016 sequenced in time. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. 2016 snowmelt data are included, where available.The data presentation is intended to emphasize post-release trends.

Table 9-6. Results of Statistical Analyses Comparing Pre-event and Post-event Dissolved and Total Metals Concentrations in the Animas River at RK 94 (Durango, CO). Flow during the post-event sampling period varied from 2.8-6.0 m^3/s. Concentrations were logged (base 10) prior to testing. Pre-event includes data from 2009 to 2014. There were no pre-event sediment samples at this location. Mean concentrations are shown, SE=standard error of the mean.

Animas River at Durango (RK 90-96)

Dissolved Concentration — **Fall 2015**

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	24	2.0	27	4	0.45	0.65
Cadmium	1.00	0.01	0.14	0.02	Non-Detection Bias	
Copper	1.4	0.12	1.9	0.10	Non-Detection Bias	
Iron	21	2.5	33	14	0.06	0.56
Lead	3	0.08	0.34	0.16	Non-Detection Bias	
Manganese	69	6.3	53	5.1	0.02	0.07
Zinc	36	3.0	29	1.9	0.01	0.04
n=	**40**		**57**			

Total Concentration — **Fall 2015**

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	152	55	94	13	0.005	0.03
Cadmium	0.25	0.02	0.22	0.03	0.27	0.90
Copper	2.7	0.40	3.0	0.73	0.67	0.90
Iron	301	85	211	9.3	0.017	0.12
Lead	3.7	0.54	2.0	0.33	Non-Detection Bias	
Manganese	102	10	83	4.1	0.02	0.05
Zinc	54	6.1	44	1.6	0.02	0.15
n=	**37**		**57**			

Time series of dissolved metals concentrations in water combined from samples are shown in Figure 9-18. Dissolved metals at Durango did not generally trend up or down strongly, except for manganese. Dissolved concentrations showed episodic spikes, some quite large. Dissolved aluminum, for example, increased through much of the first week after the plume passed. Dissolved lead spiked over two orders of magnitude on multiple occasions during the fall, as did copper and arsenic.

The time series of sediment measurements at Durango are shown in Figure 9-19. There were 57 sediment samples collected from the Durango reach of the Animas River, with data more evenly spread through the fall and winter months. Sediment metals did not show declines like total water concentration (Figure 9-17). Seven sediment samples collected by CDPHE on August 13-14 show much higher metal concentrations than the general population. They note that their samples reflect extreme cases and may not be representative of general conditions.

With the exception of these samples, sediment concentrations for each metal reside within a range during the fall months with no pattern of increase or decrease. However, a number of metals increased during spring snowmelt. There were no pre-event bed samples available for statistical comparisons for this segment of the Animas River.

Table 9-7. Results of Statistical Analyses Comparing Pre-event and Post-event Dissolved and Total Metal Concentrations at Sites at RK 103 to 132 (Southern Ute Indian Tribe Reservation). Sample size varied by metal. Pre-event includes data collected from 2009 to 2014. Flow in the post-event period varied between 7.1 and 18.4 m^3/s. Concentrations were logged (base 10) prior to testing. There were no pre-event sediment samples available at this location. Mean concentrations are shown, SE=standard error of the mean.

Southern Ute Indian Reservation (RK ~104-132)

Dissolved Concentration Fall 2015

Metal	Pre-Event (μg/l)	SE	Post-Event (μg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	36	14	46	4.2	0.41	0.37
Cadmium	0.61	0.24	0.06	0.003	Non-Detection Bias	
Copper	4.3	0.33	1.8	0.22	Non-Detection Bias	
Iron	40.8	12	50.8	13	0.37	0.43
Lead	7.8	1.9	0.39	0.09	Non-Detection Bias	
Manganese	27.0	7.5	20.0	3.4	0.32	0.19
Zinc	8.3	40	10.0	0.96	Non-Detection Bias	
n (varies with metal) =	**13-25**		**30-34**			

Total Concentration Fall 2015

Metal	Pre-Event (μg/l)	SE	Post-Event (μg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	387	335	280	49	0.30	0.64
Cadmium	1.4	0.29	0.15	0.19	Non-Detection Bias	
Copper	5.0	0.82	3.9	0.39	0.18	0.05
Iron	435.6	237	543.1	93	0.42	0.18
Lead	13.0	2.2	5.6	1.6	Non-Detection Bias	
Manganese	75.6	4.6	79.7	5.9	0.72	0.27
Zinc	25.2	3.3	27.8	2.2	0.62	0.69
n (varies with metal) =	**15-23**		**30-34**			

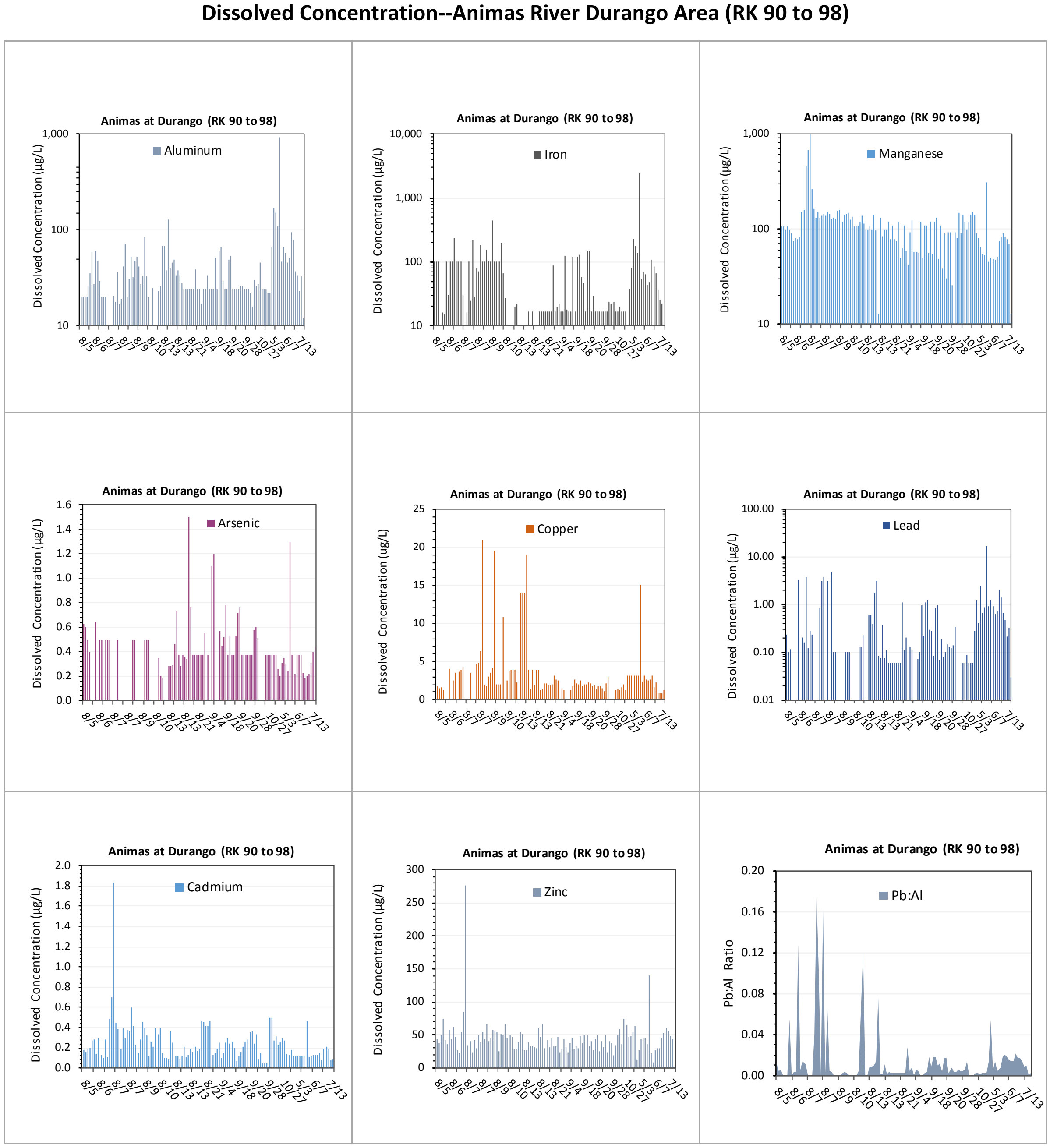


Figure 9-18. Dissolved water concentration of samples collected from the Animas River from RK 90 to 98 from August 5, 2015 to June 30, 2016 sequenced in time. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. 2016 snowmelt data are included, where available. The data presentation is intended to emphasize post-release trends.

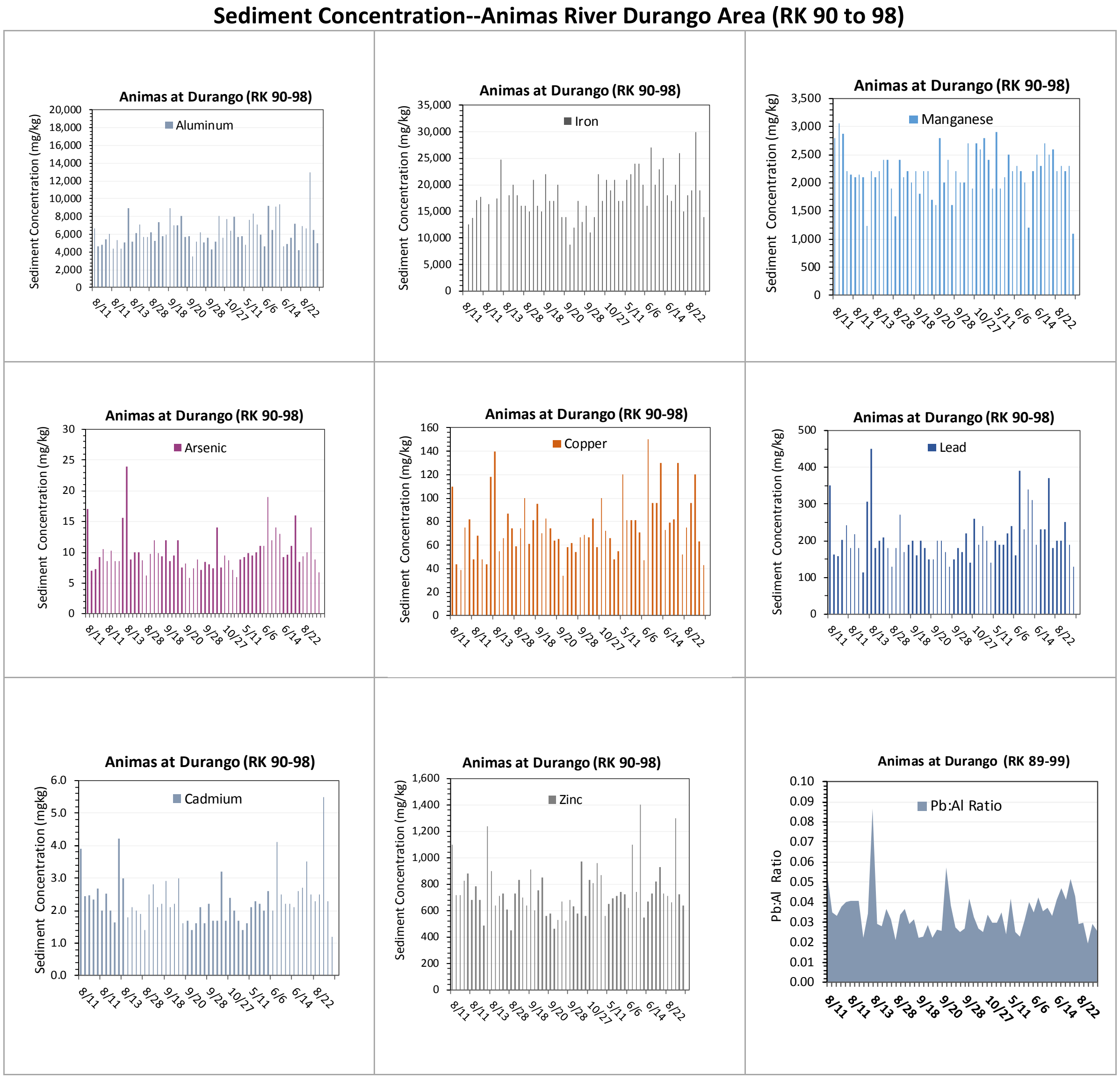


Figure 9-19. Sediment concentration of samples collected from the Animas River between RK 90 and RK 98 from August 5, 2015 to June 30, 2016 sequenced in time. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured less frequently. August 28, 2016 is the last date of measurement. Data from sites collected by multiple providers in close proximity are combined. 2016 snowmelt data are included. The data presentation is intended to emphasize post-release trends.

9.4.3 Spring Snowmelt Middle Animas

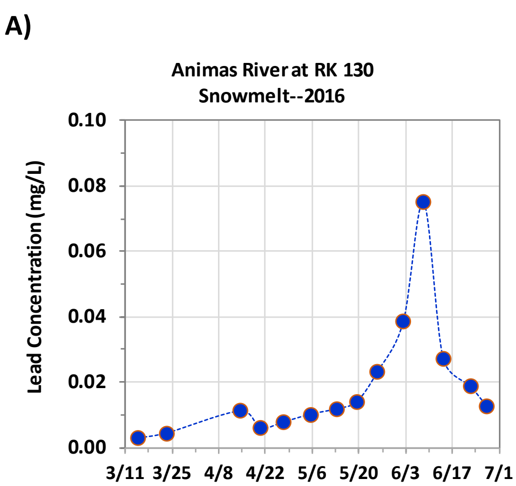
A large mass of metals was deposited in the Animas River as the GKM plume moved through, much of it between RK 16.4 (Silverton) through RK 100 (Durango) (See Chapter 6.) The first high flows that could have mobilized this material from the streambed of the Animas upstream of Durango occurred during spring snowmelt from April to June 2016.

Historically, metals concentrations rise with spring runoff, and water concentrations of all the metals increased with snowmelt runoff in 2016. The trace of total lead in water at RK 91 to 96.1 (Figure 9-20A) and at RK 130.1 (Figure 9-20B) sampled in 2016 is shown in Figure 9-20. Lead concentrations tracked the hydrograph closely. A portion of the increased concentrations in 2016 probably resulted from mobilization of Gold King Mine deposits, and a portion is attributable to higher flows as demonstrated by Church *et al*. (1997).

Regressions of water concentrations as a function of flow were developed in Chapter 6-4 and Appendix E to support modeling daily estimates of metals load (e.g., Figure 6-24.) Samples were collected at higher flows in 2016 than had been previously measured. Observed lead concentrations during high flows were consistent with regressions built from historic data. Peak lead concentration was predicted to be about 0.08 mg/L in Durango. Observed concentration peaked at 0.14 mg/L at Durango (RK 94.2–95.8) and at 0.08 mg/L at RK 130.1 (SUIT; Figure 9-20). Peak concentration of total lead during the Gold King Mine plume was 2.9 mg/L at Durango.

Total and dissolved concentrations of aluminum during snowmelt, historically and in 2016, are shown in relation to streamflow in Figure 9-21 as an example of patterns that were observed for several metals during the spring. USGS sampled metals during snowmelt in 1995 as part of the AMD studies in the headwaters of the Animas River (Church *et al.* 1997). EPA has also sampled metals during the snowmelt period as part of Superfund risk assessment studies.

Aluminum concentrations were elevated during snowmelt sampling. Total and dissolved aluminum was positively correlated with flow (Figure 9-21A and C). In 2016, a few of the samples appeared very high relative to historical data, while others fit within the general population at higher flows. The 2016 data show strong hysteresis (Figure 9-21B), with much larger concentrations on the rising limb than observed



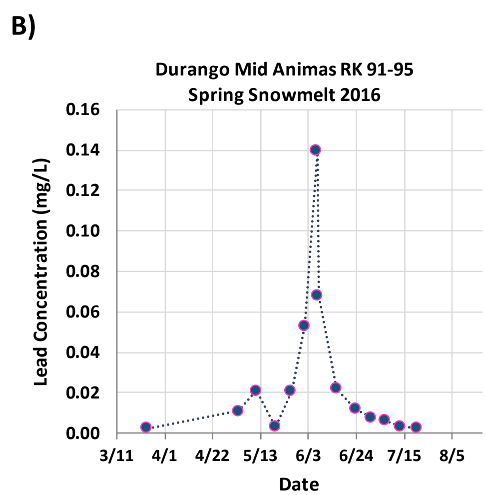


Figure 9-20. Total concentration of lead in water samples collected from the Animas River during the 2016 snowmelt hydrograph A) at RK 130 (Southern Ute Indian Tribe [SUIT] Reservation), and B) at sites combined from RK 91 to 95.

historically, but similar concentrations at the peak and on the falling limb. Figure 9-21C highlights 2016 samples within the regression of aluminum concentration with flow. Four samples that were collected earlier in the snowmelt period are markedly higher, while later samples fall into the predicted range. This suggests that Gold King Mine deposits mobilized earlier on the snowmelt hydrograph.

The simulated daily concentrations of total lead and copper based on the regressions of concentrations relative to flow are shown in Figure 9-21D and E. Regressions for additional metals are provided in Appendix E. Background concentrations are constructed with historic data and average daily flow at the Durango gage. The regressions were updated with 2016 data for the 2016 trace. The WASP model was also used to predict concentrations. WASP resuspended material according to the same particle and hydraulic criteria calibrated to model deposition during the plume (see Appendix B). The GKM plume deposits were an atypical mixture of aggregated and disaggregated colloidal/particulates compared to inert particles normally modeled. Nevertheless, the estimates of concentration at moderate flows was within the range of observed. Observed and modeled estimates of peak using empirical regressions based on historic data and WASP are all similar in their range of predicted concentrations.

Sediment concentration also responded to snowmelt. Bed sediment concentrations were much lower during 2016 snowmelt than observed immediately after the Gold King Mine plume and tracked water concentrations over the snowmelt period (Figure 9-22). Metals began the snowmelt season at about the same concentrations as in the fall, rose tracking the hydrograph, then fell back to the starting concentration after the peak.

The time sequence of sediment concentrations during the 2016 snowmelt period at RK 63.8 and RK 95.1 is shown in Figure 9-23. At Baker's Bridge (RK 64), sediment metals were initially high and declined in the early phase of snowmelt. Sediment concentrations at Durango, 30 km downstream, increased as they were declining upstream, suggesting deposition for a time in Durango. Bed concentrations of aluminum and iron peaked in Durango within the week of May 19 to May 26, while flow did not peak until 12 days later. Lead and copper peaked with snowmelt. The last sample collected on the fall limb was close to starting levels.

The annual metals load from October 2015 through the spring snowmelt season of 2016 was determined based on the daily concentration estimates illustrated in Figure 9-21. The regressions were updated with samples collected from April to June 2016, as shown in Figure 9-21D and E. The daily mass was computed with the updated 2016 regression, but using the average long-term flow rather than 2016 observed flow to focus on the importance of the sample concentrations (rather than the higher peak flow that occurred in 2016). Measured mass results are shown in Figure 9-24.

A significant mass of individual metals was transported in the Animas River past Durango during snowmelt in 2016. For example, 1.3 million kg of iron was transported during snowmelt. The observed mass of individual metals transported during 2016 snowmelt was far in excess of the mass deposited in the Animas River upstream of Durango during the Gold King Mine plume. Observed mass transport was determined by interpolating daily concentrations (e.g., Figure 9-20) and multiplying by flow volume from the USGS gage.

The concentrations constructed with historic and 2016 snowmelt data, shown in Figure 9-21, indicate that the same general level of metals can be expected to be transported through this reach of river each year, depending on flow. The higher concentrations and mass in 2016 partially reflected the large peak flow in 2016, and partially resulted from resuspension of the GKM deposits. The excess mass due to concentration change only (i.e., excess above background) was calculated as the difference between the 2016 regression and historic data regression, where both were computed with average flow. The estimated excess mass, not attributed to flow, was similar to the Gold King Mine mass deposited in the entire length of the Animas upstream of Durango. Exceptions would include iron and lead, for which the excess transported mass was smaller than the deposited mass. In both cases, the actual transported mass is quite large relative to the deposited mass. These results suggest that a major portion of the mass deposited by the Gold King Mine plume has been transported out of the Animas River at least to this location.

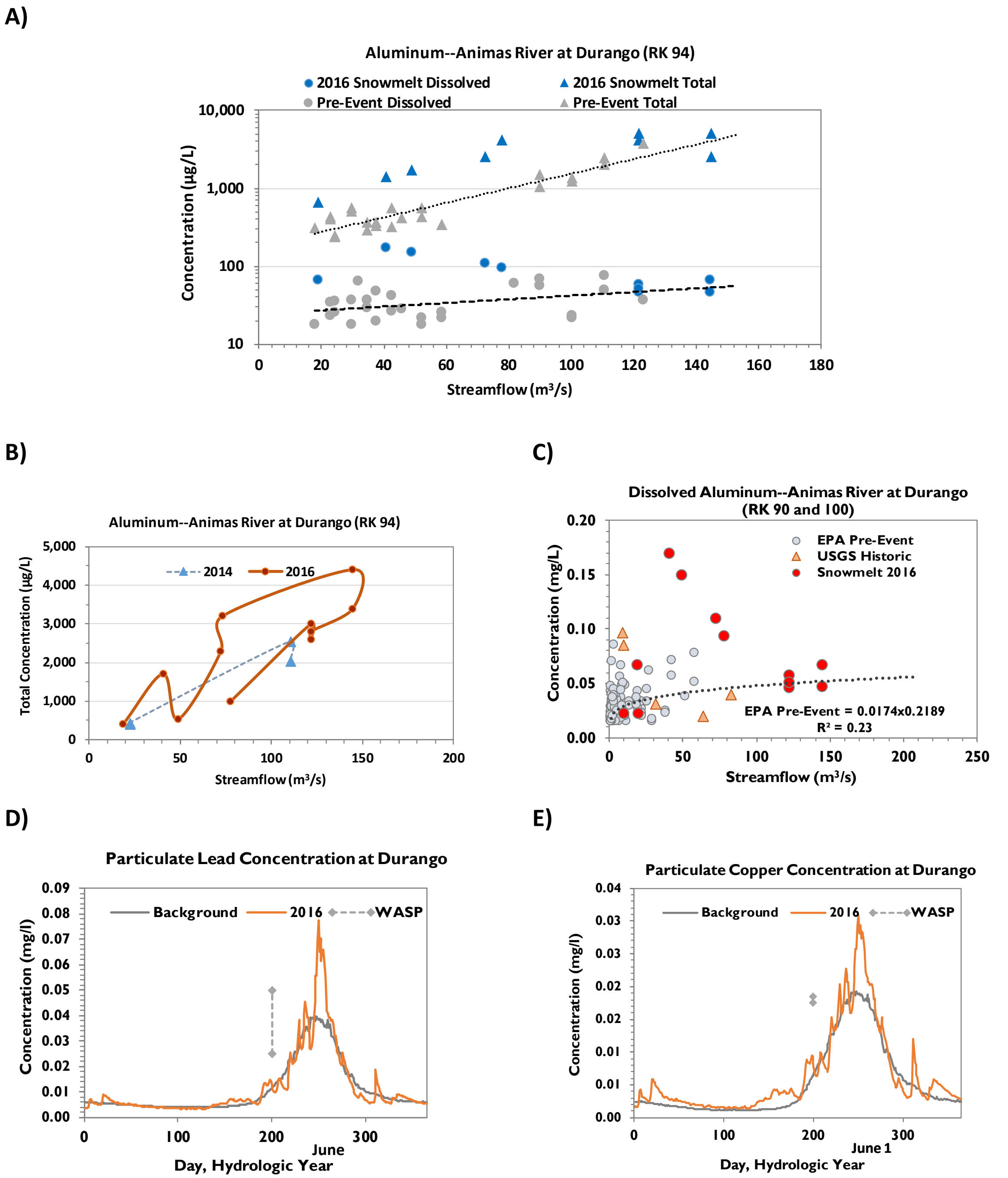


Figure 9-21. Characteristics of metals concentrations during snowmelt hydrographs comparing historic data with 2016 snowmelt. A) Relationship between total and dissolved concentrations of aluminum; B) Demonstration of hysteresis in total aluminum concentration of sequential samples in 2014 and 2016; C) Relationship between flow and dissolved aluminum concentrations post-Gold King Mine release (gray), historically (USGS; triangles), and in 2016 snowmelt (red) samples. Daily load was empirically simulated from daily concentrations of particulate D) lead and E) copper predicted with regressions between flow and metal concentrations computed with historic data only (background), and then including 2016 data. The range of peak concentration predicted by the WASP model concentrations for moderate flow levels from particle mobility of deposited material is shown.

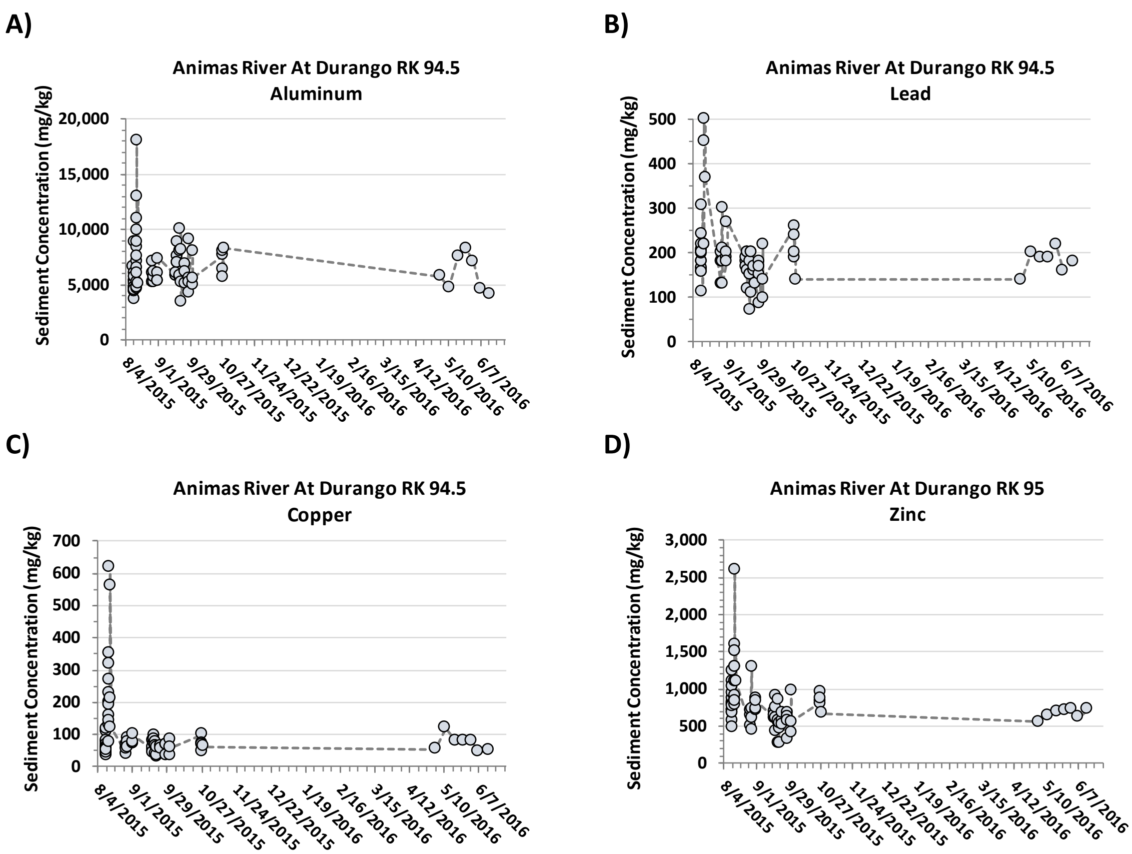


Figure 9-22. Time series of sediment concentrations in the Animas River at RK 94.5 from August 5, 2015 to June 30, 2016 for A) aluminum, B) lead, C) copper, and D) zinc. 2016 snowmelt data are included.

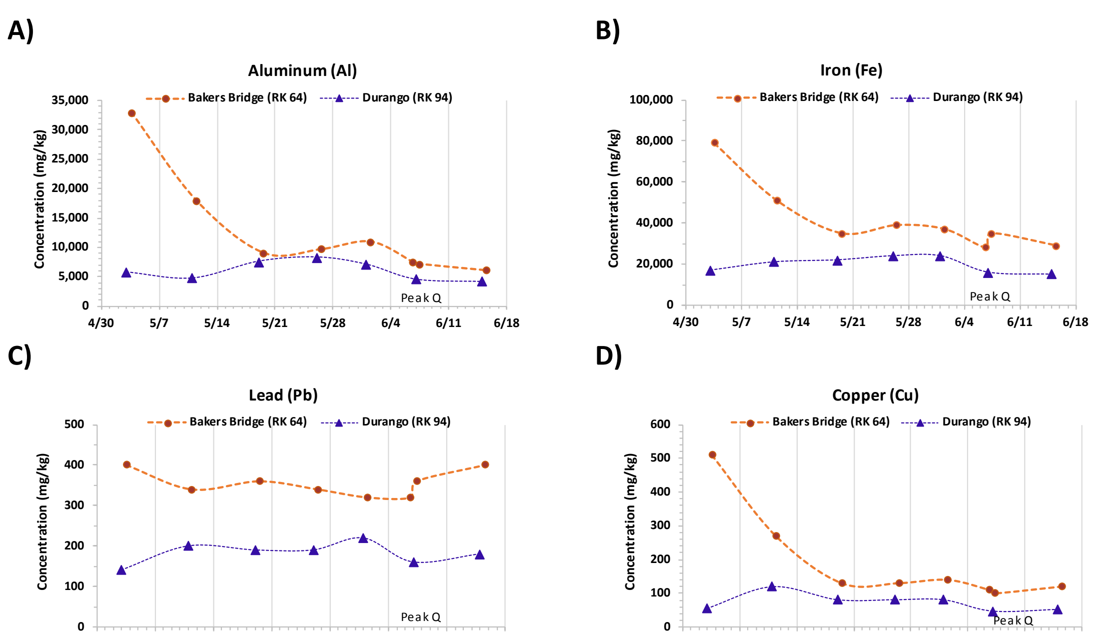


Figure 9-23. Time sequence of sediment samples collected during 2016 snowmelt for four metals comparing the Animas River at RK 63.8 (Baker's Bridge) and RK 94.2 (Durango). A) aluminum, B) iron, C) lead, and D) copper.

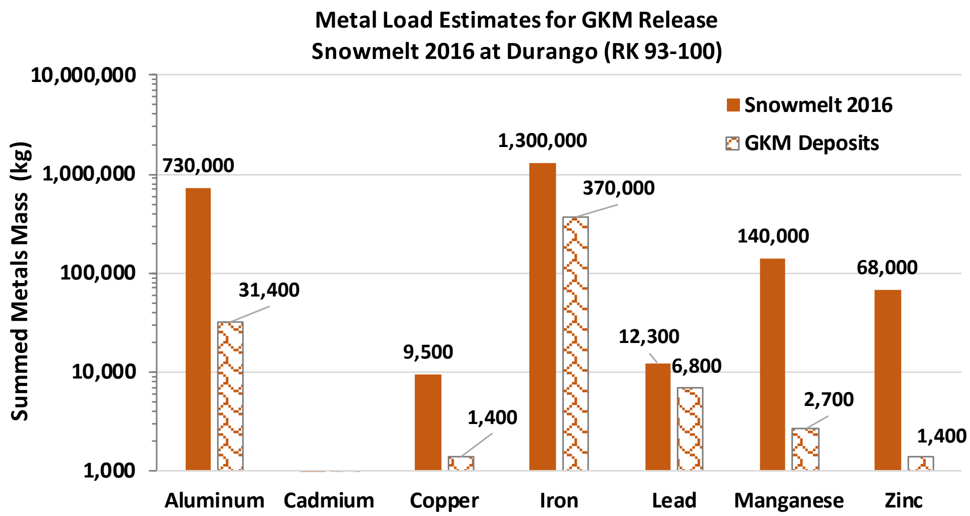


Figure 9-24. Comparison of 2016 annual metals load in excess of average annual load compared to the mass of metals deposited by the Gold King Mine (GKM) plume from RK 13 to RK 100. Measured mass was computed with average daily flow at the USGS gage and concentration interpolated on a daily basis from samples (e.g., Figure 9-20).

9.5 Lower Animas River Post-Event Metals Concentrations

For purposes of this study, the lower Animas River is the segment within New Mexico beginning at approximately RK 140 to the confluence of the Animas and San Juan Rivers at RK 190.2 (Farmington) (Figure 9-25A). There were a number of locations sampled routinely by EPA or NMED within this segment. WASP identified parts of this segment as depositional zones for Gold King Mine metals (Figure 9- 25B). Bed sediment sampling along the Animas River confirmed that aluminum and iron concentrations increase within this local segment (Figure 9-26). Sufficient pre-release data are available at Farmington, NM [anywhere else?] to support a statistical comparison of pre- and post-release metals.

The GKM plume delivered higher concentrations of colloidal/particulate metals than were found in the river prior to the event, although concentrations were much lower at this point in the river than at Durango and northward. Plume analysis found that metals were deposited in the reach, especially within the portion indicated in Figure 9-25 (RK 147.5 to 162.9) as generally predicted by WASP.

The post-event time sequence of water sample concentrations was demonstrated at three monitoring locations in the lower Animas, including the Animas River at RK 151. 6 (NSW-020 below Cedar Hill), RK 162.9 (ADW-010 near Aztec) and RK 190.2 (FW-040 just above the confluence with the San Juan River at Farmington). The Gold King Mine plume concentrations and masses were empirically modeled at RK 162.9 and RK 190.2. Other sites within this segment followed the same temporal patterns as the two shown, with slightly different concentrations reflecting their location. Time series of total concentrations of six metals are shown at these three locations RK 151.6 at NSW-020 below Cedar Hill (Figure 9-27), ADW-010 at RK 162.9 near Aztec (Figure 9-28), and FW-040 at RK 190.2 in Farmington (Figure. 9-29).

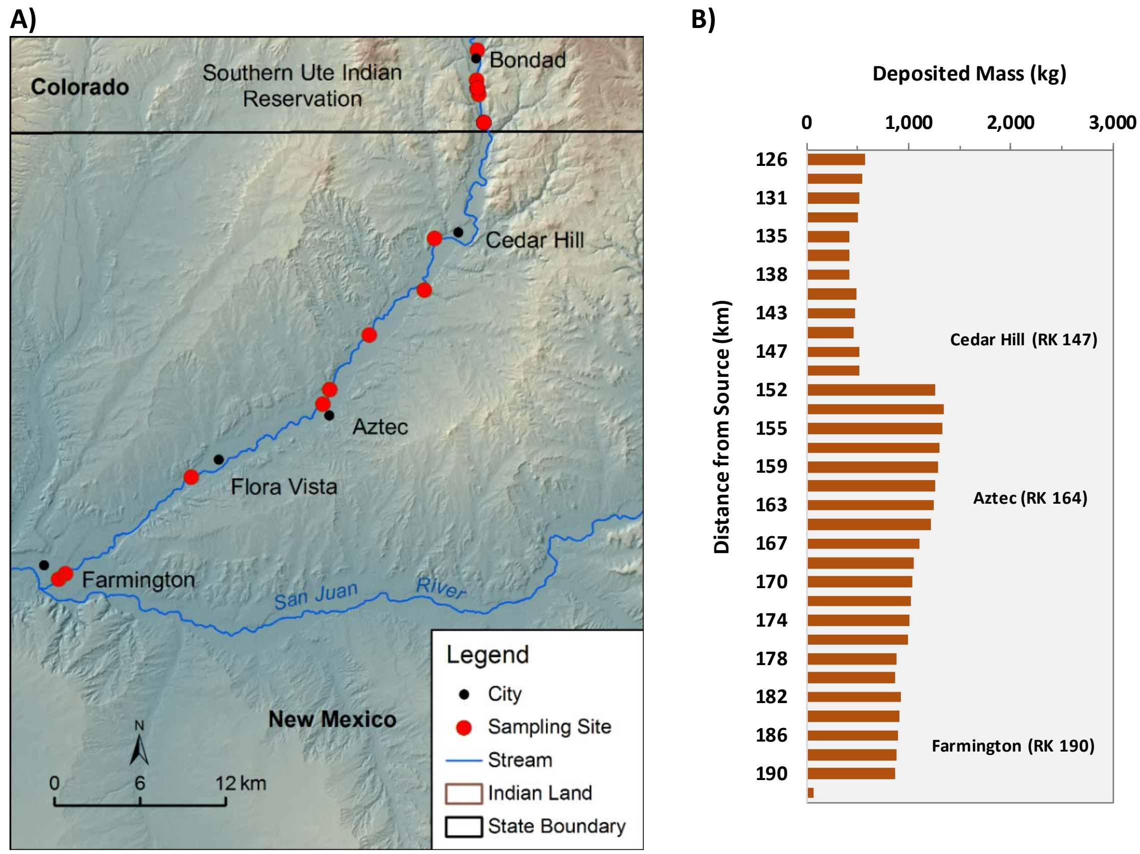


Figure 9-25. Location map of the lower Animas River segment. A) Lower reach of the Animas River from approximately RK 140 to RK 192 at the confluence of the Animas and San Juan Rivers in Farmington. Sampling locations are shown as red dots. B) Mass deposits estimated with Water Quality Analysis Simulation Program (WASP) modeling in approximately 2-km segments throughout the lower Animas reach as an indicator of localized deposition zones.

Water and sediment concentrations of most metals steadily declined for three weeks after the plume passed. Total lead, arsenic, copper, and zinc were particularly active during this time. There are several common observations at these 3 locations. Water concentrations of most metals declined after the high concentrations during the Gold King plume (far left observations on the time sequence). The decline continued for 2 weeks. The sites episodically responded to a series of fall storms starting on August 27.

At individual sites, total lead in the water declined by 1 to 3 orders of magnitude during this period, depending on site. Concentrations for several metals, including lead, initially declined rapidly, plateaued for a period, then declined steeply again through August 26. Total aluminum tended to behave differently than the other metals by not declining during this interval to the same level or at all (e.g., at RK 162.9); part of the increase was in the dissolved fraction that elevated episodically during this period.

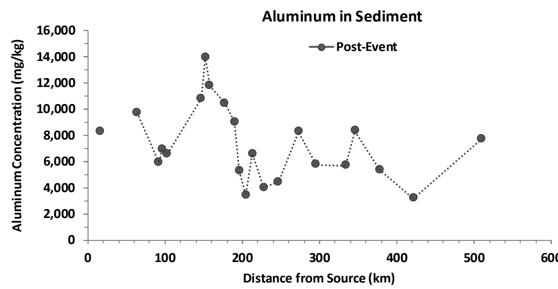
A time series of sediment concentrations of three metals are shown at five locations within the lower Animas River (Figure 9-30). There was a wide range of metals concentrations along the lower Animas, with the highest concentrations found between RK 151.6 and RK 162.9, indicating that these sites are likely historically high deposition zones. Sediment concentrations briefly increased for several weeks after the Gold King Mine plume passed at some locations. Sediment concentrations peaked at most sites by August 12–16, 2015. At the sites with lower concentrations, on the north and southern end of the segment, sediment concentrations began to decline immediately after the passage of the plume.

An intense storm occurred the night of August 26-27, with rainfall of three inches recorded at Aztec Monument. The storm generated high flow in the lower Animas, but did not affect the middle Animas, including Cedar Hill (in the northern portion of this segment). See Figure 9-5B for the storm hydrograph measured at Farmington. The peak from this storm was similar to the June 2016 peak during snowmelt. Two additional storms that affected flow in the lower Animas (and San Juan Rivers) occurred on September 6 and September 24. The flows were large enough in each of these events to resuspend solids deposited during the plume.

Each storm elevated metals significantly, with a subsequent decline back towards pre-event levels, as can be clearly seen in the time series plots. For the August 27 rainfall, storm runoff was rapid and not well-sampled, having peaked during the night. Nevertheless, the storm generated large water concentrations measured long after the hydrograph peak (Figures 9-28 and 9-29) that equaled or exceeded the Gold King Mine plume concentrations. Comparing sites, concentrations increased from north to south.

Importantly, the August 27 storm effectively mobilized plume-deposited metal-rich sediments in the lower Animas (Figure 9-30). After the storm, bed sediment concentrations remained low through the fall. One exception was arsenic, whose concentration increased slowly through the fall. The source of metals in the subsequent fall storms is not clear since the middle and upper Animas did not contribute flow to these events. It was also interesting that the subsequent storms strongly affected water concentrations, but did not strongly affect the streambed, which is likely the case under normal circumstances (i.e., when no plume deposits are present).

A)



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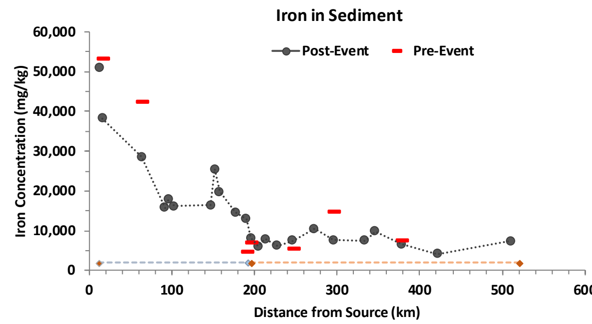


Figure 9-26. A) Aluminum, and B) Iron concentrations averaged at sampling locations plotted by distance from Gold King Mine (GKM) from immediately following the GKM release through September 1, 2015 illustrating the general pattern of existing and GKM release deposition. Higher metals concentrations suggest depositional zones, including the entire upper Animas and locations along the lower Animas and San Juan Rivers. Historic average concentrations are shown as red bars where data was available.

Statistical comparison to pre-event sediment data was possible for the Animas at Farmington (Table 9-8). Many metals in sediment in the post-event period were the same as pre-event samples. This location had the lowest concentrations and deposition within the segment as evident in Figure 9-30.

The storm carried a significantly greater mass of metals through Farmington than the Gold King Mine plume deposited within the lower Animas (Figure 9-31). The minimum estimate of mass for the storm (i.e., 1,300,000 kg) far surpassed the mass carried during the plume and the mass deposited within the reach. Total metals mass calculated from concentrations of the one sample (collected late in the hydrograph of the storm) suggest that GKM deposits could account for only 2% of the mass transported in this one storm (Figure 9-31). The two additional storms would have transported similar amounts. Sediments concentrations did not appear to change with the latter storms, although water concentrations did respond to each storm by rising with the increased stormflow, and then declining over the following several days.

Total Water Concentrations Animas River below Cedar Hill (RK 151.6)

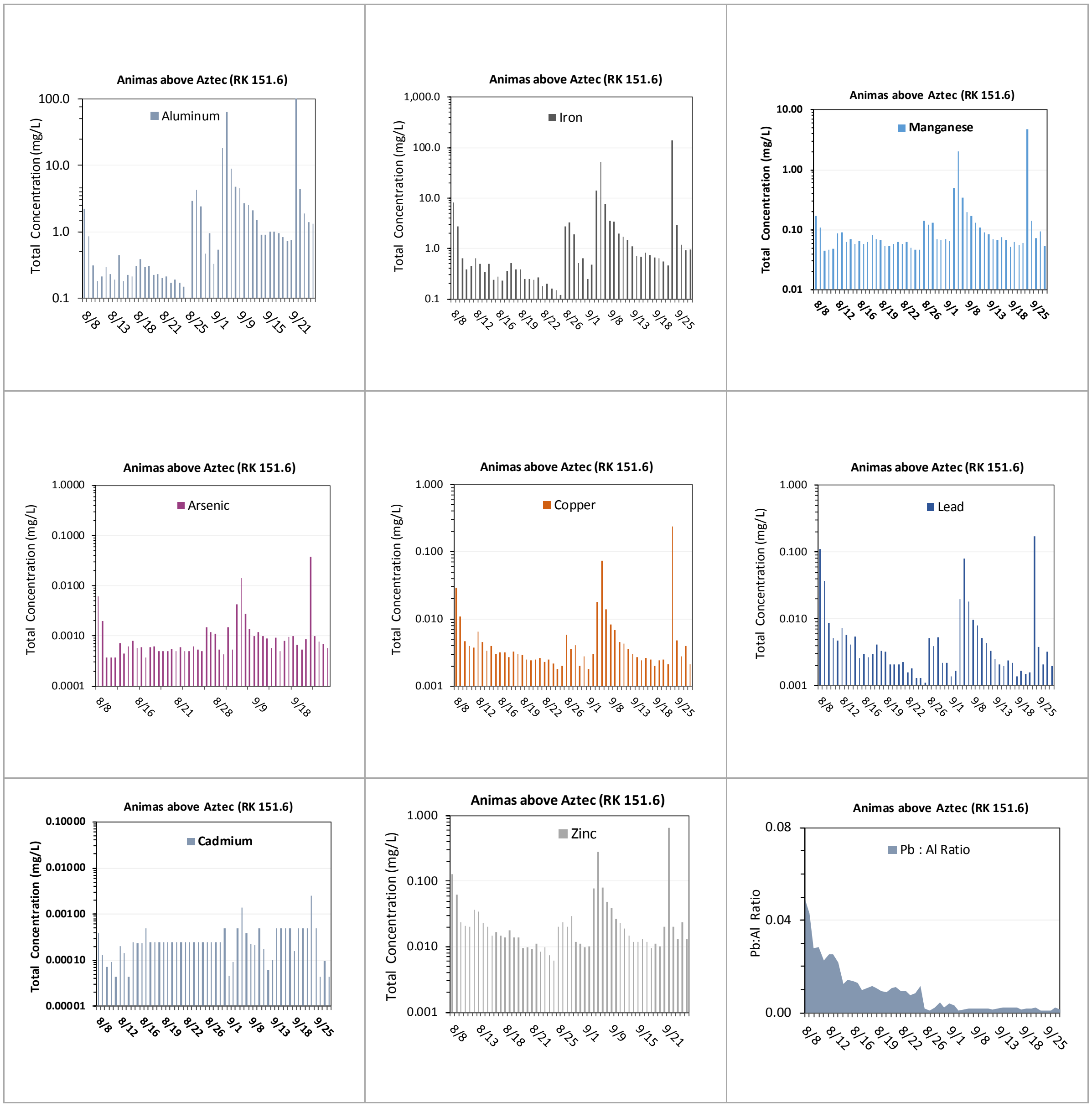


Figure 9-27. Total water concentration of samples collected from the Animas River at RK 151.6 from August 5, 2015 to June 30, 2016 sequenced in time. The last sample shown was collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. October 14, 2015 is the last date of measurement. The data presentation is intended to emphasize post-release trends.

Total Water Concentrations Animas River near Aztec (RK 162.9)

Figure 9-28. Total water concentration of samples collected from the Animas River at RK 163 to 164 from August 5, 2015 to June 30, 2016 sequenced in time. The last sample shown was collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. August 24, 2016 is the last date of measurement. The data presentation is intended to emphasize post-release trends.

Total Water Concentration Animas River at Farmington (RK 190.2)

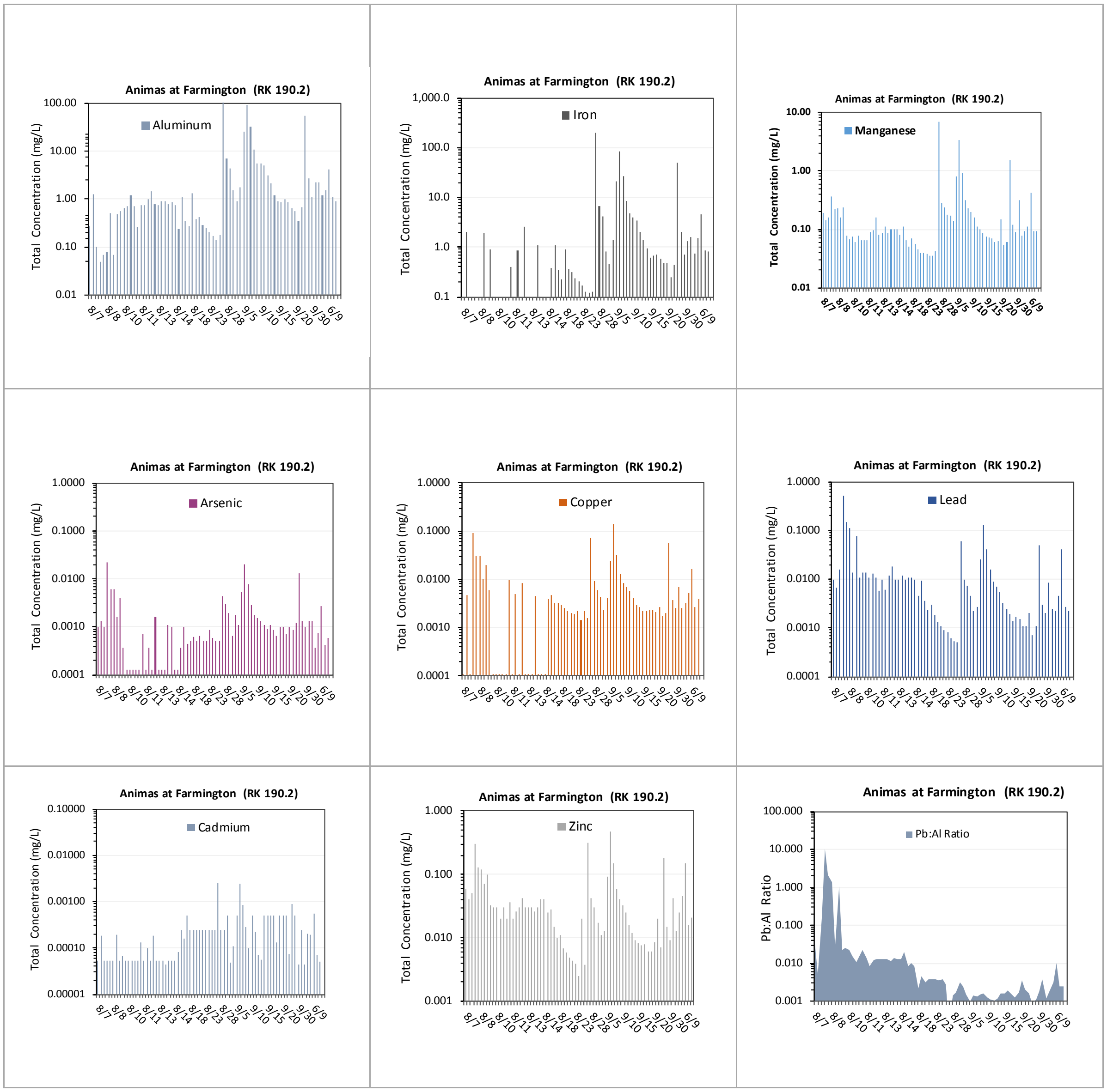


Figure 9-29. Total water concentration of samples collected from the Animas River at RK 190.2 from August 5, 2015 to June 30, 2016 sequenced in time. The last sample shown was collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one sample could have been collected on the same day and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. The last sample was collected November 4, 2016. The data presentation is intended to emphasize post-release trends.

Cedar Hill (RK 147. 5)	below Cedar Hill (RK 151.6)	Aztec (RK 162.9)	Flora Vista (RK 176.6)	Farmington (RK 190.2)

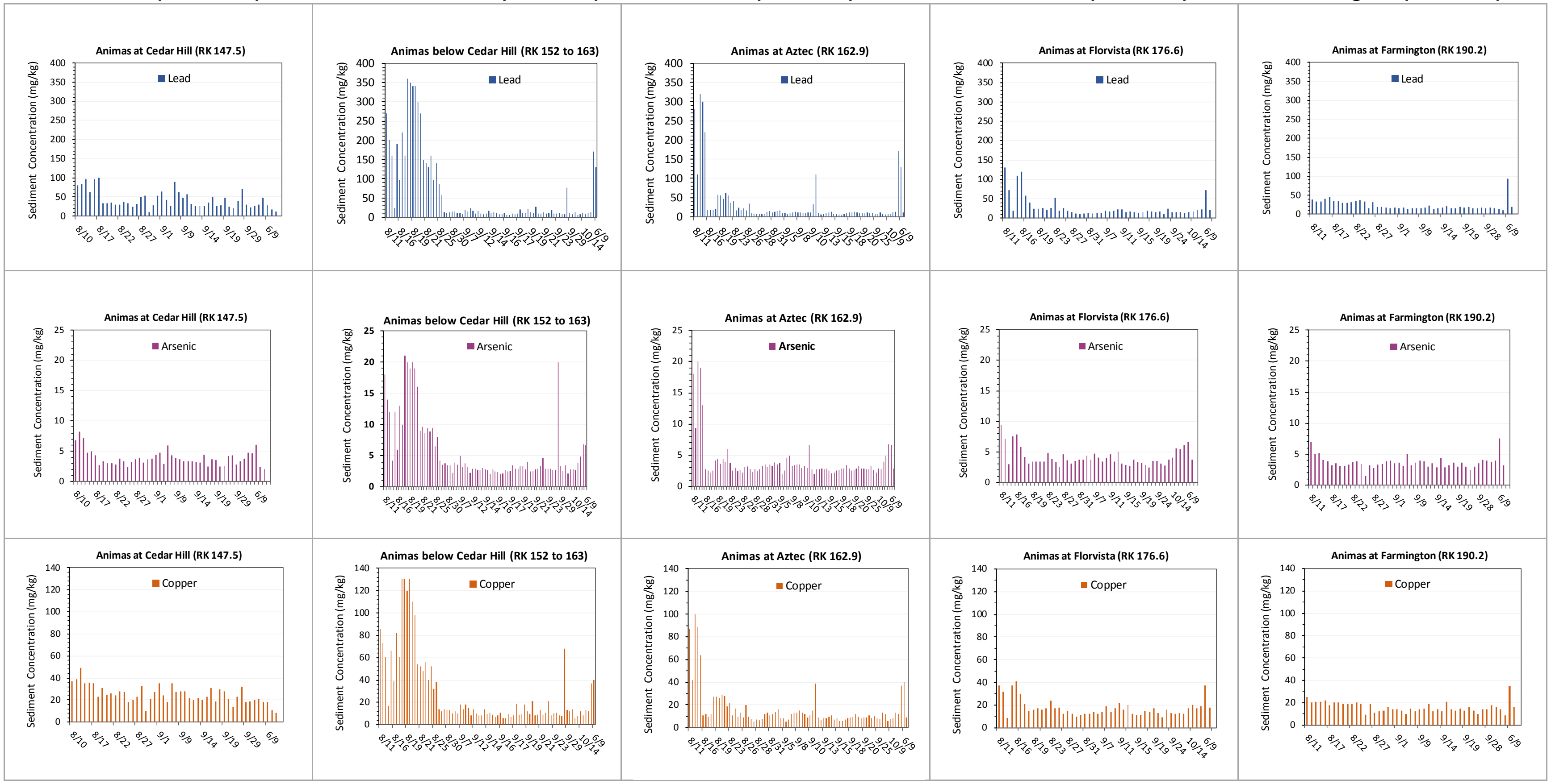
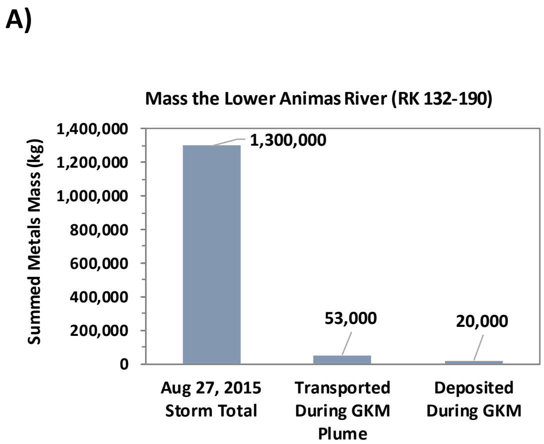


Figure 9-30. Concentration of sediment samples collected from the Animas River at RK 190.2 from August 5, 2015 to June 30, 2016 sequenced in time. The last sample shown was collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one samples could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. August 24-28, 2016 are the last dates of measurement. The data presentation is intended to emphasize post-release trends.



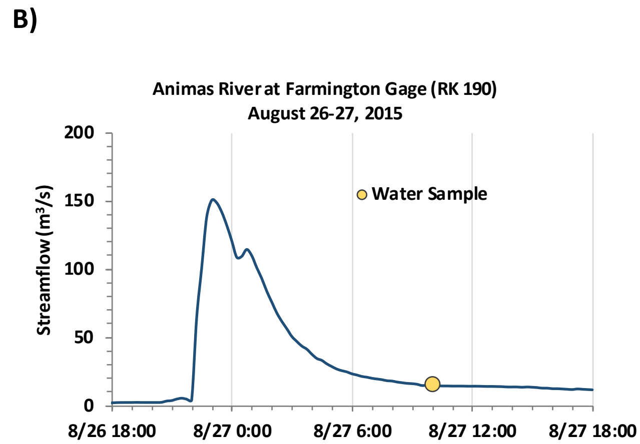


Figure 9-31. A) Summed total metals mass transported in the lower Animas River at Farmington during the storm event on August 27, 2015 three weeks after passage of the Gold King Mine (GKM) plume. Only one sample was collected during this largely nighttime event. B) Lower Animas River streamflow during storm on August 27, 2015, with sampling time plotted. The storm event affected the Animas River from approximately RK 140 to the confluence with the San Juan River and the entire San Juan River at RK 192.

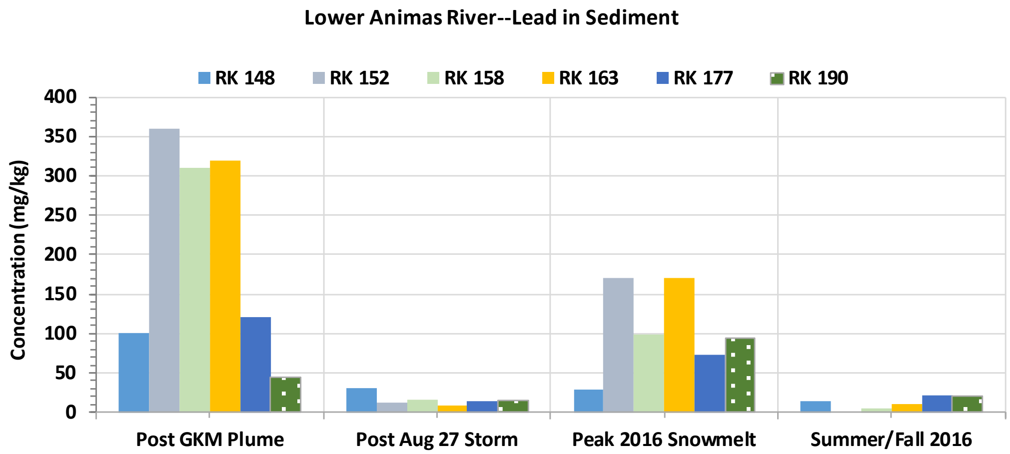
There were little data available for water or sediment concentrations from the lower Animas during the spring snowmelt period of 2016. Water and sediment sampled on June 8 and 9, 2016 were included as the last observation in the time series analysis. Bed sediment metals increased at all sites in the lower Animas River, except Cedar Hill. One sample cannot be statistically tested, but the z-score approach was used to assess if the single sample from the Animas at RK 190.2 was elevated above pre-event levels (Table 9-8). Sediment lead and copper concentrations appeared high during the snowmelt relative to pre-event observations.

The lower Animas received metals transported from the upper Animas over the full snowmelt period, although evidence suggests that Upper Animas GKM deposits were transported relatively early in the 6-week snowmelt runoff. Water concentrations of most metals were somewhat elevated in the lower Animas in the sample collected very near the hydrograph peak, varying by site and metal. More complete sampling at other Animas River locations showed that water concentrations rose and fell throughout the snowmelt hydrograph (e.g., Animas River at RK 130 shown in Figure 9-20).

Bed sediments appeared to follow that pattern as well. Sediment metal concentrations were elevated in the lower Animas, especially lead, copper, and arsenic at each of the sampling locations (Figure. 9-30). The question remained whether sediment and water concentrations would decline in the lower Animas as snowmelt progressed (e.g., as observed at Durango) or deposited materials would be left behind. Samples from August 2016 were examined to answer that question.

To assist comparison of the magnitude of changes to sediment and water metal concentrations in the lower Animas, Figure 9-32 shows the peak concentration of lead during or after the plume (e.g., in the case of sediment, in which samples could be collected up to 10 days later); immediately following the August 27, 2015 storm; and in the snowmelt sample for all six locations in the lower Animas where data were available. Metals deposited in the sediments during the Gold King Mine plume were largely moved out during the August 27 storm. Snowmelt brought more metals into the lower Animas, which, at the peak of snowmelt, were at about 50% of what they were immediately after the GKM plume passage.

A)



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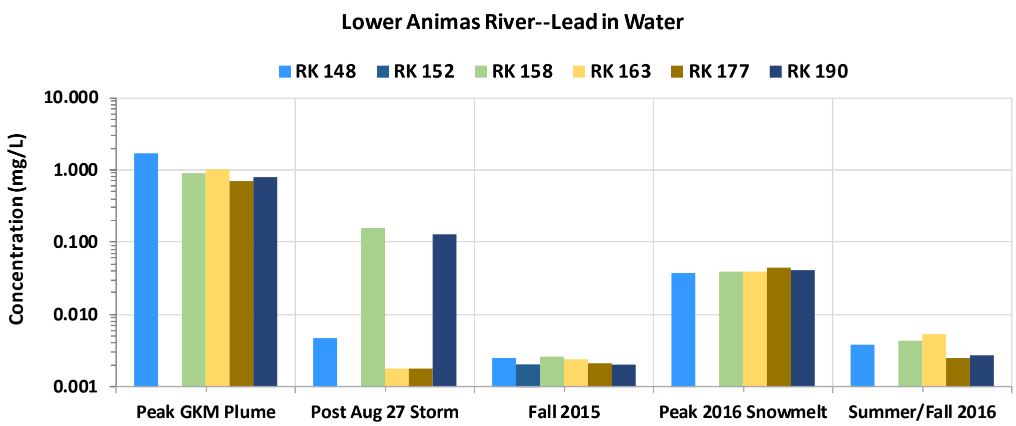


Figure 9-32. Comparison of A) sediment concentrations and B) total water concentrations of lead at five sites within the lower Animas River during key periods. Data during plume was the maximum observed concentration during the time when the Gold King Mine plume passed within a one-week period. The storm occurred on August 27, 2015. Post August 27 storm begins with sampling on August 28. Snowmelt was sampled once in June, near the peak of the snowmelt hydrograph.

Table 9-8. Results of Statistical Analyses Comparing Pre-event and Post-event samples in the Animas River at RK 190.2 (Farmington, New Mexico). Total metal concentrations were not measured in the pre-event period at Farmington. Pre-event included data from 2009 to 2014. In the post-event period, samples were included from flow between 7.1 and 14.2 m^3/s. Mean concentrations are shown, SE=standard error of the mean.

Animas River at Farmington (RK 190)

Dissolved Concentration Fall 2015

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	10	2.9	126	306	0.0002	0.0004
Cadmium	0.05	0.01	0.11	0.06	0.15	0.27
Copper	2.52	1.1	2.49	0.34	0.97	0.97
Iron	7	1.4	78	220	0.0003	0.001
Lead	0.22	0.30	0.34	0.40	0.53	0.52
Manganese	31	17	28	10	0.85	0.59
Zinc	12	14	5	1.4	0.14	0.11
n=	**9**		**16**			

Bed Sediment Concentration Fall 2015

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	SE	t-test p-value	Wilcoxon p-value
Aluminum	Not Measured	-	9800	479	-	-
Cadmium	1.1	0.70	0.2	0.02	0.022	0.001
Copper	8.6	3.2	15	0.58	0.47	0.57
Iron	4476	2807	13300	381	0.18	0.12
Lead	23	7.5	21	1.3	0.31	0.34
Manganese	318	145	420	12	0.72	0.51
Zinc	89	68	93	6.0	0.41	0.19
n=	**6**		**46**			

Bed Sediment Concentration 2016 Snowmelt

Metal	Pre-Event (mg/kg)	SE	Post-Event (mg/kg)	z-score
Aluminum	Not Measured	-	9500	-
Cadmium	1.1	0.7	0.88	-0.11
Copper	8.6	3.2	35	3.4
Iron	4476	2807	17000	1.8
Lead	23	7.5	94	3.9
Manganese	318	145	840	1.5
Zinc	89	68	350	1.6
n=	**6**		**1**	

Water concentrations in the lower Animas during the passage of the Gold King Mine plume were low relative to the upper and mid Animas River segments, but were elevated well above background. Metal concentrations declined towards background over a period of weeks and reached low values after the August 27 storm. Water concentrations rose during each fall storm event, and reverted back towards pre-storm levels in the days that followed (Figure 9-29). Snowmelt brought metals from upstream and elevated total water concentrations, but to a lesser degree than the fall storms (Figure 9-32).

Historic data were available for statistical comparisons for dissolved metals only (Table 9-8). Dissolved metals in water are not shown because they generally followed the patterns shown for Durango in Figure 9-18, although with less variation at this downstream location. The statistical comparisons to pre-event data showed no significant differences, except for dissolved aluminum and iron, which elevated significantly in the post-plume period (Table 9-8; Figures 9-27 to 9-29, Figure 9-34).

The majority of the material transported in and deposited from the Gold King Mine release was colloidal/particulate iron and aluminum. Most of the statistically significant post-event increases in water or sediment concentrations observed in the Animas River, and as will be shown, in the San Juan River, involved dissolved or particulate forms of aluminum and iron. The longitudinal distribution of dissolved iron and aluminum for the Animas and San Juan Rivers is shown in Figure 9-33, along with trace metals copper and lead. Data are displayed at immediately post event (samples collected from August 5 to August 19, 2015), and later (mostly in September and October 2016). There was a significant increase in dissolved concentrations in the later period in the lower Animas River (approximately RK 150 to 190). The statistical means from the tables are also plotted longitudinally and show the generally increasing trends in dissolved aluminum and iron concentrations through the river system (Figure. 9-34A and B). The mean increases were small, but persistent.

Change in dissolved metal may result from chemical transformations in the large quantities of incipient amorphous iron and aluminum minerals that formed and settled where they adhered/cohered to the river bottom through the fall. When minerals precipitate from solution, more soluble mineral phases generally are the first to precipitate for a combination of thermodynamic and kinetic reasons (Steefel and van Cappellen 1990). Over time, the less stable incipient phases recrystallize to more stable phases.

For iron, a mineral ripening sequence might be: amorphous $Fe(OH)^3$, short-range-order ferrihydrite, ferrihydrite, and then goethite (goethite might form directly from ferrihydrite or by dissolution and re-precipitation). For aluminum, the sequence might be: amorphous $Al(OH)^3$, microcrystalline gibbsite, then gibbsite. The solubility diagrams for aluminum and iron are shown in Figure 9-34E and F. Looking at the aluminum solubility diagram, data from Farmington places Al at the stable gibbsite solubility limit before the event and at the microcrystalline gibbsite solubility limit afterwards Durango fell in between these regions and did not change through time. Silverton did not plot on the solubility line, either because of an inaccurate representation of the $SO_4^{=}$ concentration at Silverton or because of the approximation of the geometric means for pH or Al^{3+}. Nevertheless, it also shifted upward (less crystalline stability) from pre-plume to post-plume. The biggest observed change in dissolved Al and Fe was observed in the lower Animas (Figure 9-33).

Post-event statistics indicate that there was a longitudinal pattern in the status of Fe and Al that reflects post-deposition reactions within the minerals precipitated and deposited in the Animas River (Figure 9-34). If the river bottom was dominated by incipient phases, the water would tend to have higher solution concentrations. This seemed to be the case for aluminum-based precipitates, which appeared to dominate in the lower reaches of the Animas River. Alternatively, if the river bottom was dominated by stable ferric oxides, the stable oxides would act as a sink for any elevated metals the water receives from dissolution of the incipient phases. This appeared to be the case for the middle and upper Animas, where iron oxides dominated and increased slightly in the middle and upper Animas relative to pre-existing conditions (Figure 9-33D). This condition would explain the decrease in metals observed there. Over time, there should be a net transfer of metals from incipient phases to stable phases.

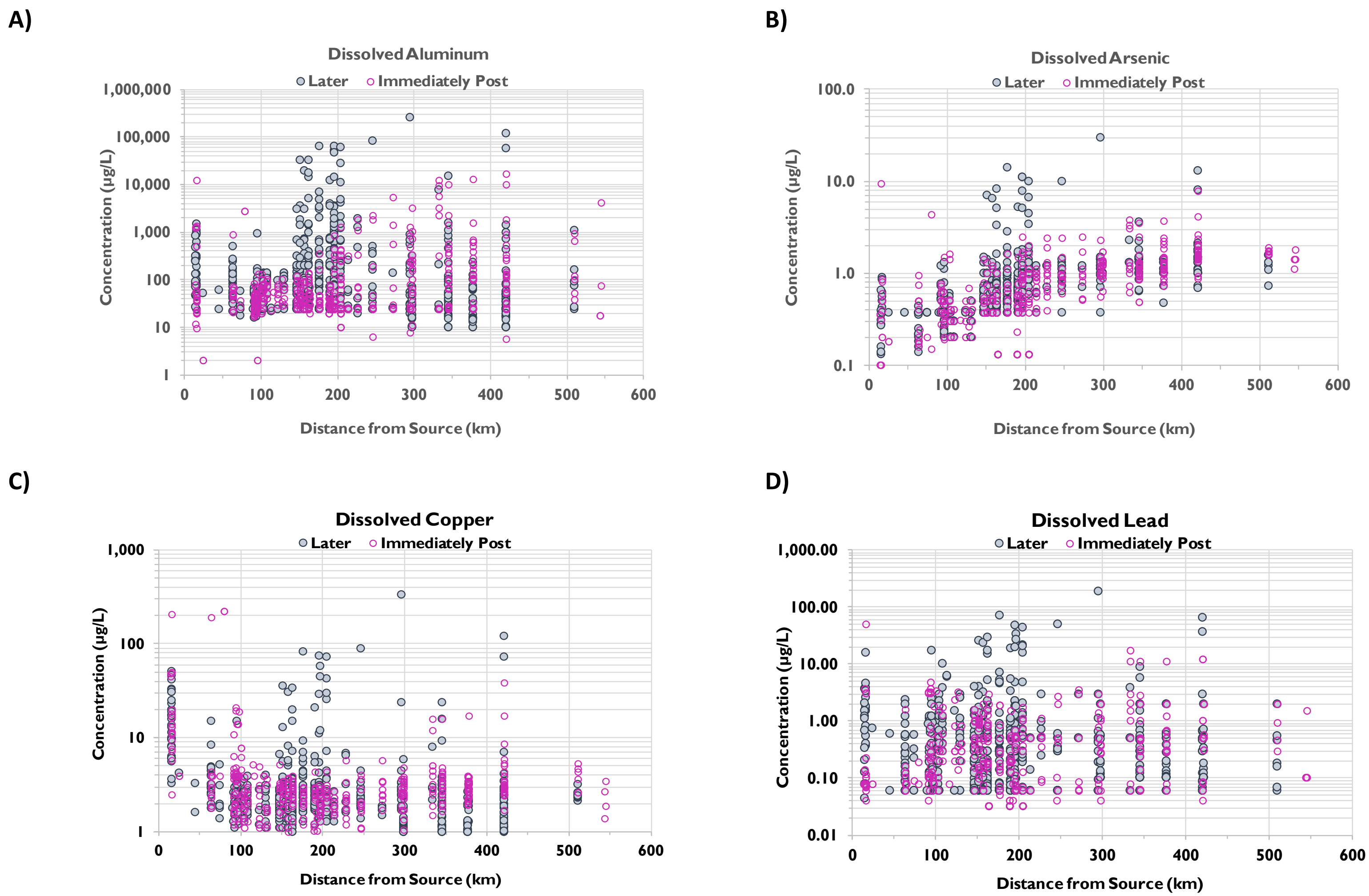


Figure 9-33. Dissolved concentrations of A) aluminum, B) arsenic, C) copper, and D) lead at sites plotted in relation to distance from Gold King Mine (GKM). Open purple points are immediately post-GKM release (August 5 to August 20, 2015). Later (gray filled points) are post this date, with most samples collected before November 2015.

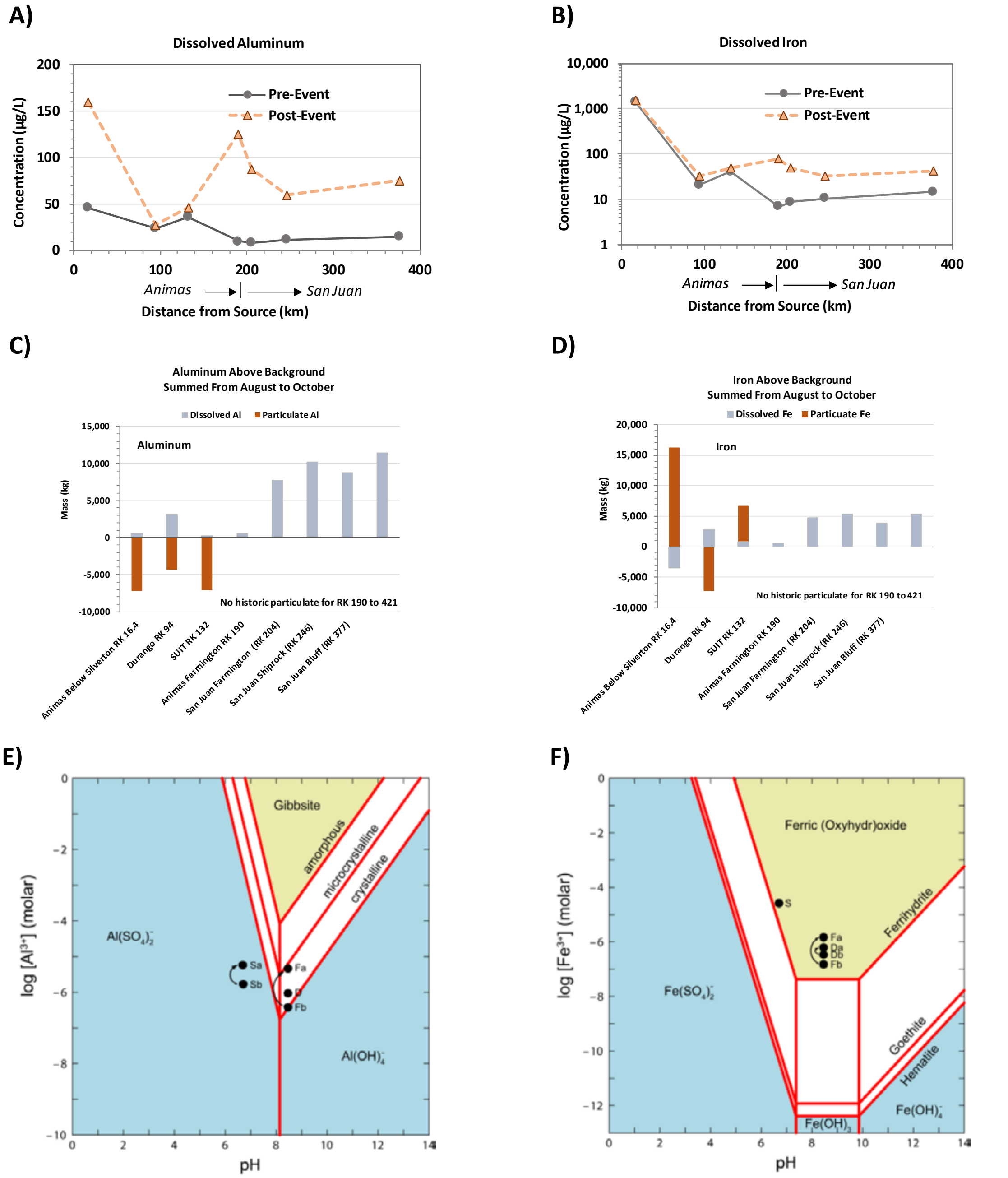


Figure 9-34. Mean dissolved A) aluminum and B) iron concentrations of historic data (pre-event) and post-event sampling. Means are plotted longitudinally along the Animas and San Juan Rivers where pre-event data were available. Means were taken from the statistical tables (Tables 9-3 to 9-10). C) and D) Mean concentrations are translated to mass (kg) by multiplying the average concentration at each location by taking the average flow at the nearest USGS station for a period of 60 days. E and F) Stability fields of aluminum oxide minerals (E) as a function of [Al^{3+}] and pH, with [$SO_4^{=}$] = 90 mg/L, similar to conditions expected in the upper Animas; and ferric oxide minerals (F) as a function of [Fe^{3+}] and pH, with [$SO_4^{=}$] = 90 mg/L, similar to conditions expected in the upper Animas. Thermodynamic data were reported in Nordstrom *et al*. (1984) with additional data from Geochemist's Workbench (Bethke 1998). Aluminum and iron minerals are shown at three locations in the Animas – Silverton, Durango, and Farmington designated by their first letter, and before and after by 'b' and 'a', respectively. After Steefel and van Cappellen (1990). See Appendix C for more discussion.

The weather pattern experienced in the lower Animas River, and not the middle and upper Animas, may have facilitated the change in dissolved metals evident in Figure 9-33. This effect is illustrated using the correlation of total, dissolved, and sediment lead with aluminum (Figure 9-36), as an exemplar for other metals, such as copper and zinc. The Gold King Mine plume deposited lead precipitates in the lower Animas River at measurably higher concentrations. Aluminum was actually lower than normal during the initial phase, and lead was higher in total and dissolved fraction and very evident in the bed. During the post plume period, concentrations drifted downward toward the expected pattern in the several weeks following the GKM plume. The storm on August 27, 2015, completely reset the system, and in subsequent storms lead concentrations were as expected. Lead in the sediment returned to background conditions, as did total and dissolved lead. Lead concentrations increased above expected during the snowmelt the following spring.

The net change in the dissolved and particulate Al and Fe concentrations (Post>Pre) was converted to mass by multiplying by flow over the three-month fall period (Figure 9-34C and D). Since the Gold King Mine event, there was a net decrease in particulate Al in the headwaters and a net increase in dissolved Al. Particulate iron generally increased in the headwaters. A net increase in dissolved mass of both Al and Fe amounted to approximately 10,000 and 5,000 kg in the lower Animas, respectively. The additional dissolved Al and Fe introduced to the San Juan River moved through without change.

Spring snowmelt was the first time after the Gold King Mine plume that the upper Animas region experienced large flows. The lower Animas River experienced a significant large storm on August 27, 2015 comparable to snowmelt just weeks after the Gold King Mine release (Figure 9-5B). The storm did not affect the Animas above Durango. Gold King Mine metals deposited in the lower Animas could have been suspended and moved out in the August 2015 event. Only one sample was collected late in the storm during that event. Even holding the observed sample concentrations constant over the hydrograph, the metals mass carried in that storm far exceeded what was transported or deposited during the Gold King Mine plume. It was likely that this monsoonal storm had some effect on the GKM deposited mass.

9.6 San Juan River Post Event Metals Concentrations

The Animas River joins the San Juan River at Farmington, New Mexico. From there, the plume flowed through approximately 360 km of the river in the states of New Mexico and Utah and the reservations of the Navajo Nation, which runs the length of the San Juan, and the Ute Mountain Ute Tribe reservation before entering Lake Powell. Figure 9-35 shows WASP estimates of deposited mass from Farmington to RK 510, approximately 40 km before the San Juan River becomes Lake Powell. An estimated mass of 55,000 kg of mostly particulate iron and aluminum, along with lead, copper, zinc, and other metals was delivered to the San Juan River over a several-day period, but most arrived on August 9, 2015 (Chapter 6). By the time the GKM plume joined the San Juan, metals concentrations were relatively low due to dilution and deposition of mass distributed along almost 190 km of the Animas River upstream.

On the day the Gold King Mine plume entered the San Juan, flow was approximately equal between the Animas and San Juan Rivers due to a release of water from the Navajo Dam to mitigate impacts of the plume. The San Juan River diluted the plume that arrived by an additional 50%. The Animas River is unregulated, and typically carries a higher percentage of the flow where they merge. Because of the dam release, sediment and water was much higher than normal on an August day. The Animas River, carrying the plume, joined the San Juan River, which was equivalent in flow and concentrations of many metals due to the natural load associated with sediment (Chapter 5). Modeling of plume movement suggested that relatively little of the plume mass likely deposited within the San Juan River. Most deposition likely occurred within the first several kilometers downstream of the confluence of the Animas and San Juan Rivers.

Water and sediment has been monitored along most of the length of the San Juan River during and since the Gold King Mine release. Most of the measurement is at eight general locations and is conducted by various agencies and tribes, depending on location. Sampling has been most intensive at five of those locations and is the focus of discussion. Sufficient historic sampling of metals has occurred to allow some statistical comparison of pre- and post-event metals concentrations. The San Juan River is discussed in three segments; the upper San Juan (between Farmington at 196 km and Shiprock at 246 km), the middle San Juan to Montezuma Creek (RK 345), and the lower San Juan to the last routinely monitored sampling location at Mexican Hat (RK 421). The river at other locations within these general reaches behaved very similarly.

A)

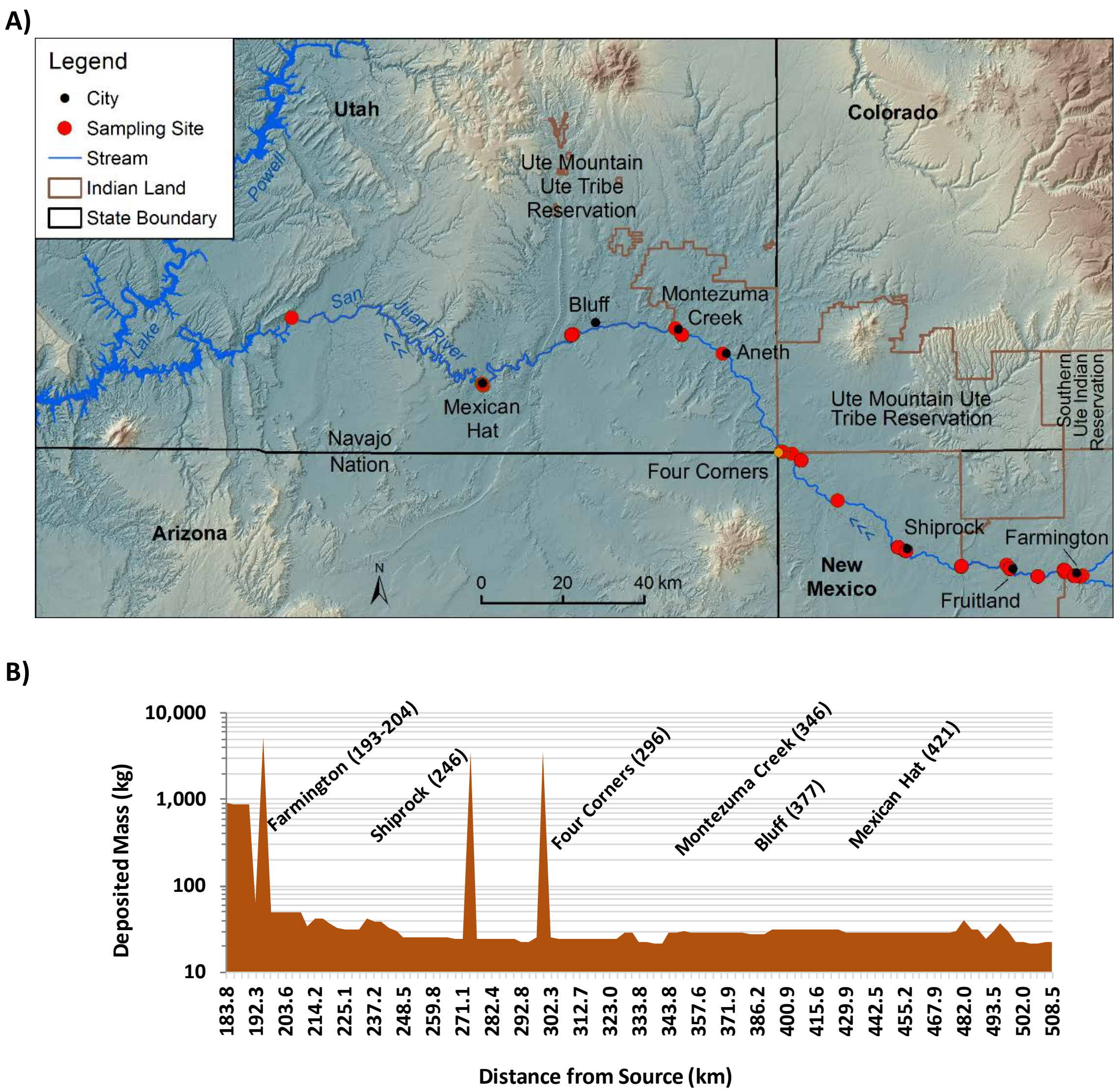
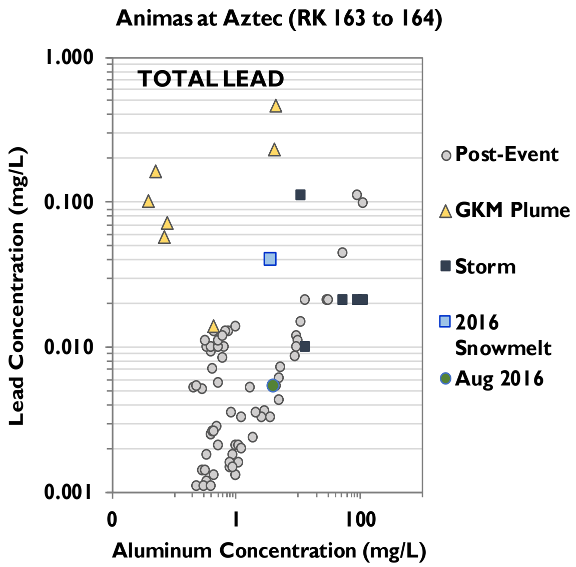


Figure 9-35. A) San Juan River from its confluence with the Animas River at RK 192 to RK 421. Sampling locations are shown as red dots. B) Mass deposition estimated with Water Quality Analysis Simulation Program (WASP) modeling in approximately 2-km segments through the San Juan River segment as an indicator of localized deposition zones.

A)



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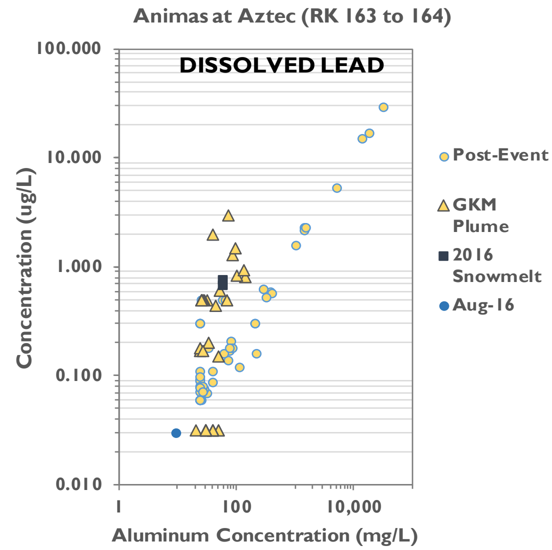


C)

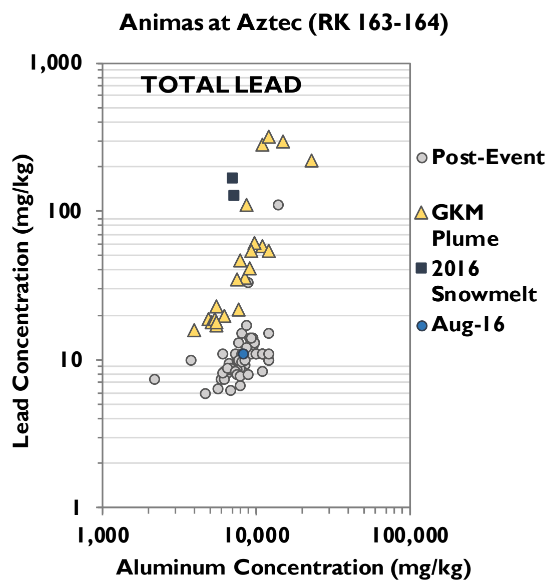


Figure 9-36. Correlation of lead with aluminum for the Animas River at RK 163-164 divided into four periods after the Gold King Mine release for A) total water concentration, B) dissolved water concentration, and C) sediment. Post-plume extends until the storm on August 21, 2015. Snowmelt data were collected June 9, 2016. Storm events occurred August 27, September 6, and September 24, 2015. One sample was collected in Summer/Fall 2016 in August.

The time sequence of total water concentrations for six metals sampled at these three locations, one in each of the river segments, are provided in Figures 9-37 to 9-39. The time sequence of lead, copper, and zinc in bed sediments at five locations is provided in Figure 9-40.

The Navajo dam released water for some period around the Gold King Mine event, creating an unusual hydrograph with higher water, sediments, and metals that lasted for a longer period than typically occurs with storm runoff. This broadened hydrograph was seen through the length of the river. The three large storm events on August 27, September 6, and September 24 also affected the entire length of the San Juan. Because of the dam release, the plume event in the San Juan River was also equivalent to a storm event in the system.

Total Water Concentration—San Juan River at Farmington (RK 196.1)

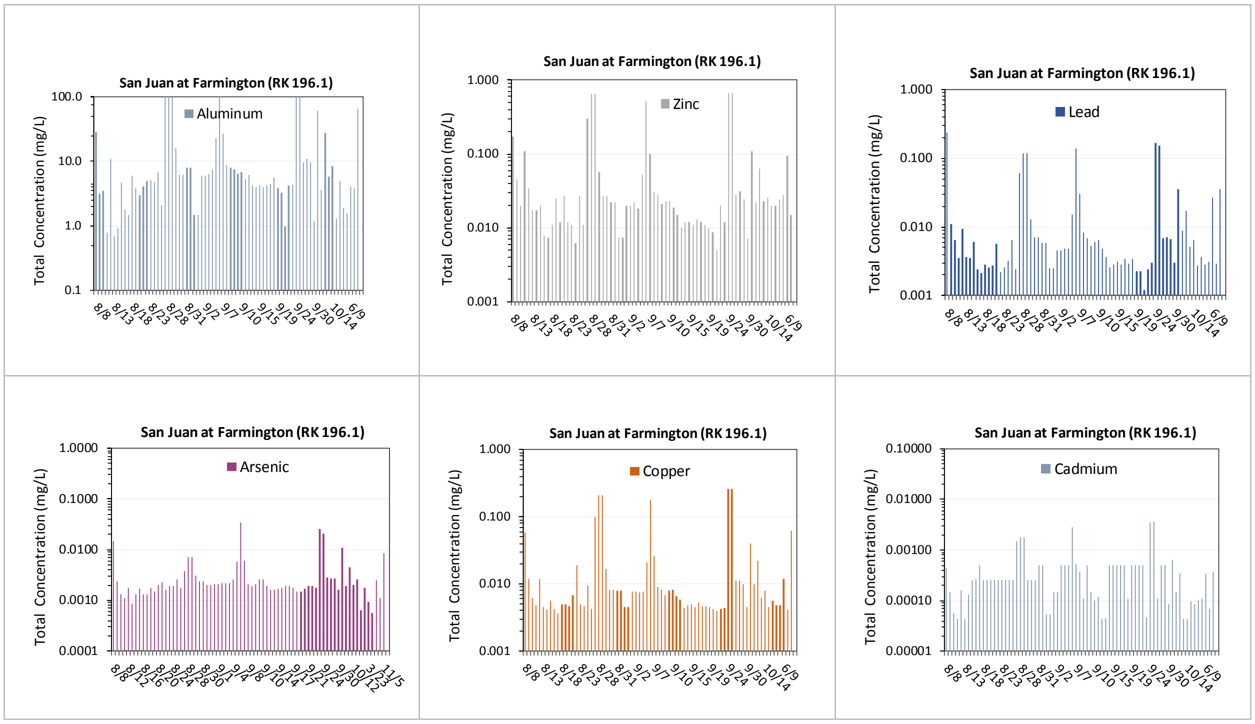


Figure 9-37. Total water concentration of samples collected from the San Juan River at RK 196.1 below the confluence with Animas River in Farmington between August 5, 2015 to June 30, 2016 sequenced in time. The last data point was collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. The last sample was collected November 15, 2016. The data presentation is intended to emphasize post-release trends.

Metals in the upper San Juan River at RK 196.1 (Figure 9-37) closely followed the temporal pattern of metals in the Animas River at RK 190.2 (Figure 9-29). This should be expected given that the Animas contributes at least 50%, and usually more, of the flow to the San Juan.

At RK 196.1, concentrations of most metals in the San Juan were low, but possibly elevated during the time the plume passed, due to the river's high flow. Interpreting the association of metals concentrations with the plume is not as straightforward as in the Animas River, because the San Juan was also carrying high loads of sediment and metals from the dam release. Metals in the San Juan tracked the Animas at RK 190.2, but were diluted in proportion to flow. Nevertheless, lead, zinc, and copper were particularly pronounced. These metals declined in the days following, while aluminum increased, probably related to sediment. Metals increased more significantly in each of the three fall storm events, peaking sharply and receding back toward what appears to be base levels in between.

Total metals concentrations in the middle and lower San Juan were also strongly driven by elevated flow. The middle and lower reaches of the San Juan, represented at RK 298.5 (Figure 9-38) and RK 421.3 (Figure 9-39), respectively, were similar to each other and differed from the upper reaches closer to the Animas River confluence. Metals responded to the same storm events as were seen in the Animas River, but with more subdued peaks and a prolonged receding limb. The Gold King Mine plume was not readily apparent in the general backdrop of the dam release flow event associated with it at either downstream site.

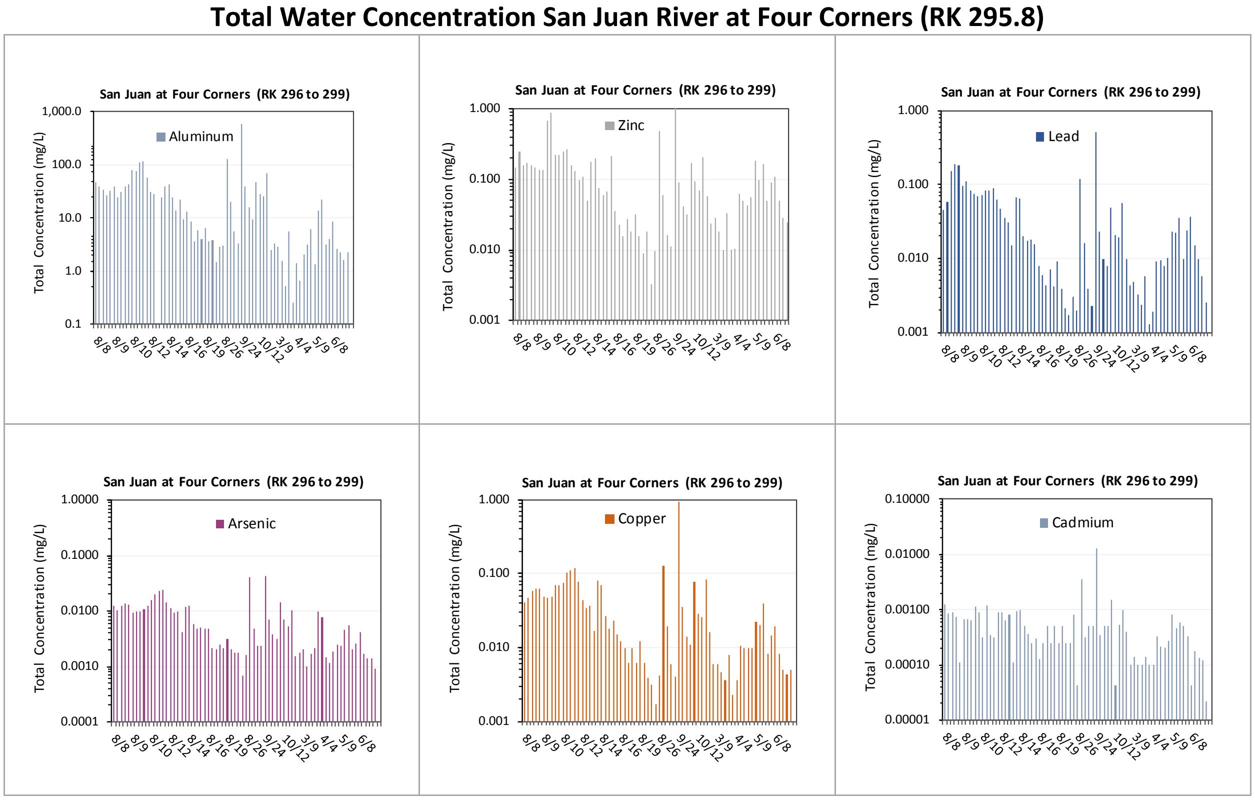


Figure 9-38. Total water concentration of samples collected from the San Juan River near RK 296 to 299 near Four Corners, Colorado between August 5, 2015 to June 30, 2016 sequenced in time. The data includes full sampling of 2016 snowmelt period. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. November 5, 2016 is the last date of measurement. The last sample was collected November 5, 2016. The data presentation is intended to emphasize post-release trends.

Metals concentrations in sediment were low in the San Juan River (Figure 9-40), especially when compared to the Animas River. Metals were fairly uniform throughout the river, although concentrations trended upward from RK 246.3 to RK 345.8, then decreased to RK 421.3. Lead in sediments appeared to be somewhat elevated immediately after the GKM plume passed RK 246.3 and possibly at RK 296.8. Sediment concentrations had only a small response to passing storms.

The spring hydrograph was measured once in the upper San Juan and numerous times during the snowmelt period in the middle and lower San Juan, so the time sequence at each of the locations has at least one snowmelt sample. Where data were more complete it is evident that metals in the water and, to varying degrees, in the sediment increased during the spring runoff, including lead, copper, and zinc (Figures 9-37 to 9-40).

Total Water Concentration San Juan River at Mexican Hat (RK 421)

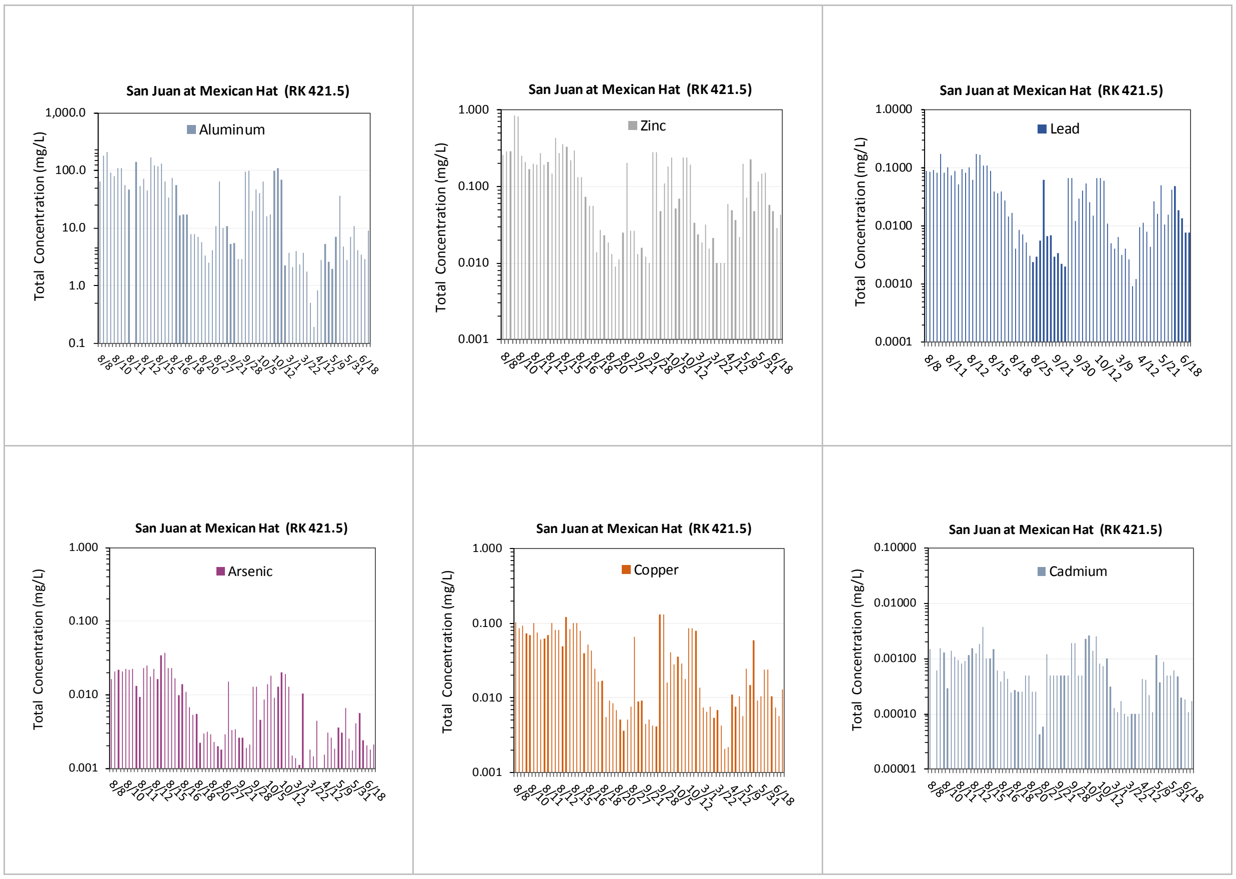


Figure 9-39. Total water concentration of samples collected from the San Juan River at RK 421 at Mexican Hat, Utah between August 5, 2015 to June 30, 2016 sequenced in time. The data includes full sampling of 2016 snowmelt period. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured more infrequently. Data from sites collected by multiple providers in close proximity are combined. Thus, the x-axis scale is not uniform among sites, but is uniform for all metals shown at this location. The data presentation is intended to emphasize post-release trends.

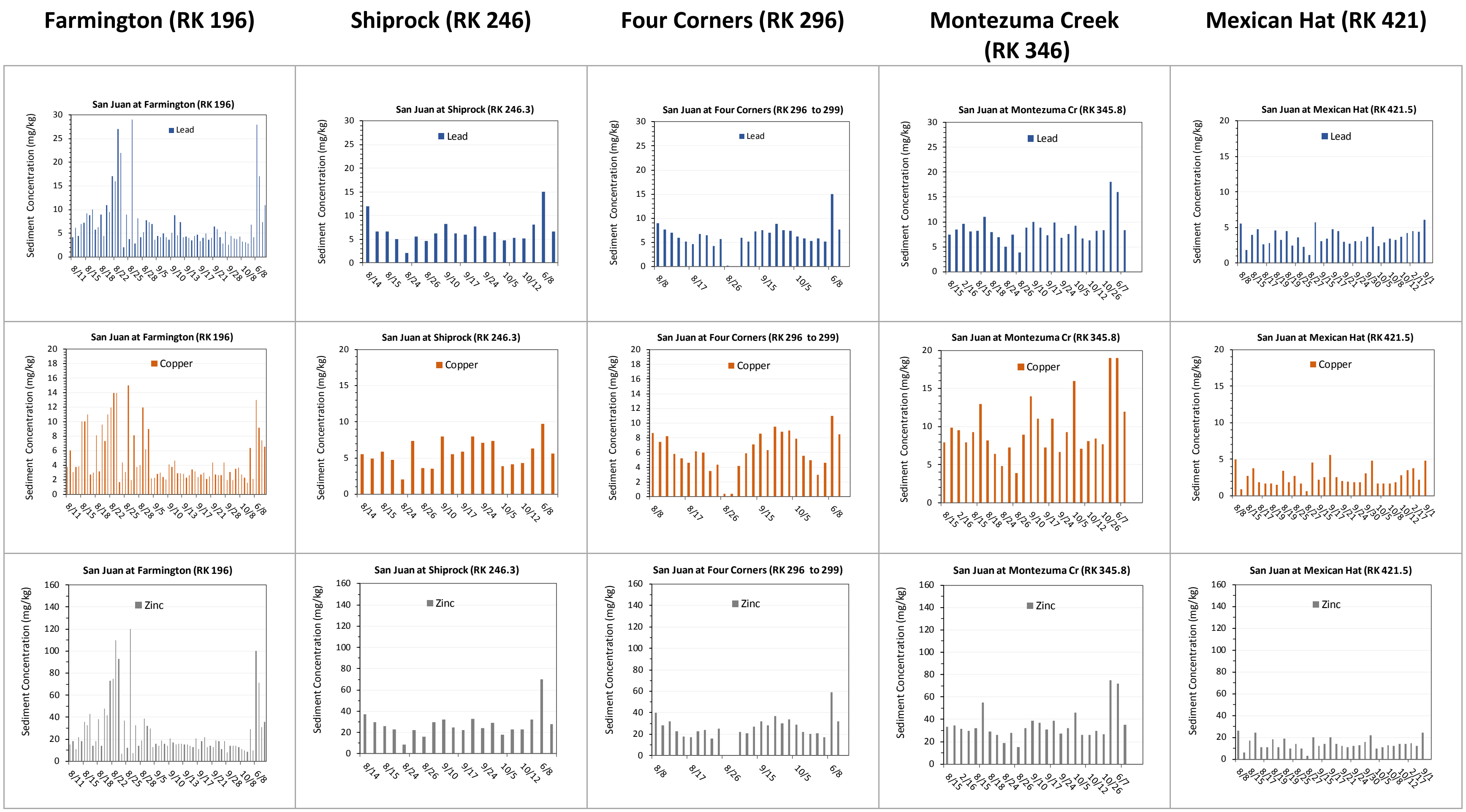
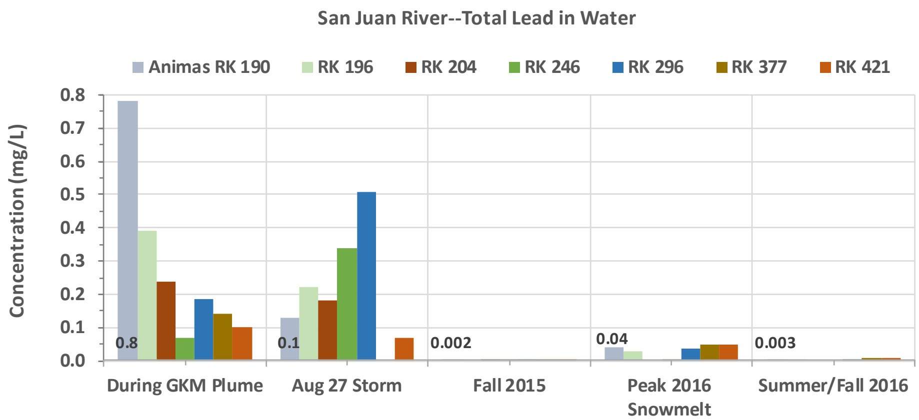


Figure 9-40. Sediment concentrations of samples collected from the San Juan River at five locations from RK 196 to RK 421 from August 5, 2015 to June 30, 2016 sequenced in time. The last two samples were collected during snowmelt in June 2016. Note that dates are not uniform among sites; more than one sample could have been collected on the same day; and some sites were measured less frequently. November 5, 2016 is the last date of measurement. Data from sites collected by multiple providers in close proximity are combined.

To facilitate comparison of the temporal traces, the total concentration of lead in water and sediments at three important response times are shown in Figure 9-41; lead was used as an exemplar for other metals, although the lead signature was stronger during the plume than other metals (Chapter 5). Six sites along the San Juan River are shown in Figure 9-41, along with the incoming concentrations from the Animas River. To represent the plume, the highest measurement during passage of the plume at each location was selected. The individual storms were not evenly measured at each location; therefore, the largest concentration observed in any of the three storms was selected to represent storms.

Snowmelt was represented by the highest measurement during the 2016 spring snowmelt season. Water was measured frequently during the spring in the middle and lower San Juan, but just once in the upper San Juan and lower Animas. Sediment was measured once or twice during the period throughout. Lead (and other metals) were clearly elevated. The temporal traces at RK 296.8 (Four Corners) and RK 421.3 (Mexican Hat) in Figures 9-37 and 9-39 had weekly measurements over the period that captured the full snowmelt period (i.e., from February 17 to June 25, 2016).

A)



B)

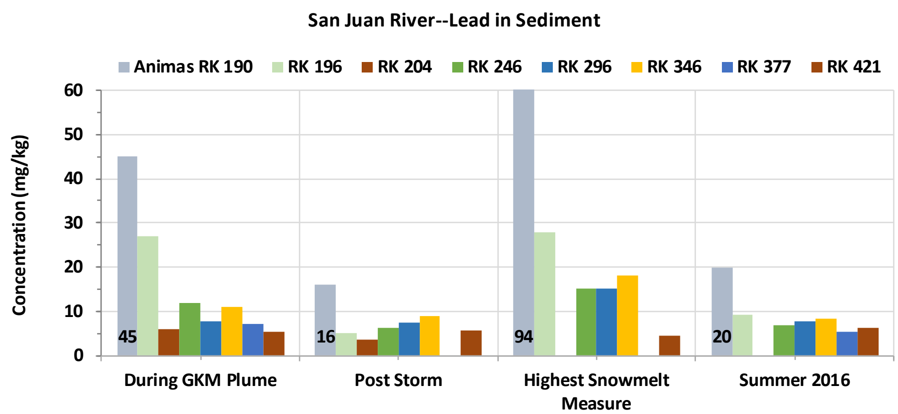


Figure 9-41. Comparison of A) total water concentrations, and B) sediment concentrations of lead at sites within the San Juan River and for the Animas River at its confluence during key periods. Data during plume were the maximum observed concentration during the time when the Gold King Mine plume passed within a one-week period. The storm value was the maximum observed concentration in any of the three storms that occurred in 2015 (August 27, September 6 or September 24). Any of the three was chosen because individual storms were not sampled at all sites.

During storms and during the plume, total lead concentrations in the San Juan River were relatively high and within comparable ranges as later storms. This can also be seen in the temporal traces. Concentrations during the plume were probably also influenced by the dam release. Concentrations declined during this "event" through the San Juan River. Storm concentrations represented in the fall 2015 data tended to increase in the downstream direction, although this could vary in individual storms based on their direction. The September 24 storm was a regional event that moved into the watershed from the southwest.

Metals concentration in water clearly rose and fell during the 2016 snowmelt period. Peak concentrations for lead shown in Figure 9-41A show that snowmelt peaks were small relative to storms. There was no apparent trend in the downstream direction during snowmelt.

Sediment concentrations during the GKM plume, storm events, and 2016 snowmelt are shown in Figure 9-41B. Lead in sediment tracked the same downstream pattern as water during the plume. Lead peaks were much smaller during storms and trended upward in the downstream direction like the water. Lead sediment concentrations during the 2016 snowmelt were higher than measured during the plume and were greatest in the upper San Juan, but apparent through most of the river system to at least RK 346. Lead in sediment at RK 421 does not appear to react much to flow events, except near the confluence with the Animas. This suggests that Gold King Mine metals mobilized in the Animas River could be seen in the water and sediments of the San Juan. The effect on sediments appeared to be greater during snowmelt than during the plume.

Due to the low concentrations of trace metals in the San Juan River, a correlation technique was used in plume analysis to detect Gold King Mine metals within the background influence of sediments in transport at the time (Chapter 5.3). Trace metals were correlated with aluminum or iron as representative of the sediment concentrations. The method was effective in identifying elevated trace metals relative to what should be expected at the level of sediment present in the water. This technique was applied to lead, copper, and arsenic total water concentrations during the snowmelt samples at an upper, middle, and lower sampling location in Figure 9-42.

Total lead, copper, and arsenic concentrations in water were well within the range typically observed in the three locations. However, all three areas appeared to have elevated lead during the spring snowmelt, suggesting the Animas River as a source. Copper and arsenic did not appear to be different from typical background concentrations at those levels of aluminum.

Figure 9-42 suggests that some of the metals appeared to be elevated relative to their background correlation with aluminum. The snowmelt time period is examined in greater detail at a Bluff (RK 377) in the lower San Juan River. UDEQ sampled locations the San Juan intensively during the period from March 29 to June 25, 2016. The correlation of 4 trace metals including lead, arsenic, copper, and cadmium to aluminum during the period is shown in the left column of Figure 5-43. The same pattern observed at other sites in Figure 5-42 is seen at Bluff (RK 377). Some observations of lead, copper, and zinc appear elevated relative to what would be expected at the relatively low level of aluminum observed during a portion of the period. The accompanying figure in the right column plots the observed metal concentration sequentially in time (gray shading). Also shown as the dotted line is the coordinate of the ratio of the trace metal to aluminum from the figure above (e.g. Pb:Al).

Three periods are generally indicated on the figure, each of which offer a possible cause for elevated metals. The "early Animas" period denotes April when flows first reached the levels that would likely mobilize Gold King release deposits, as discussed in Section 9.4.3. Evidence from the upper and middle Animas suggested that Gold King deposits were mobilized in April on the rising limb of the snowmelt hydrograph (e.g. Figure 9-21). There was a release from the Navajo Dam for most of May. Elevated flows from the dam likely increased sediment and therefore backgournd metal concentrations. The peak of snowmelt from the upper Animas occurred on June 6-7. Metals in this time period could reflect the mobilization of metals with typical high flows from the upper Animas.

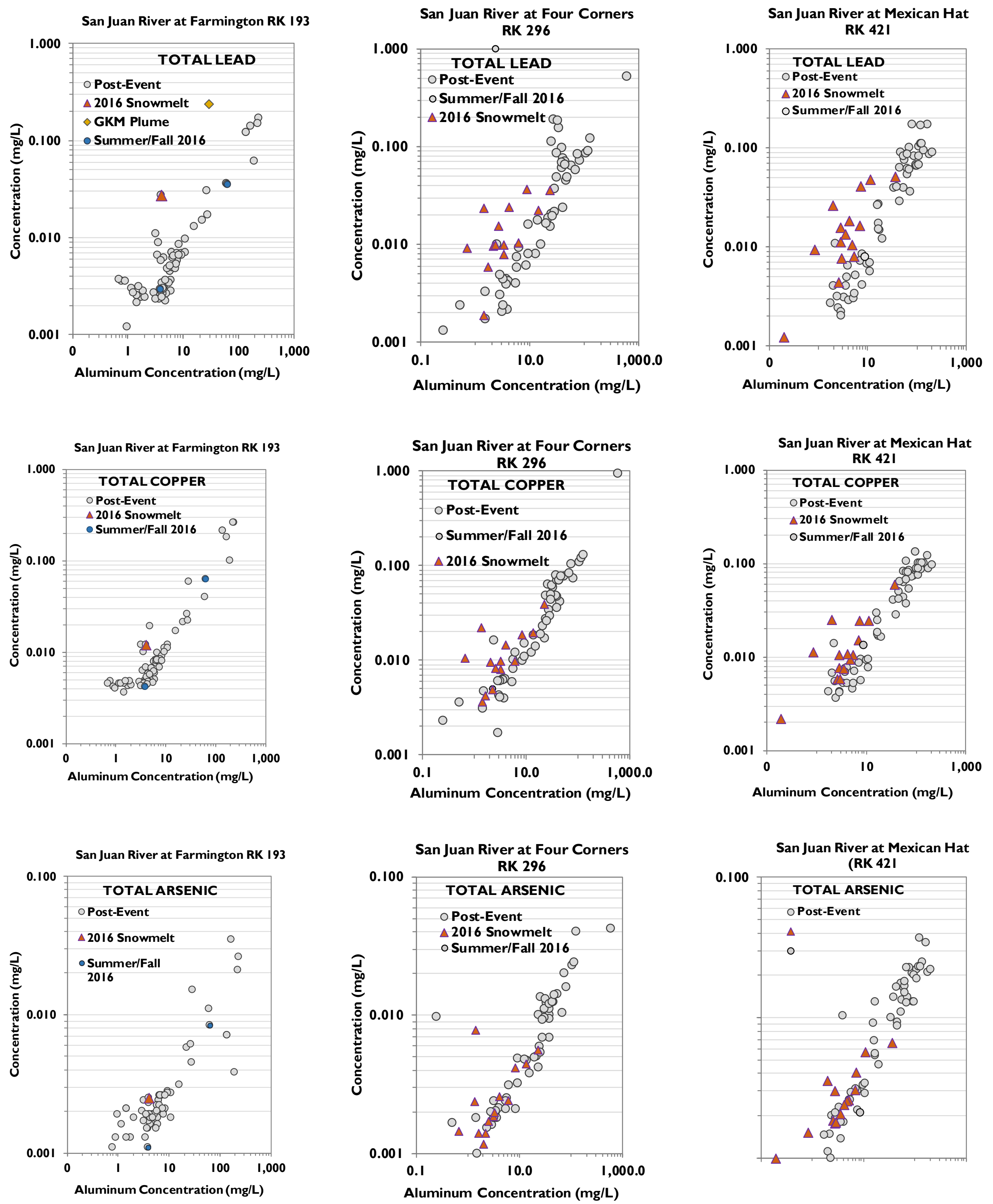


Figure 9-42. Total water concentration of metals in relation to total concentration of aluminum in post-event data collected from August 2015 to October 2015 (gray circles) and 2016 snowmelt data (red triangles) at three sites on the San Juan River: RK 193 (Farmington), RK 246 (Four Corners) and RK 421 (Mexican Hat).

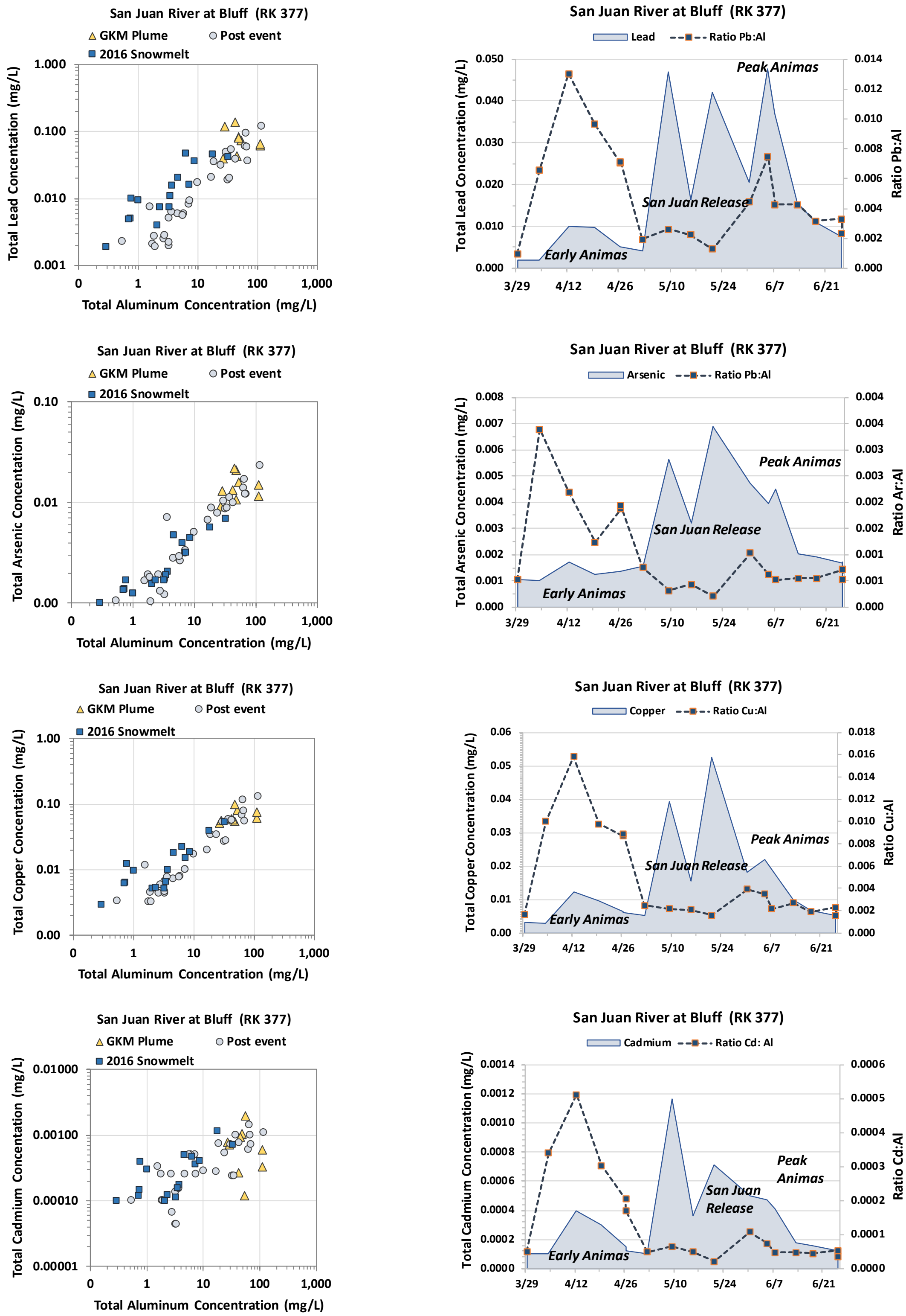


Figure 9-43. Relationship of four trace metals to aluminum (left column) and concentrations and ratio of metal to aluminum plotted in time during 2016 snowmelt (right column) in the San Juan River at Bluff, Utah at RK 377. There was a release from the Navajo Dam into the San Juan River in May.

The right column plots in Figure 9-43 clearly show that the concentrations of the metals were very low during the April period relative to what would be observed at the flow peak, but the ratio of the trace metals to aluminum was very high, suggesting the Gold King as source. All of the metals showed the same pattern, with clearer signature than displayed in the left column plot given the variability. Concentrations of the metals were high for the duration of the dam release. There was a small peak coincident with the peak flow in the Animas. The same pattern was observed at Mexican Hat (RK 421) (not shown). These data support the conclusion that the Gold King deposits that remained in the Animas River over the winter period were mobilized early in the spring snowmelt and could be observed through the system, albeit at low concentrations. Given that higher flows followed at the peak of snowmelt in the Animas, and with the dam release in the San Juan, it was likely that most, if not all, of the Gold King deposits were transported into Lake Powell during this time. This process began with fall storms in 2015 and was likely completed by May 2016. Monitoring through another snowmelt season would help to confirm that hypothesis.

The same technique is applied to bed sediment in Figure 9-44. In this case, the data included pre-event samples, post-GKM plume samples, and those collected during fall 2015 and during 2016 snowmelt in the upper San Juan (Figure 9-44A). In the sediment analysis, lead was correlated with iron because many samples did not have aluminum data. Some measurements of lead during the plume were elevated, but for the most part they were within the typical range. Lead in sediment was elevated in most of the samples collected during 2016 snowmelt, when compared to the typical relationship with iron. However, when lead concentrations in 2016 snowmelt were plotted longitudinally in Figure 9-44B, there appeared to be more deposition within the upper San Juan, especially within the first 10 km downstream from the Animas.

There were sufficient data in the upper San Juan for statistical comparison of pre- and post-event sediment metal concentrations. Table 9-9 provides statistical testing results. Pre-event data for lead is shown in Figure 9-34. Only iron was significantly higher in the upper San Juan post-event period. This is consistent with Figure 9-34, where iron concentrations were higher during the plume and during snowmelt than any other time. This may reflect the predominance of iron in the Gold King Mine release mass. Other metals, including lead, were not statistically different post-plume; however, all metals were elevated in the upper San Juan during spring snowmelt compared to pre-event data.

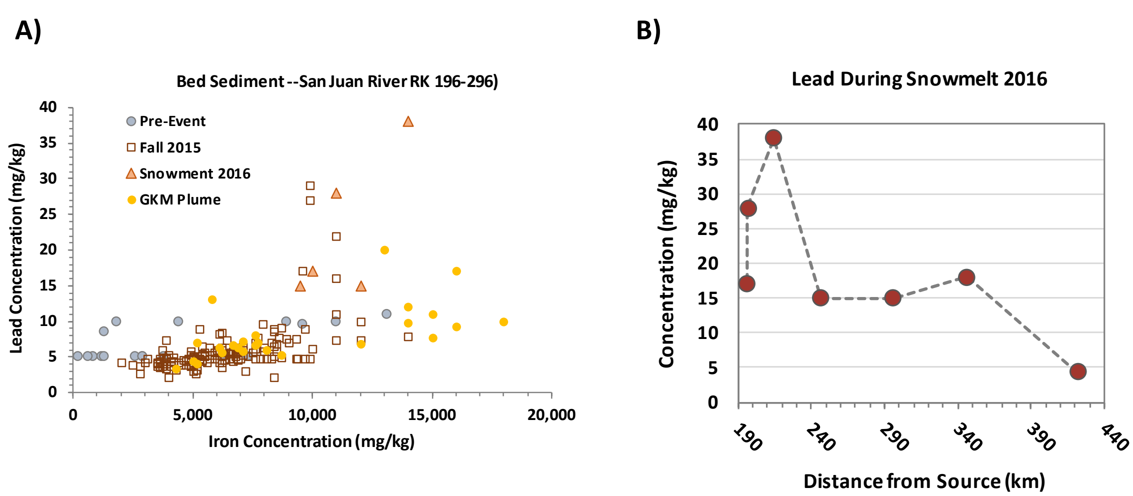


Figure 9-44. Sediment samples from multiple locations on the Upper San Juan River were taken near the peak of snowmelt runoff on June 8, 2016. A) Lead in relation to iron in sediments in the upper San Juan River. B) Bed sediment concentration of lead with distance from source. The confluence of the Animas and San Juan Rivers is located at approximately 192 RK.

Table 9-9. Results of Statistical Analyses Comparing Pre-event and Post-event Bed Sediment Metal Concentrations in the San Juan River Downstream of the Animas (RK 196 to 214; Farmington/Fruitland area and RK 246 to 296; Shiprock to Four Corners. Concentrations were logged (base 10) prior to testing. Mean concentrations are shown, SE=standard error of the mean. Pre-event data included all available.

Bed Sediment Concentration		Upper San Juan River				
Metal	**Pre-Event (mg/kg)**	**SE**	**Fall 2015 (mg/kg)**	**SE**	**t-test p-value**	**Wilcoxon p-value**
Aluminum	Not Measured	-	3950	207	-	-
Cadmium	Predominantly Non-Detects	-	0.055	0.01	-	-
Copper	4.3	1.4	4.5	0.20	0.85	0.66
Iron	3500	1374	6300	214.2	0.004	0.005
Lead	**7.1**	**2.7**	**5.6**	**0.28**	**0.03**	0.004
Manganese	165	14	185	4.6	0.3	0.57
Zinc	21	2.6	20	1.2	0.94	0.18
n=	**36**		**175**			

Bed Sediment Concentration		Snowmelt 2016				
Metal	**Pre-Event Mean (mg/kg)**	**SE**	**Post-Event (mg/kg)**	**SE**	**t-test p-value**	**Wilcoxon p-value**
Aluminum	Not Measured	-	6000	848	-	-
Cadmium	Predominantly Non-Detects	-	0.26	0.06	-	-
Copper	**4**	1	**12**	2.2	0.0023	0.01
Iron	**3,500**	1,374	**11,200**	800	0.0004	0.04
Lead	**7**	3	**21**	4.5	0.005	0.0017
Manganese	**165**	14	**340**	35	0.0003	0.0014
Zinc	**21**	3	**85**	16	0.0003	0.0014
n=	**36**		**5**			

Table 9-10. Results of Statistical Analyses Comparing Pre-event and Post-event Dissolved Metal Concentrations Within Various Sections of the San Juan River Downstream of the Animas. There were few total metal concentrations available for this analysis. Concentrations were logged (base 10) prior to testing. Analyses were divided into three regions of the river: the upper San Juan (RK 196 to 214; Farmington/Fruitland area), the middle San Juan (RK 246 to 296; Shiprock to Four Corners), and the lower San Juan (RK 345 to RK 421; Montezuma Creek to Mexican Hat). Flow in the post-event period varied between 14.2-32.0 m^3/s. There were 117-154 samples spread across the three regions in the post-event period and 50-100 samples across the three regions in the pre-event period. Mean concentrations are shown, SE=standard error of the mean.

Upper San Juan River (RK 193-214)

Dissolved Concentration **Fall 2015**

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	8.3	1.6	87.1	55	<0.0001	<0.0001
Cadmium	0.31	0.04	0.47	0.01	Non-Detection Bias	
Copper	1.5	0.19	2.2	0.11	Non-Detection Bias	
Iron	8.9	0.49	50.1	34	<0.0001	<0.0001
Lead	0.14	0.03	0.19	0.06	Non-Detection Bias	
Manganese	14.1	1.5	10.5	27	0.11	0.007
Zinc	4.3	0.23	3.2	0.29	Non-Detection Bias	

Middle San Juan River (RK 215-297)

Dissolved Concentration **Fall 2015**

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	11.7	142	60.3	49.8	<0.0001	<0.0001
Cadmium	0.38	0.05	0.50	0.00	Non-Detection Bias	
Copper	2.1	0.25	2.4	0.17	Non-Detection Bias	
Iron	10.5	0.89	32.4	31	0.00036	0.0018
Lead	0.17	0.14	0.15	0.05	Non-Detection Bias	
Manganese	**8.3**	**1.9**	4.7	**1.5**	**0.023**	**0.04**
Zinc	4.1	0.47	3.8	0.58	Non-Detection Bias	

Lower San Juan River (RK 298-421)

Dissolved Concentration **Fall 2015**

Metal	Pre-Event (µg/l)	SE	Post-Event (µg/l)	SE	t-test p-value	Wilcoxon p-value
Aluminum	15.1	10	75.9	287	<0.0001	<0.0001
Cadmium	0.52	0.08	0.50	0.00	Non-Detection Bias	
Copper	4.0	0.28	2.8	0.26	Non-Detection Bias	
Iron	14.8	8.6	43.1	308.1	0.00027	<0.0001
Lead	0.15	0.06	0.20	0.27	Non-Detection Bias	
Manganese	4.6	**2.7**	**3.0**	**4.8**	**0.04**	**0.02**
Zinc	5.1	1.1	5.2	1.1	Non-Detection Bias	

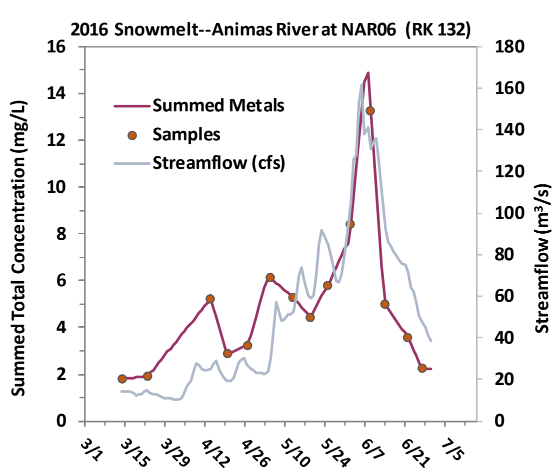
Time series of dissolved metals are not shown because they were generally fairly uniform through time and very similar from site to site. Baseline concentrations for most trace metals were typically less than 1 µg/L. Background dissolved concentrations were generally similar throughout the San Juan River and varied much less along the length of the San Juan River than observed in the Animas. However, dissolved metals were responsive to the storm events when most metals spike briefly. Aluminum and iron were higher in the lower San Juan than upstream reaches and were very responsive to storms.

There were sufficient pre-event data for dissolved metals to statistically compare with post-GKM samples; only dissolved metal concentrations were available from historical datasets in the San Juan. Table 9-10 provides statistical results. Dissolved aluminum and iron increased significantly after passage of the Gold King Mine plume in all three of the segments of the San Juan River compared to historic data. Relative increases were largest as dissolved aluminum increased from 5 to 10 times and iron increased from 3 to 5.5 times. Concentrations were low, however, and absolute increases were small. The net increase in aluminum and iron was observed throughout the lower Animas River following the GKM release, as shown in Figure 9-33. It appears from the mass estimates that the dissolved aluminum input to the San Juan River from the Animas continued to flow through the Animas without change or deposition.

Average metal concentrations in Table 9-10 were historically low relative to the appropriate state chronic and acute aquatic criteria, although average cadmium concentrations were close to exceeding when hardness was 200. The average increase in aluminum and iron did not change this status, although mean dissolved aluminum is now closer to UDEQ warm water fish 4-day criteria. Changes in metals concentrations post-plume and during 2016 snowmelt are assessed relative to water quality criteria in Section 9.9.

9.7 Metals Mass from the Gold King Mine Transported During Snowmelt 2016

Metals concentrations were elevated throughout the Animas and San Juan Rivers during snowmelt runoff in 2016. We estimate the total mass and the portion attributable to the Gold King Mine release at two locations. On the Animas River, mass was estimated at RK 132 (NAR 06) where the river flows through the Southern Ute Indian Tribe Reservation. This portion of the river is downstream of the largest depositional zone of Gold King release mass between Silverton (RK 16.4) and Durango, CO (RK 94) where plume mass estimates suggested that 85% of the Gold King metal had been deposited. (See Section 6.2.) Much of the deposited GKM material, estimated to range from 394,000 and 418,000 kg, likely remained in the upper Animas river until flow during snowmelt accessed the channel margins and out-of-channel deposits. NAR 06 is also upstream of the lower Animas segment where deposits were resuspended in the fall 2015 storms. Water and sediment samples collected in the lower Animas River within New Mexico during 2016 snowmelt indicated elevated metals there as well, but there were too few water samples to accurately estimate metal mass transport.



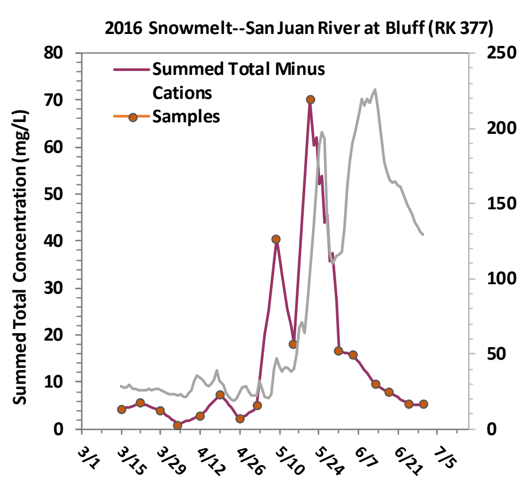


Figure 9-45. Summed metals concentrations (minus major cations) interpolated from water samples and daily streamflow from USGS gages during the 2016 snowmelt period. A) Animas River at NAR 06 at RK 132, B) San Juan River at Bluff, Utah RK 377.

Metal transport through the San Juan River was estimated at RK 377 (Bluff, Utah) located near the last USGS gage before the river flows through the remaining 170 km before Lake Powell. Water was sampled at the Animas and San Juan River locations on an approximately weekly basis beginning prior to or near the start of snowmelt in mid-March 2016 and continuing until the end of June 2016. Samples were assumed to represent the daily average concentration. Daily average metals concentrations were interpolated between weekly samples. Summed metals concentration at each site is shown with flow in Figure 9-45. Mean daily flow in the two rivers was obtained from nearby USGS flow gages (09364500 near Cedar Hill, CO at RK 129, and 09379500 near Bluff, UT). Snowmelt metal mass was also estimated at RK 421 on the San Juan River at Mexican Hat using the flow measured at Bluff (RK 377). Only the final mass calculations are provided for this location.

Daily flow was converted to volume and multiplied by metals concentration to determine a daily mass, which was then cumulatively summed for the snowmelt period from March to June 30, 2016. The daily and cumulative mass of summed metals (excluding the major cations Ca, Mg, K, Na) is shown for the Animas and San Juan River locations in Figure 9-46. Daily metal load was 10,000 kg/day or less early in the snowmelt period when flow was still relatively low at both locations. This suggests that the Animas River was the primary source of metals to the San Juan during this period. As the snowmelt hydrographs began to rise in mid-May, flow was partly augmented by a release from the Navajo Dam into the San Juan River (Figure 9- 42). The large volume of water coupled with a relatively small increase in metal concentrations produced a dramatic increase in metal load to 100,000 kg/day or more until the peak June 6-8. Suspended sediment also increased in the San Juan River with flow, driving the increased metal load.

Several lines of evidence were used to identify GKM release metals within the background metal mass. The behavior of metals concentrations and mass transport relative to historic patterns during snowmelt runoff for the middle Animas was also discussed in Section 9.4. Metal concentrations appeared to be elevated in the Animas River relative to historic observations early in spring snowmelt in April 2016 at RK 64 and RK 94. By the end of March, the flow in the Animas had risen to a similar level as during the Gold King plume, allowing resuspension of the remaining deposits. The ratio of trace metals to aluminum (e.g., Pb:Al), used as a signature of the Gold King Mine release throughout the study (e.g. Section 9-3), increased significantly at all locations in the San Juan River from the period March 29 to May 8 (see Figures 9-41 and 9-42). The Pb:Al ratio of samples collected at RK 132 and RK 377 is shown for the 2016 snowmelt season in Figure 9-46C. There was also a small persistent increase in this ratio in the Animas River from late March to approximately May 4 that was echoed in the San Juan River. Note that the ratio in the Animas River followed a different pattern than in the San Juan by increasing with streamflow in the later snowmelt period, suggesting a different dominant source of metals. Processes controlling background Pb:Al ratios in the Animas River were not extensively explored in this study. Earlier USGS studies looked extensively at acid mine drainage in the headwaters of the Animas River (Church *et al*. 2007), finding that streams draining different portions of the Animas headwaters varied in dominant metals. The addition of Navajo Dam water to the San Juan River mid-snowmelt period also changed the relationship of metals between the two rivers.

Based on several lines of evidence also discussed in Section 9.4, we conclude that Gold King deposits were resuspended and transported through the river system early in 2016 snowmelt runoff during a period from March 29 to May 8 in the San Juan River and offset 3 days earlier on the Animas River. The analysis assumes that most of the metals transported during this relatively low flow period resulted from mobilization of Gold King deposits. A background metal mass that allowed for other metal sources was estimated for the period by applying a constant concentration observed in the earliest samples (on the order of 1-3 mg/L).

The estimated metal mass transported at three locations during the entire snowmelt period and during the early season attributed to the GKM release are provided in Table 9-11. Gold King release material was calculated as the difference between the total observed and estimated background mass. The estimate of 275,000 kg attributable to Gold King deposits at RK 132 in the Animas River was close (≈66%) to the estimated deposited mass after the Gold King plume in the river upstream (Figure 6-10). Estimated Gold King mass in the San Juan at RK 377 (Bluff, Utah), where the dates were more clearly indicated by the Pb:Al signature, was 433,000 kg and 463,000 kg at RK 421 (Mexican Hat). The estimated mass at RK 377 was within 10% of the empirically-estimated deposited mass that remained in the upstream reaches of the Animas River after the fall 2015 storms (see Chapter 6). It was also noteworthy that the estimated annual metal mass derived from concentration/flow regression equations discussed in section 6.4 produced similar cumulative estimates as the sampling based data presented in this section.

We are confident in the daily metal mass estimates at these locations due to the intensive sampling and good flow records. Partitioning the snowmelt mass to Gold King Mine deposits has greater uncertainty. The estimation of cumulative mass of the GKM release was sensitive to small differences in metal concentrations applied to background, as well as the number of days that metal movement was assigned to the Gold King release, especially once flow and daily load began to rise in mid-May.

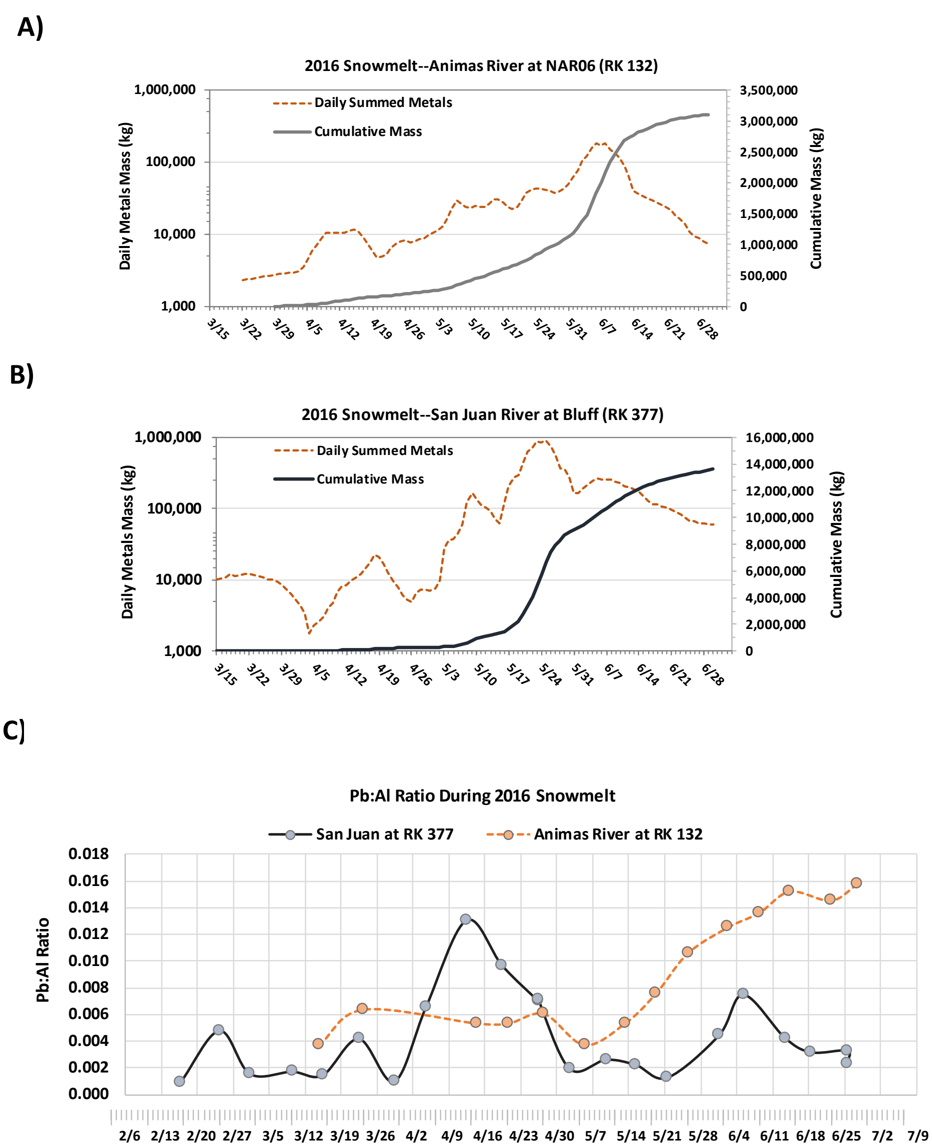


Figure 9-46. Daily and cumulative mass of summed metals (minus major cations) (kg) during the snowmelt period from Feb 15 to Jun 30, 2016. A). Animas River at NAR 06 (RK 132) samples at each location. B) San Juan River at Bluff, Utah (RK 377). C) Ratio of total lead to aluminum (Pb:Al) from samples at each location.

Table 9-11. Estimated metals mass(kg) transported by the Animas and San Juan Rivers during 2016 snowmelt estimated at three locations. Gold King Mine related mass is attributed to the early portion of the snowmelt season. Estimated metals mass does not include the major cations (Ca, Mg, K, Na).

Summary of Estimated Metals Mass During 2016 Snowmelt

River	Location	Period		Summed Metals Mass[&] (kg) All Sources	Summed Metals Mass[&] (kg) Gold King Mine Deposits
Animas River	NAR 06 (RK 130)	Total Period March 15-June 30	Total Observed	3,130,000	274,700
		Early Snowmelt March 26-May 5	Total Observed	346,300	
			Estimated Background	71,600	
San Juan River	Bluff, Sand Hills (RK 377)	Total Period March 15-June 30	Total Observed	13,700,000	433,000
		Early Snowmelt March 29-May 8	Total Observed	619,000	
			Estimated Background	186,000	
	Mexican Hat (RK 421)	Total Period March 15-June 30	Total Observed	13,200,000	463,000
		Early Snowmelt March 29-May 8	Total Observed	742,000	
			Estimated Background	279,000	

& Minus major cations (Ca, Mg, K, Na)

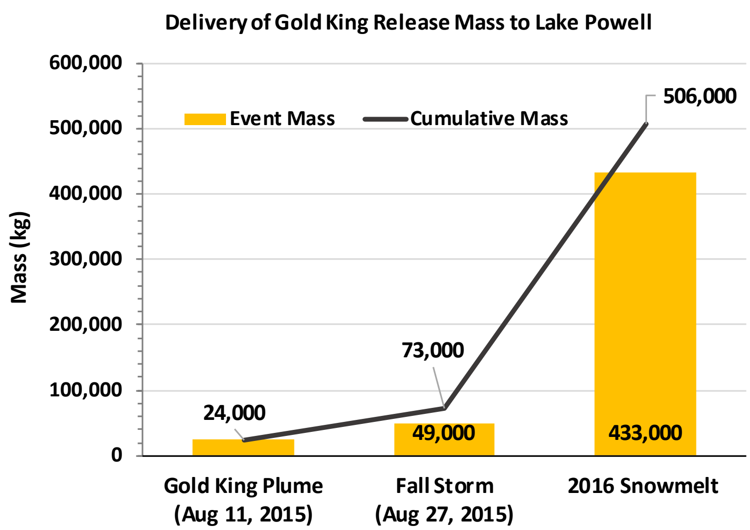
9.8 Summary of the Fate of the Gold King Mine Release 2015-2016

The Gold King release mass was delivered to Lake Powell in three primary events distributed over a 9-month period, beginning with the plume. The mass associated with each event is shown in Figure 9-47A. Metal mass estimates were based on empirical reconstruction of water samples and flow measured at USGS gages supported by process-based water quality modeling with WASP that simulated the contaminant transport as the plume flowed through the rivers.

The first mass of Gold King metals arrived with the plume approximately 9 days after the release (see Chapters 4, 5, and 6). Only 5% of the plume mass (~24,000 kg) reached Lake Powell in the initial release event. The remainder was deposited throughout the Animas and San Juan Rivers, with most resting in the headwaters of the Animas River between Silverton and Durango, Colorado. The empirically estimated deposited mass was provided in Figure 6-10; WASP estimated deposition at finer spatial resolution shown in Figures 9-14, 9-25, and 9-35. The Gold King Mine deposits remained within the river bed, along the channel margins, and within slower areas in the channel until they were resuspended by flows large enough to carry them.

The second delivery event was triggered by a storm centered in the lower Animas and San Juan Rivers that occurred the night of August 27, 2015, approximately 20 days after the Gold King plume passed. The stormflow resulting from three inches of rain in a few hours resuspended Gold King Mine deposits in the Animas River below Cedar Hill, Colorado (approximately RK 140) to the confluence with the San Juan River in Farmington, New Mexico (RK 193) as well as the entire length of the San Juan River. There was insufficient sampling during this rapid storm to quantify the mass transported through the lower Animas based on measured concentrations. The Gold King mass delivered to Lake Powell during the August storm event was assumed to equal the deposited material within the affected river length as streambed sediments returned to pre-event conditions (Figure 9-30).

A)



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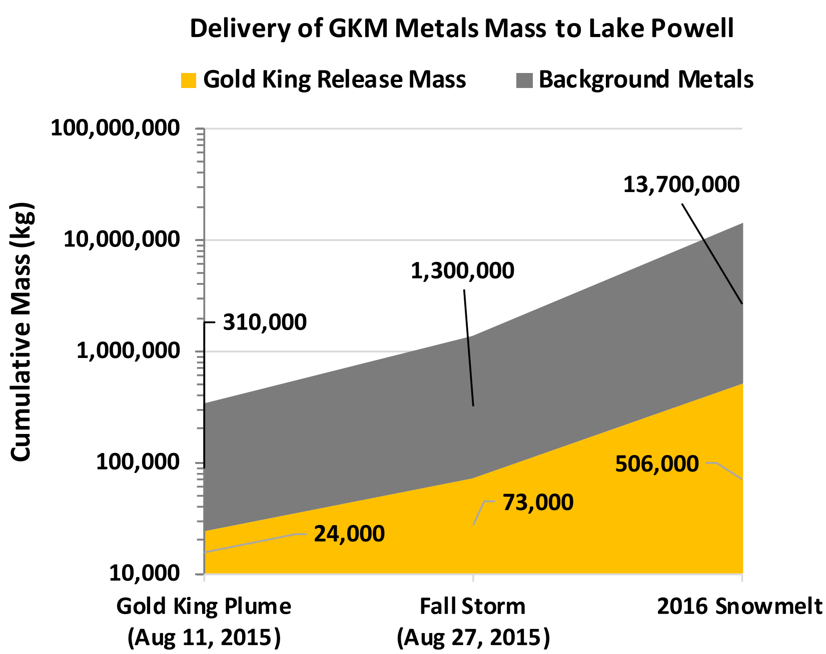


Figure 9-47. Summation of delivery of Gold King Mine (GKM) released metals mass to Lake Powell (kg). Metals from the Gold King Mine release reached Lake Powell in three separate events over a 9-month period. A) Estimated GKM mass transported during each of three events and cumulative total for the 9 months. B) Estimated event and cumulative Gold King release mass and background metals delivered in the three events.

The third event was snowmelt runoff in 2016. The largest mass of Gold King deposits remained in the Animas River within Colorado in the 125-km segment between Silverton CO at RK 16.4 to the Colorado/New Mexico border near RK 140 through the fall and winter months following the release. This material was mobilized during snowmelt runoff in 2016. Water samples confirmed elevated metals in water samples collected throughout the Animas and San Juan Rivers. Although somewhat higher metal concentrations would be expected each year during snowmelt in the upper Animas River, as shown in earlier USGS studies (Church *et al*. 1997), evidence of the Gold King release metal signature in water samples suggested GKM materials added to concentrations. Snowmelt analysis (Section 9.7) found that GKM deposits were re-suspended primarily in April to early May in 2016. During this period 433,000 kg attributed to GKM deposits was transported past RK 377 (confirmed at RK 421) which presumably then flowed the remaining 130 km to Lake Powell.

The total mass of metals attributed to the Gold King Mine release delivered to Lake Powell in the three events amounted to 506,000 kg, with most reaching the lake during April 2016. This sum was very close to the initial estimate of 490,000 kg delivered from Cement Creek to the Animas River during the release. Given the uncertainties in the initial release estimates in Cement Creek (Chapter 3), this close of a corroboration between the Gold King release mass and what was delivered through the San Juan River over 9 months was not expected. The results suggest that mass estimates guided by intensive water and sediment sampling were reasonable.

Movement of the GKM release mass in three stages was accompanied by significant amounts of sediment that also contained the same elemental metals as the Gold King material, but in different mineral form. The metal content of the sediment transported in the San Juan River largely reflects the composition of the rock formations they are weathered from. The mass of background metals associated with the sediment carried in the three events is also shown in Figure 9-47. The Gold King release mass of 490,000 delivered to Lake Powell was mixed with 13,700,000 kg of sediment associated metals. There were at least two other large storms in 2015 (September 6 and September 24) that also delivered a significant mass of sediment to Lake Powell that was not accounted for in the cumulative mass estimate.

Metal mass accounting suggests that the released metals from the Gold King Mine has been transported out of the rivers with snowmelt runoff in 2016. Water monitoring during Summer/Fall 2016 suggest that metals concentrations resulting from the Gold King release have returned to pre-event conditions, although ongoing AMD contamination may continue to affect water quality. That hypothesis is explored more fully in the following analysis.

9.9 Trends in Post Gold King Mine Release Water Quality

In this section we perform an analysis of trends in water quality during and following the Gold King Mine release. The nature of trend analysis differs from the statistical comparisons of pre- and post-event water quality provided throughout this chapter. The structure of the statistical analysis narrowed what data could be used to a limited number of locations and further restricted data to narrow ranges of flow to ensure comparability of historical and GKM event-related data. This significantly reduced the number of samples that that could be used in analysis. The approach taken for trend analysis overcomes these constraints.

Trend analysis looks at the frequency of water quality exceedances in metals concentrations in historic data through the period of impact of the Gold King Mine release including post-event monitoring through November 2016. Each metal concentration reported for a sample was compared to multiple criteria appropriate for the location, designated use, and jurisdiction where it was collected. The number of exceedances were counted. The test was binary; the sample concentration either exceeded a criteria or it did not (yes or no). The test parameter was the percent exceedances (% exceedances) calculated as the number of observations exceeding criteria relative to the number of comparisons of the metal-criteria combination. The process of comparing a sampled concentration to criteria is referred to as “screening.

$$\% \, Exceedances = \frac{\# \, Exceedances}{\# \, Comparisons} \qquad \text{Equation 9.2}$$

where the number of comparisons is a function of the metal-criteria combination for the designated uses and jurisdictions at the location where the sample was collected.

The role of water quality criteria in determining risk and the relationship of criteria to designated uses is further discussed in Chapter 7 and the water quality criteria are displayed in Table 7.1. Water quality criteria reflect the risk levels applicable to each designated use for each of the state and tribal jurisdictions and have three components: magnitude, duration and frequency. The trend analysis is indicative of frequency of exceedances. Magnitude of exceedance is only addressed in this analysis to the extent that a criteria was exceeded (not by how much), and duration is not addressed. Like the statistical testing, this analysis should not be construed as a risk assessment.

9.9.1 Water Quality Screening Organization and Methods

All of the water samples collected by EPA, states, tribes, municipalities, and NGO's as part of the GKM release monitoring were screened, along with historic data. These data have been presented in analyses throughout this report. An overview of the data including methods and sampling locations is provided in Chapter 2 and additional detailed information about data sources is available in Appendix A. For purposes of displaying results, screening was organized by time periods, designated uses, and regional jurisdictions. First these categories are defined and then the screening procedure is described.

Time Period. The data record was divided into time periods according to Figure 9-48. The Gold King plume period was taken as August 5 to August 21, 2015. All of the sites had receded from the high concentrations observed during the plume and returned towards pre-event concentrations by this time. This is visually evident in many of the displays of chronologically ordered sample data in this chapter. This date is prior to the August 27, 2015 storm that significantly changed the pattern of water quality in the lower Animas and San Juan Rivers. The post-plume period included samples from August 22 through the winter low flow period until March 14, 2016. A few samples collected in February 2016 were lumped with the Fall 2015 data. This was the largest proportion of observations due to the intensive monitoring that occurred after the GKM release. Virtually all of the data were collected prior to November 2015. The 2016 snowmelt period included data collected from March 15 to June 30, 2016. Spring snowmelt started to raise river water level near the beginning of April 2016 (Figure 9-5) and the snowmelt hydrograph peaked in early June. All data obtained from July 1 through November 2016 were grouped into a category called "Summer/Fall 2016". Historic data were classified as "snowmelt" or "normal" based on the same dates applied in 2016. It is important to note that the availability of data differs significantly among time periods (Table 9-12).

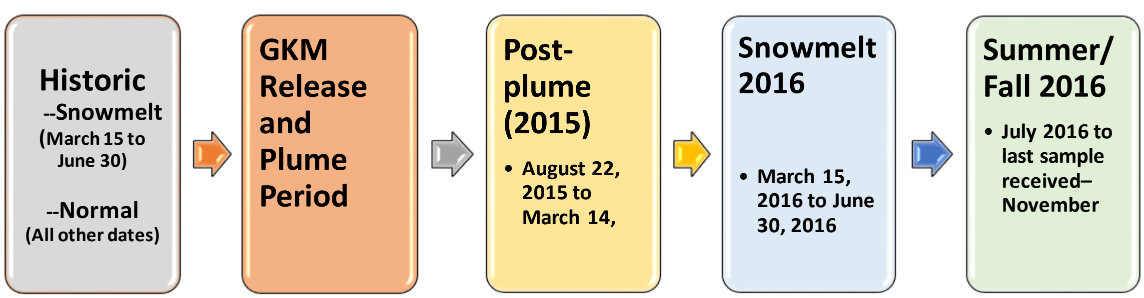


Figure 9-48. Time periods used for water quality screening analysis of water samples collected in the Animas and San Juan Rivers to assess Gold King release effects relative to designated use criteria.

Designated uses. Seven designated use categories were screened. These included domestic supply, human contact (includes various aspects such as recreation or tribal ceremonial uses), fish consumption, agricultural uses and irrigation, livestock watering, and acute and chronic aquatic habitat. Each of the states and tribes has one or more criteria in these use categories (see Table 7-1.) Each state and tribe applies a unique name to the use category and determines how it will be applied. For display purposes, the designated use is referred to by the names above. The trend analysis reports exceedances by designated use categories.

Locations/sites. EPA's conceptual monitoring plan (EPA 2016a) designated 30 sites as primary monitoring locations distributed throughout the Animas and San Juan Rivers. Most of the 2015-2016 data were collected at or near these locations during the Gold King plume and post-event. Multiple agencies and organizations sampled at similar places due a limited number of locations with good access for field crews. Within the 510 km of river length sampled during the Gold King release during and after the event, only 4 sampling locations fell outside of a distance ± 4.8 km (3 miles) of one of the 30 locations, all of which were close to that distance. Therefore, data from all sites were included in the trend analysis and no sites were rejected due to their proximity to sites identified in EPA (2016a). (The earlier statistical tests restricted comparisons to closer locations to ensure comparability.)

Region. Each sampling location was assigned to a category termed "region", which is the combination of river and jurisdiction that "owns" that location. For example, the upper Animas River within Colorado is assigned to the Colorado "region" and those in New Mexico are assigned to the New Mexico "region". Sites in the San Juan River may be assigned to New Mexico, Colorado or Utah, as well as to the Navajo Nation and the Ute Mountain Ute Tribe. Each sampling location may be included in up to 3 regions, depending on the overlap between state and tribal reservation boundaries. See Figures 2-4 and 2-5 for jurisdictional boundaries. The state/tribe "region" also reflects the broad river segments used to group findings elsewhere in the report, such as the upper, middle and lower Animas and San Juan Rivers, as well as the jurisdictional boundaries.

Water Samples. A total of 2,036 historical and GKM-related water samples were available for analysis. The number of samples screened by time period and within state boundaries is provided in Table 9-12. Samples collected within state boundaries were collected by multiple data providers. A total of 1,138 samples collected from the Animas River and 892 samples collected from the San Juan River were screened relative to water quality criteria.

Nearly all samples had dissolved and total metal concentrations from samples collected simultaneously. Water quality criteria specify either the dissolved or total fraction, so the sample count in Table 9-12 is taken as the site visit where the total and dissolved samples were combined (rather than counted as unique samples).

Metals. Most samples reported concentrations for the 23 TAL metals plus molybdenum. Some data providers did not test all samples for all metals.(See Chapter 2). There are at least one water quality criteria for most of the metals except for the major cations (calcium, magnesium, potassium, and sodium). All metals were screened.

A unique value was applied to each metal for each designated use reflecting criteria thresholds. Most of the metals are specified in a number of the designated uses giving them multiple criteria. Criteria for each metal draw from either the total or dissolved concentration, but not both. The designated uses often differ as to whether they refer to the total or dissolved fraction. Metal concentration thresholds also vary over a wide range among the beneficial uses.

Table 9-12. Number of samples collected from the Animas and San Juan Rivers within state boundaries by time period. (See Figure 9-49 for dates of time periods.

	Historic Normal	Historic Snowmelt	GKM Plume	Post-Plume 2015	Snow-melt 2016	Summer / Fall 2016	Grand Total
Animas River	155	65	347	378	163	37	1,138
Colorado	134	54	199	109	119	22	637
New Mexico	21	11	148	269	44	8	501
San Juan River	188	65	247	269	122	7	898
Colorado	8	2	20	19	17	0	66
New Mexico	143	57	114	129	16	5	464
Utah	37	6	113	121	89	2	368
Grand Total	343	130	594	647	285	37	2,036

Water quality Criteria. Due to the number of metals, designated uses and jurisdictions, there are a large number of criteria to apply, as indicated in Table 7-1 where water quality criteria for states and tribes are arrayed by metal. There are 372 individual water quality criteria appropriate to some location in the Animas and San Juan Rivers affected by the Gold King Mine release.

Many of the water quality criteria are fixed threshold values. Some of the criteria for some metals vary with hardness of the water such as the aquatic acute and chronic thresholds. The lower the hardness value, the lower the threshold value. States and tribes cap the modification of water quality criteria by hardness at a value of 400 mg/L.

Criteria that vary with hardness were computed with hardness. Hardness was obtained in one of three ways. If the sample reported hardness, the data value was used. Hardness can also be estimated from some of the major cations in the sample, which create the "hardness" of the water. The most common measure of water hardness (permanent hardness) can be calculated using the total concentrations of calcium and magnesium (expressed in mg/L) according to an equation obtained from (http://www.lenntch.com/ro/water-hardness.htm:

$$Hardness = 2.497\ x\ [Ca] + 4.118\ x\ [Mg] \qquad \text{Equation 9.3}$$

Figure 9-49 compares the calculated to measured hardness from 589 samples collected in the Animas and San Juan Rivers. The range of data is trimmed to 800 mg/L in the figure, although measured hardness was as high as 1,600 mg/L. The relationship is quite good with R^2=0.94. There was somewhat more scatter within the range between 0 and 400 mg/L. The calculation overestimated hardness in the relatively few cases that were not well predicted. For the screening process, this results in a more conservative screening for higher hardness values in that the 400 mg/L cap would be reached more quickly, lowering the water quality criteria threshold for the metals in that sample.

If there were values for calcium and magnesium in the sample, then hardness was computed from these values (expressed in mg/L). If there were insufficient data to perform the calculation, a hardness value was assigned. The value was 185 mg/L for the Animas River and 250 mg/L for the San Juan. These assigned values tend to be on the low end of typically observed hardness.

Treatment of Non-Detect Concentrations. All laboratory tests have a lower detection limit and metals concentrations are reported as "non-detects" when they occur in quantities less than the testing procedure can measure. Non-detection does not typically occur for the metals that have been emphasized in this report such as aluminum, lead, copper and so on, but non-detects are common for many of the trace metals. There are approximately 22,000 non-detects for individual metals in the almost 1,600 post-event samples. The logic of how non-detects are treated in the trend analysis is based on the premise of criteria application. That is, it is generally assumed that an organization sampling to evaluate attainment of water quality criteria applies a laboratory test capable of detecting the criteria threshold. For this reason, the trend analysis assumed that non-detected concentrations must be lower than the criteria and were not an exceedance. A non-detect was assigned a value of 0 (no), and the sample was included in the sample size as an observation for all criteria it was screened against. This assumption was applied to historic and GKM related monitoring data.

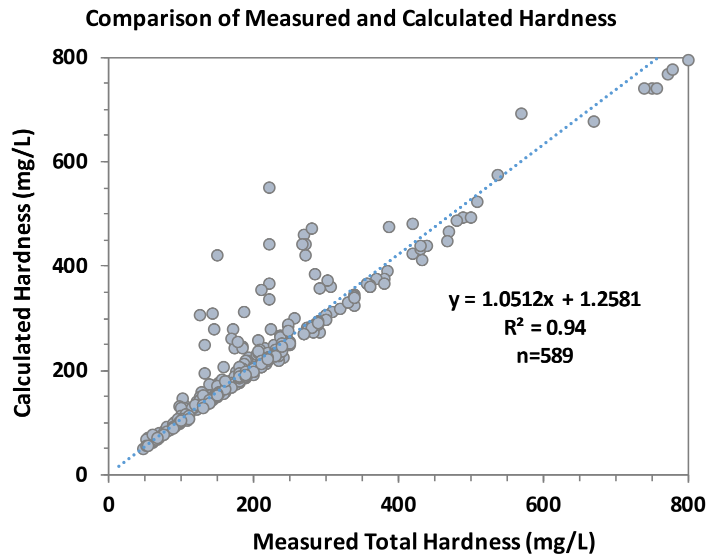


Figure 9-49. Comparison of calculated total hardness to measured hardness in data collected from the Animas and San Juan Rivers. Data presentation is clipped to the range of 0 to 800 mg/L. The maximum observed value was 1,600 mg/L.

An alternative approach to non-detects would be to assign them the value of the detection limit. This option was not taken to avoid over-counting exceedances. Many samples collected by multiple organizations before and after the Gold King release event were not necessarily expected to be applied to test against a particular jurisdiction's water quality criteria. In this case, the laboratory detection limit may not have been capable of detecting an exceedance for every other jurisdiction's criteria. This aspect of sampling was especially relevant where both state and tribal criteria were applied, as some tribal criteria thresholds are orders of magnitude lower than comparable designated use thresholds used by the states.

The possibility of misinterpreting exceedance is most likely realized when the detection limit and a criterion are near the same value. The potential for counting an exceedance assuming the detection limit concentration was examined by comparing the detection limits to the lowest criteria for each metal (e.g. minimum value in a metal column on Table 7-1). For most metals, the laboratory detection limits were low enough to detect the lowest criteria. Selenium and mercury were found to occupy the gray area, where detection limits are respectively sometimes or frequently greater than the minimum applied criteria based on either dissolved or total concentrations.

Overall, the assumption that non-detects should be considered non-exceedances did not affect the screening results very much. Fewer than 0.3% of all comparisons would have had a different assignment of exceedance if the concentration of a non-detect was assumed to equal the detection limit rather than 0. The exception was mercury which would have a 75% error rate because the criteria concentrations are close to detection limits. Because of the high potential for error mercury exceedances are not presented. Only a very small amount of mercury was introduced to the rivers from the Gold King release.

Procedure. Each sampled metal concentration was compared to every water quality criteria threshold. The appropriate criteria for each site were applied to each location. The sample concentrations were processed in batch mode using a computer code written in R-3.1.2 (R Core Team 2014). Original sample files obtained from the data providers were synthesized into several large data sets used throughout the analyses as described in Chapter 2, focusing on metals concentrations.

Data parameters included the assigned distance from the Gold King Mine that identified the sample location in many of the analyses. The R-program assigned the time period based on date, and the region based on distance. The program determined the hardness, and selected the water quality criteria threshold based on the region. The program than compared each metal in a sample against all the appropriate criteria and tracked the exceedance counts and number of comparisons by the designated use categories. These two parameters were output to a text file that was then processed in Excel® using the pivot table feature that then created the graphical displays that follow.

The number of metal concentrations compared to water quality criteria was much larger than the number of samples collected in the field. Each sample had multiple comparison opportunities depending on the number of beneficial uses, metals and applicable jurisdictions. One sample could be screened several hundred times. There were close to 189,000 comparisons to water quality criteria utilizing the pre- and post- GKM event and historic water samples performed in the screening. Exceedances are expressed as % of the number of comparisons in the category reported (equation 9.2).

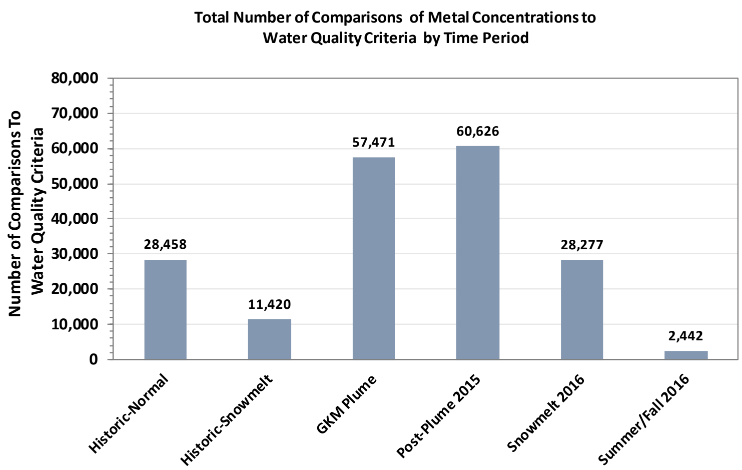
To avoid confusion with number of samples collected in the field (Table 9-12), we refer to the screening sample size that is used to calculate the % exceedance test statistic as the number of comparisons (to a criteria). The number of comparisons by time period is shown in Figure 9-50 and the number of comparisons by time period and jurisdiction is provided in Table 9-13. The majority of the comparisons were performed on GKM-plume and Post-plume 2015 data. There were relatively fewer historic comparison opportunities but there were sufficient numbers for reasonable assessment of trends. Historic data were distributed throughout the year so that snowmelt periods could be isolated. The 2016 summer/fall period had the fewest opportunities for comparisons.

Table 9-13. Count of comparisons of metals to water quality criteria by time period and state or tribe.

Time Period	Colorado	New Mexico	Utah	Navajo Nation	UMUT[&]
Historic-Normal	3,625	9,022	7,043	8,472	296
Historic-Snowmelt	2,083	3,480	2,797	2,957	103
GKM Plume	8,210	16,093	11,183	20,855	1,130
Post-Plume 2015	4,902	23,336	9,776	21,683	929
Snowmelt 2016	5,238	3,198	8,775	10,097	969
Summer/Fall 2016	878	771	198	595	0
TOTAL	24,936	55,900	39,772	64,659	3,427

[&] Ute Mountain Ute Indian Tribe

A)



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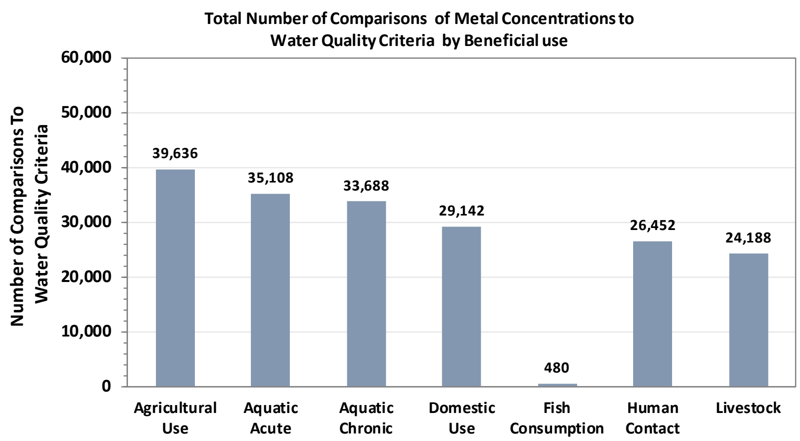


Figure 9-50. Number of comparisons of metal concentrations to water quality criteria summed by A) time period, and B) designated use.

9.2.1 Water Quality Screening Results

Water quality screening results are summarized in this report at a high level, organized by state or tribe and general river location. Data are displayed by the seven designated use categories, and arranged ordered in time to identify trends during and since the Gold King plume as well as existing pre-event conditions. The Gold King Mine-related monitoring documented water quality exceedances during and following the event due to the released metals as well as pre-existing episodic and chronic exceedances. When summarized at a broad level, many designated uses had some exceedances in most time periods, including historically. The percentage of exceedances in a time group is essentially the rate of exceedance in this application.

Trends in the rate of exceedances of all metals combined are shown by designated use for state/river combinations in Figures 9-51 through 9-55 and for tribal/river combinations in Figures 9-56 and 9-57. Note that if there is no exceedance in the designated use category in any time period, the use category does not appear on the chart. The overall trends are summarized at the designated use level in the figures. The influence of individual metals is discussed but results are not shown, except for lead, arsenic and aluminum in Figures 9-58 to 9-60. Complete results are available as supplemental material.

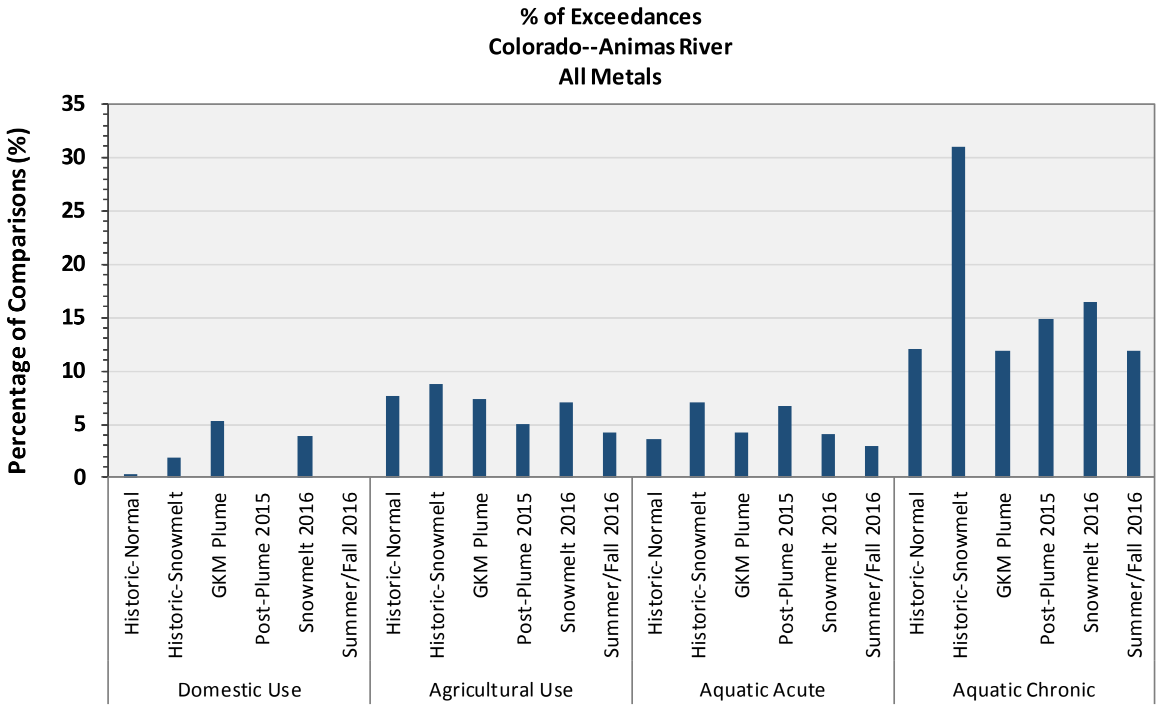


Figure 9-51. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the Animas River in Colorado. Data are organized by time periods defined for the Gold King release in Figure 9-48.

Animas River in Colorado. The rates of exceedances for the Animas River in Colorado from approximately RK 14 to RK 140 are provided in Figure 9-51. Exceedances for all designated uses occurred historically and after the Gold King release, with aquatic chronic exceedances the most common. Post Gold King release exceedance rates were generally similar to historic but have actually trended downward since the release, consistent with discussion in Section 9-4.

However, domestic water exceedances have occurred during historic snowmelt and were elevated in the Gold King plume and 2016 snowmelt periods. Many of these exceedances were due to lead. Agricultural use criteria were exceeded in 5 to 8 percent of the observations prior to the GKM release. (Agricultural criteria also cover livestock watering in Colorado.) The frequency of agricultural exceedances was the same during the Gold King plume period and has trended downward since the GKM release period. Many of these exceedances were due to manganese.

Aquatic chronic exceedances occurred relatively frequently historically. Frequency increased somewhat after the Gold King release to similar levels typically observed in snowmelt. Exceedances jumped in the 2016 snowmelt period but appear to have returned to typical levels in Summer/Fall 2016. Exceedances of aquatic acute criteria are infrequent and remained the same after the Gold King release. A spike in acute exceedances was observed in the 2016 Summer/Fall period.

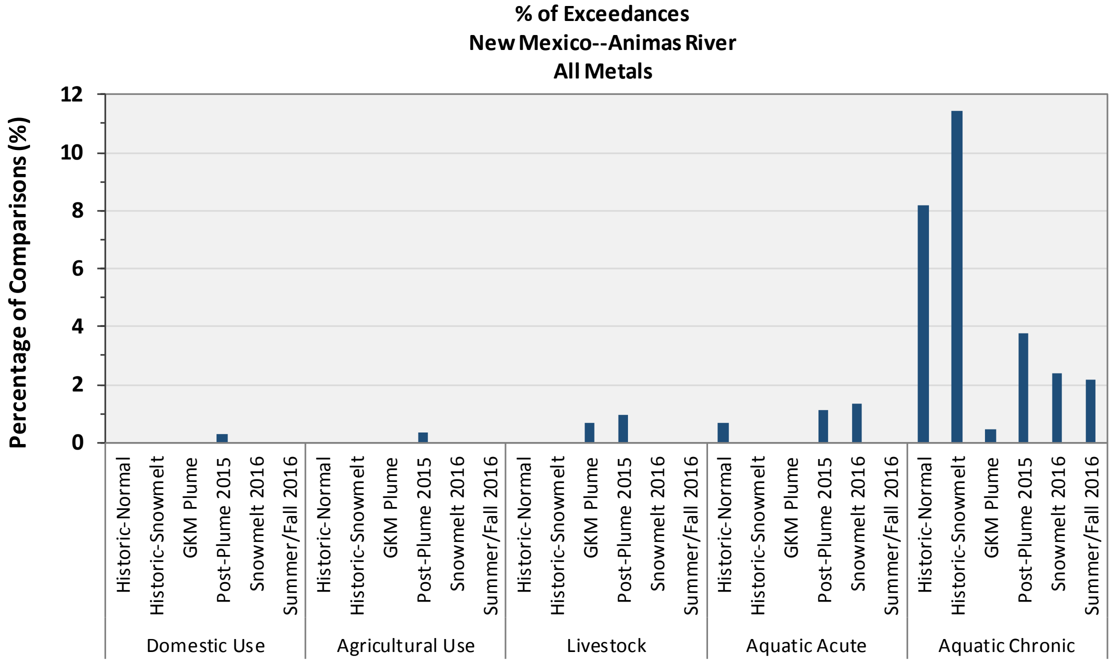


Figure 9-52. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the Animas River in New Mexico. Data are organized by time periods defined for the Gold King release in Figure 9-48.

Animas River in New Mexico. The rates of exceedance of water quality criteria in the Animas River in New Mexico from approximately RK 140 to the confluence with the San Juan River in Farmington (RK193) are provided in Figure 9-52. With the exception of the aquatic chronic criteria, there were not many exceedances of criteria in the Animas River in New Mexico historically. Domestic use criteria were exceeded in 2% of the samples in the Post-plume 2015 period, due primarily to lead and, to a lesser extent arsenic and beryllium. Livestock criteria were also exceeded infrequently in the Post-plume 2015 period. No exceedances for domestic, agricultural or livestock were observed since 2015.

The rates of exceedances of aquatic chronic criteria were greatest in the historic period. Exceedances have trended downward since the Gold King release and have been low in 2016 relative to pre-event. Most of the aquatic exceedances that occurred during and after the Gold King release were due to aluminum and lead. Exceedances of aquatic chronic criteria were less after the Gold King release than historically, and have trended downward in the Post-plume 2015 and Summer/Fall 2016 periods.

San Juan River in New Mexico. The rates of exceedance of criteria in the San Juan River in New Mexico from approximately RK 193 in Farmington to the Four Corners area (~RK 296) are provided in Figure 9-53. Exceedances of domestic, agricultural and livestock uses in the San Juan River within New Mexico were similar to those observed in in the lower Animas River. Exceedances of criteria for these uses were infrequently observed historically, occurring primarily during snowmelt. Infrequent exceedances were also observed in the post-plume 2015 period and were not observed in 2016. Domestic use criteria were occasionally exceeded for lead, cadmium and beryllium. The agricultural exceedances were primarily associated with aluminum.

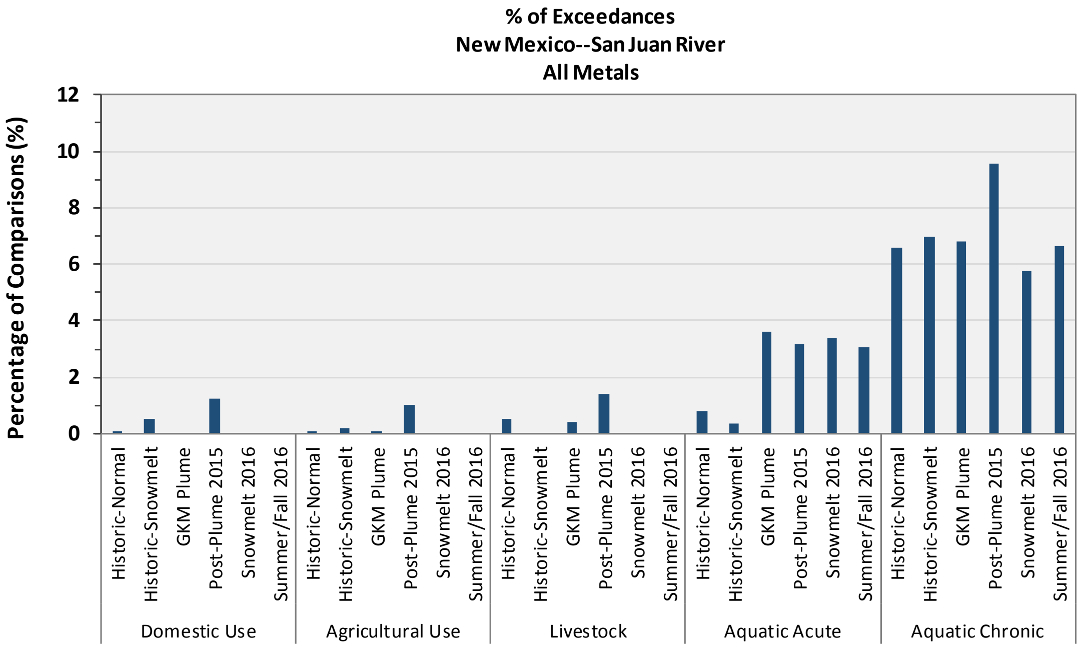


Figure 9-53. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the San Juan River in New Mexico. Data are organized by time periods defined for the Gold King release in Figure 9-48.

The frequency of exceedance of aquatic acute criteria increased since the Gold King release in all time periods, while aquatic chronic criteria ae exceeded relatively frequently at a rate that has not changed since increasing in the 2015 Post-plume period. Virtually all of the aquatic acute exceedances are associated with aluminum. These have not trended toward pre-event conditions. The aquatic chronic exceedances were also due primarily to aluminum, while the historic exceedances were due more to cadmium and aluminum. Lead and copper contributed to Post-plume 2015 exceedances and were not observed in 2016.

San Juan River in Colorado. There is a short segment of the San Juan River that flows within Colorado in the Four Corners area (~RK 296). Samples collected at near RK 296 were screened relative to Colorado criteria, although the state did not sample here. The rates of exceedance of criteria in this segment are provided in Figure 9-54. Most of Colorado's criteria for most uses have been exceeded relatively frequently in the San Juan River historically, with the exception of acute criteria. Exceedances of Colorado criteria occurred more often in the San Juan River than observed relative to New Mexico criteria. This is probably because many of the Colorado's criteria are based on total concentrations and most of New Mexico's are based on dissolved fractions (with the exception of aluminum-based criteria.) Thus, sediment loads in the river could contribute to exceedances due to the metals associated with them.

Exceedances for domestic use, agriculture and aquatic chronic criteria were elevated in the 2015 Post-plume period relative to historic rates. Many of the additional exceedances during the GKM-plume and Post-plume 2015 period were associated with total lead, chromium and cadmium. There were no exceedances due to these metals in 2016. These same metals contributed to the spike in agricultural exceedances, although this use category was also affected by manganese through the 2016 snowmelt season. Aquatic chronic criteria exceedances were relatively frequent historically. Iron and cadmium contribute to most of these exceedances with lead and copper exceeding criteria 100% of the time during snowmelt. These same metals caused exceedances in the Post-plume 2015 period and during 2016 snowmelt. There was no trend in the rate of aquatic chronic exceedances.

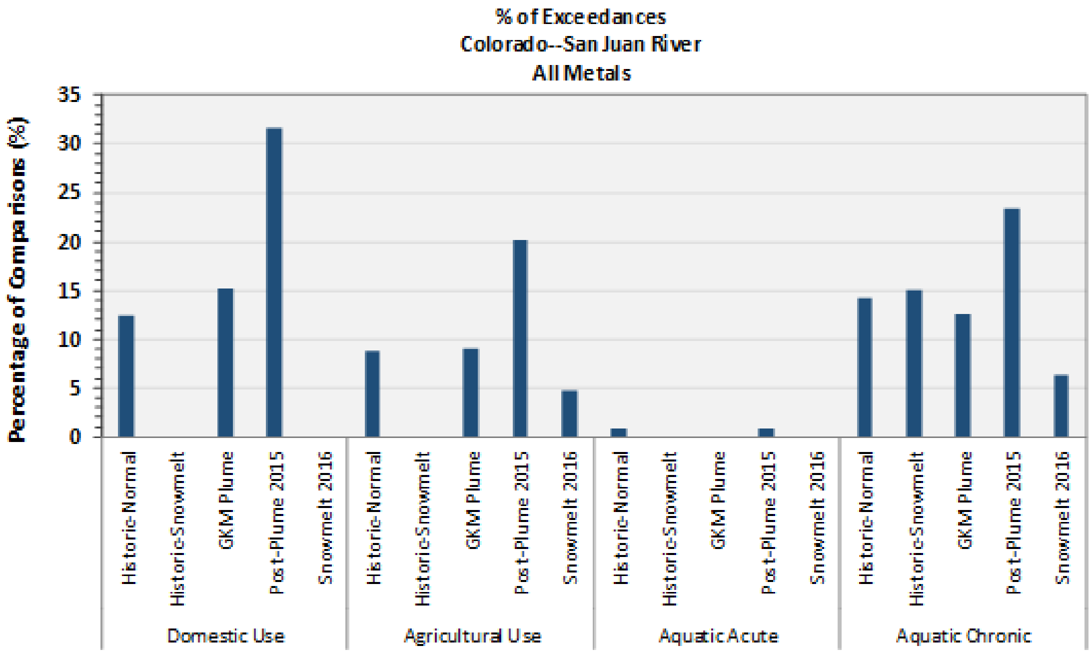


Figure 9-54. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the San Juan River in Colorado. Data are organized by time periods defined for the Gold King release in Figure 9-48.

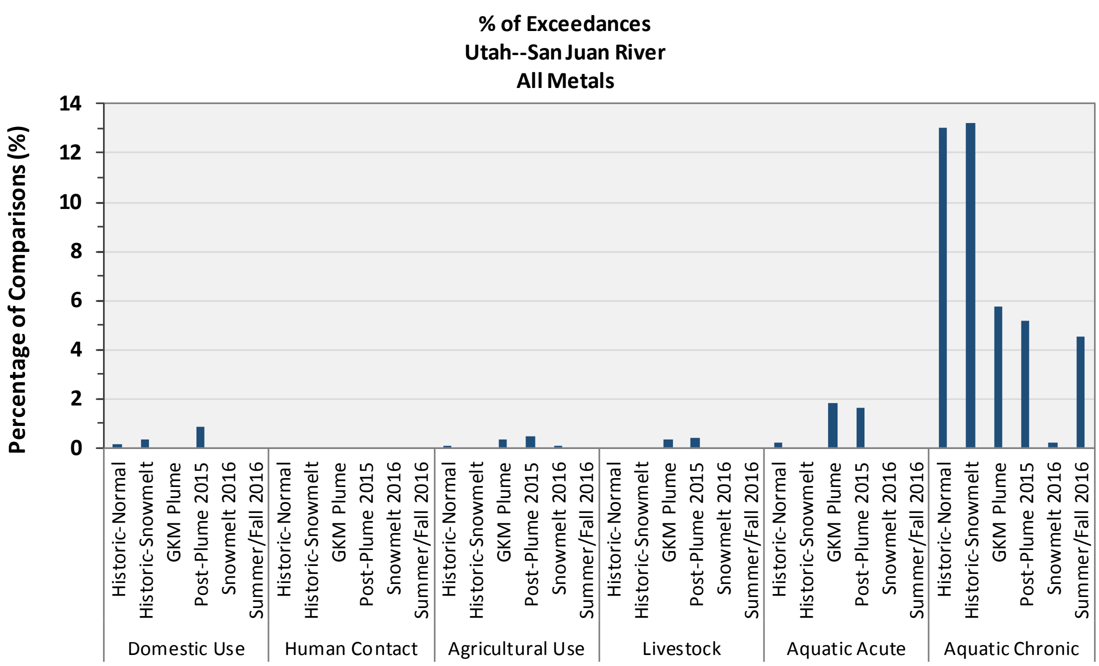


Figure 9-55. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the San Juan River in Utah. Data are organized by time periods defined for the Gold King release in Figure 9-48.

San Juan River in Utah. The rates of exceedance of criteria in the San Juan River within Utah are provided in Figure 9-55. This segment begins in the vicinity of RK 296. There are few exceedances of Utah water quality criteria in the San Juan River in any time period, probably since the dissolved fraction is the basis for all but recreational contact. Domestic use criteria are rarely exceeded historically, but there were infrequent exceedances due to arsenic and lead during the post event 2015 period. Exceedances were not observed in 2016. Similarly, there were some exceedances of agricultural criteria during the GKM-plume and Post-plume period due to aluminum, iron, manganese, and cobalt that had not been observed previously. There were no exceedances of agricultural criteria due to these metals in 2016. Livestock criteria were briefly exceeded during the same period by aluminum.

Aluminum, iron, and copper caused aquatic acute exceedances during and following the Gold King release, but did not cause exceedances in 2016. Aquatic chronic criteria were also affected by aluminum during and since the release, but generally exceedances have trended downward from historically higher rates. Cadmium has caused most exceedances historically. With the exception of aquatic chronic use, there were no exceedances of criteria in 2016.

San Juan River in the Navajo Nation. The Navajo Nation includes the entire length of the San Juan River within the sampling area (RK 193 to RK 510). The rates of exceedance of Navajo Nation water quality criteria in the San Juan River are provided in Figure 9-56. There were no strong upward trends in exceedance rates for most designated uses associated with the Gold King release, with the exception of aquatic acute criteria. The exceedance rate of several uses (domestic water, human contact related) have trended downward from historic rates.

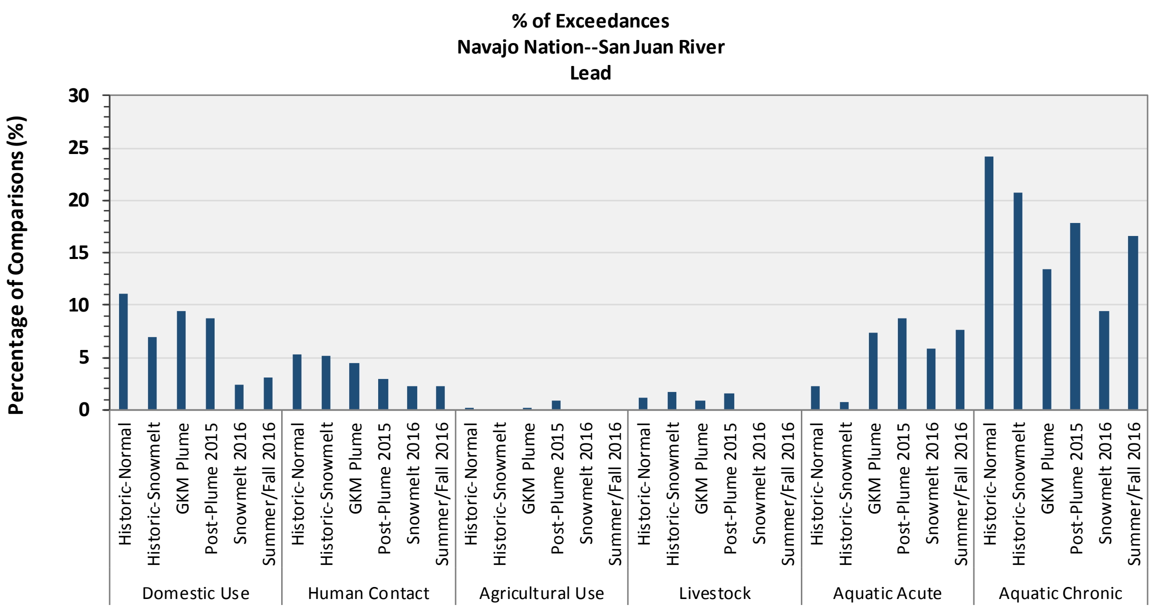


Figure 9-56. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the San Juan River in the Navajo Nation. Data are organized by time periods defined for the Gold King release in Figure 9-48.

Most of the Navajo Nation criteria are based on total concentrations, except the aquatic habitat criteria and a few of the agriculture and livestock criteria. Because the criteria are based on total concentrations, they are also likely to be exceeded more frequently due to the sediment loads in the river. Lead and arsenic typically contribute to the domestic use exceedances historically. The exceedance rate for arsenic was somewhat elevated during the GKM period and exceedances for beryllium were uniquely observed during this period. Other metals, including lead were elevated during the plume, but the exceedance rate was similar to the historic periods. Exceedances for lead occurred at the same rate after the GKM release as observed historically. The decline in domestic use exceedances from historic levels was due to fewer exceedances of criteria involving cadmium, arsenic, lead, barium, and other metals. Almost all human contact exceedances were due to lead. There was no indication that the Gold King release affected their rate of occurrence.

Agricultural exceedances of Navajo Nation criteria occur very infrequently. Within this category, aluminum exceedances spiked during the GKM plume and Post-plume 2015 periods. A few exceedances of cobalt, copper, and vanadium were also observed during 2015 Post-plume period that were not observed previously. There were no exceedances of any agricultural criteria in 2016. Exceedances of livestock criteria occurred historically. The rate of livestock exceedances has declined from historic levels since the Gold King release and there were no exceedances in 2016. The livestock exceedances were all due to lead. Similarly, the rates of aquatic acute and chronic exceedances remained unchanged from historic rates with no obvious response to the Gold King plume.

Exceedances of aquatic acute and chronic criteria were relatively frequent and were almost exclusively associated with aluminum. Exceedances of aquatic acute criteria increased since the GKM release while exceedances of chronic criteria remained the same. Cadmium, and selenium have caused exceedances historically but these metals did not cause many exceedances in 2015 and 2016.

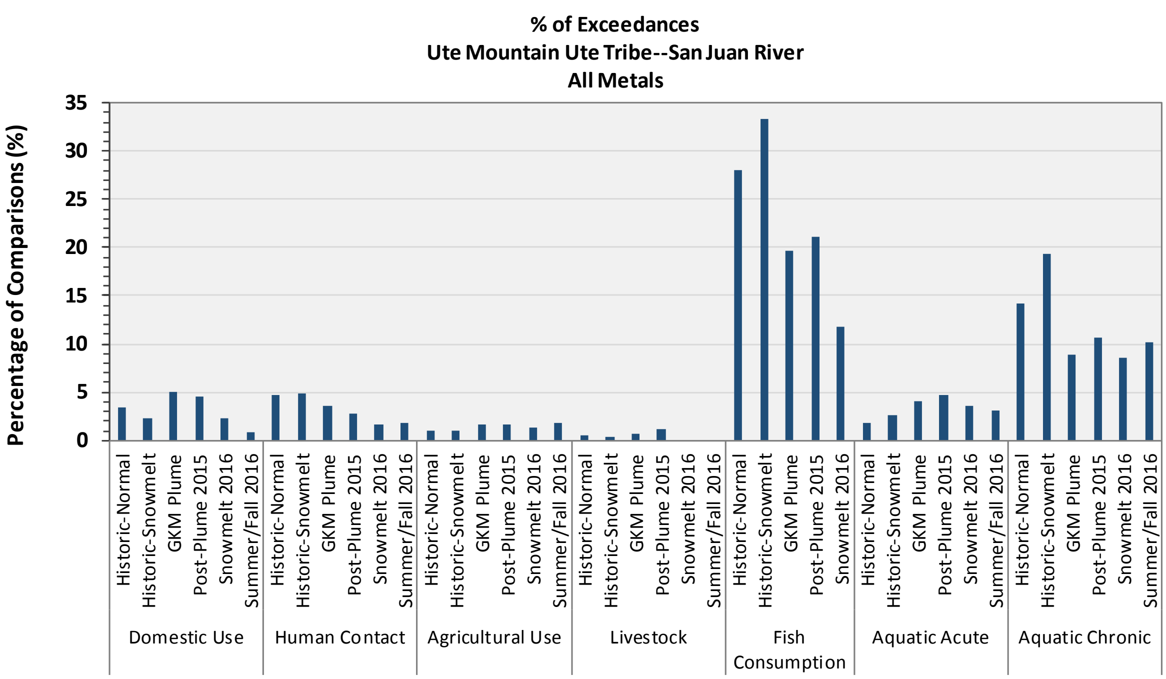


Figure 9-57. Percentage of exceedances of water quality criteria relative to the number of comparisons of all metal concentrations to all appropriate water quality criteria by designated use in the San Juan River in the Ute Mountain Ute Tribe Reservation. Data are organized by time periods defined for the Gold King release in Figure 9-48.

San Juan River in the Ute Mountain Ute Tribe Reservation. The San Juan River flows through the Ute Mountain Ute Tribe (UMUT) Reservation from approximately Shiprock New Mexico at RK 246 to near Montezuma Creek, Utah at approximately RK 346. The rates of exceedance of criteria in the San Juan River within the UMUT reservation are provided in Figure 9-57. Many of the Ute Mountain Ute Tribe criteria are based on total concentrations with the exception of the aquatic habitat criteria. Some of the criteria, such as arsenic and aluminum are lower than other jurisdictions, in some cases by several orders of magnitude.

Considering all metals, there appeared to be a small increase in the exceedance rate of UMUT domestic use criteria in the Gold King plume and 2015 Post-plume periods. Historically aluminum and arsenic domestic use criteria were exceeded 100% of the time, with occasional exceedances of lead. The frequency of lead exceedances increased after the GKM release. Nickel exceedances also increased, although nickel was not much of a factor in the Gold King release. No exceedances of domestic lead criteria were observed in 2016. Human contact arsenic criteria were also historically exceeded 100% of the time, with less frequent lead exceedances. The frequency of lead exceedances, chromium and nickel increased during the Gold King plume and 2015 Post-plume periods. Only arsenic exceedances persisted in 2016.

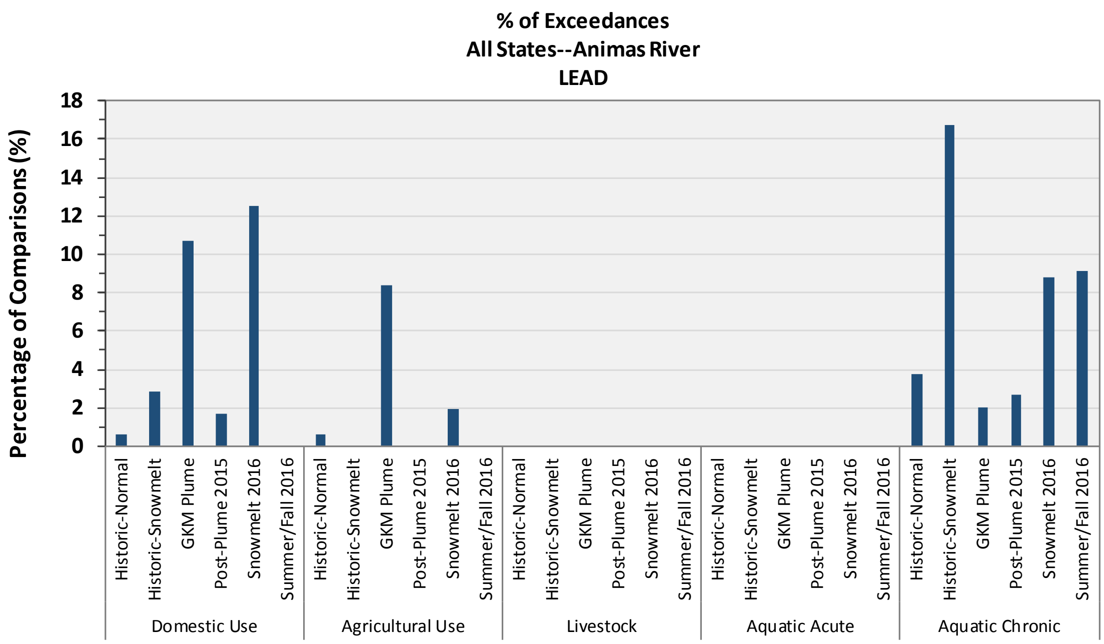
Agricultural exceedances for arsenic, copper and lead occurred historically. Exceedances did not increase during the Gold King plume period. However, post-plume exceedances were observed in chromium, copper, lead and nickel. No exceedances of these metals were observed in 2016. Exceedances in fish consumption criteria occur frequently (almost 100% of observations). These are due to arsenic and mercury. (Mercury occurances may be entirely or partially due to the non-detection issue described in the methods). There was no indication that fish consumption exceedances changed after the Gold King release.

Exceedances of aquatic acute criteria were due primarily to aluminum and have not changed since the Gold King release. Exceedances of copper criteria occurred infrequently in the Post-plume 2015 period and were not observed in 2016. Chronic aquatic habitat exceedances have trended downward, including during and after the Gold King release. Cadmium played a role in historic exceedances but was not observed in 2016.

Overview of Metals Frequently Associated with the GKM Release. Several metals have been identified throughout this report and this chapter as most prevalent in affecting water quality during and after the Gold King release event at widely distributed locations. These include lead and aluminum primarily, and arsenic to a much less extent. The rate of exceedances of designated uses due to lead and arsenic are shown by river grouping states in Figures 9-58 and 9-59. Aluminum exceedances of state criteria are shown in Figure 9-60.

In the Animas River, the rate of lead-related exceedances for domestic water increased immediately after the GKM release and declined to pre-event levels within the Post-plume 2015 period that began about two weeks after the plume passed (Figure 9-58A). Another spike occurred during the 2016 Snowmelt period as the Gold King metals were mobilized and transported through the system. Lead exceedances occurred historically during snowmelt runoff, but the rate was higher in 2016. There were no lead exceedances during the Summer/Fall 2016 period. Agricultural exceedances due to lead were infrequent but followed the same pattern as domestic water. Arsenic exceedances were not observed in the San Juan River historically
(Figure 9-58B). There were infrequent exceedances of domestic use and agricultural criteria due to arsenic in either the GKM-plume or Post-plume 2015 periods, depending on metal. Other designated use criteria related to arsenic were not affected by the GKM release and there were no exceedances in 2016, including during snowmelt.

A)



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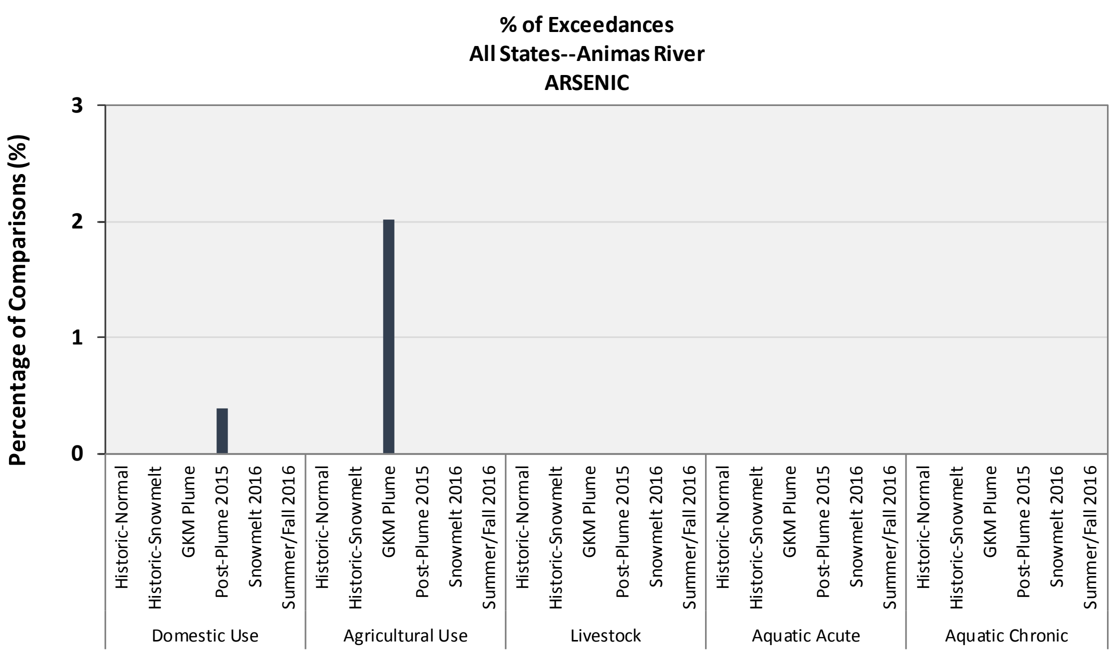


Figure 9-58. Percentage of exceedances of water quality criteria relative to the number of comparisons of metal concentrations to all appropriate state water quality criteria by designated use in the Animas River: A) lead and B) arsenic. Data are organized by time periods defined for the Gold King release in Figure 9-48.

A)

B)

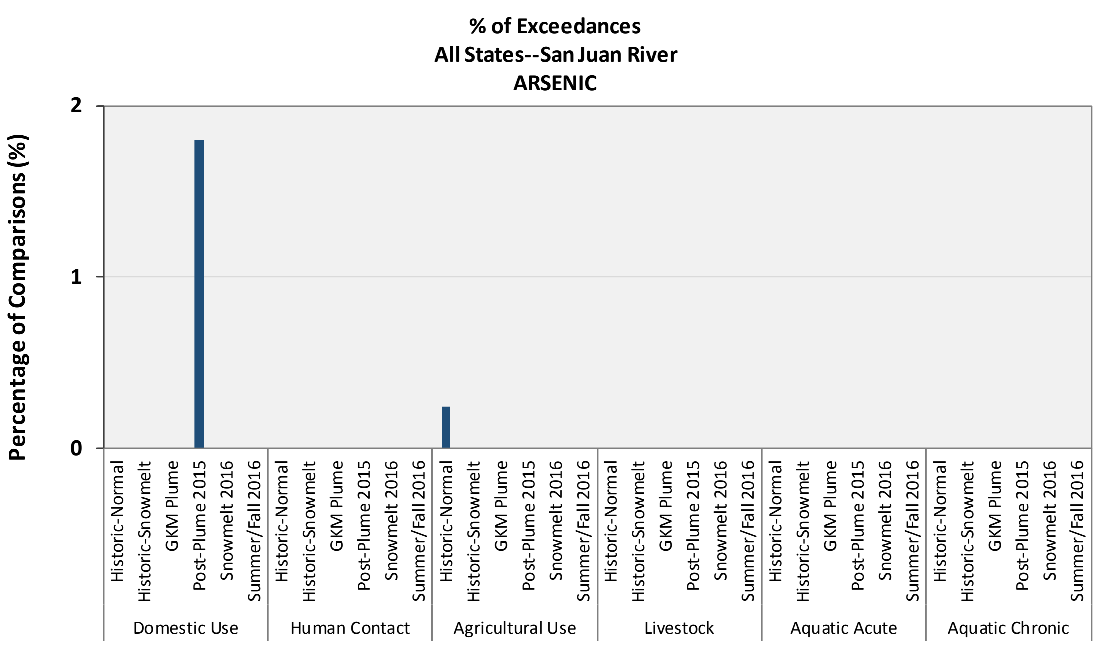
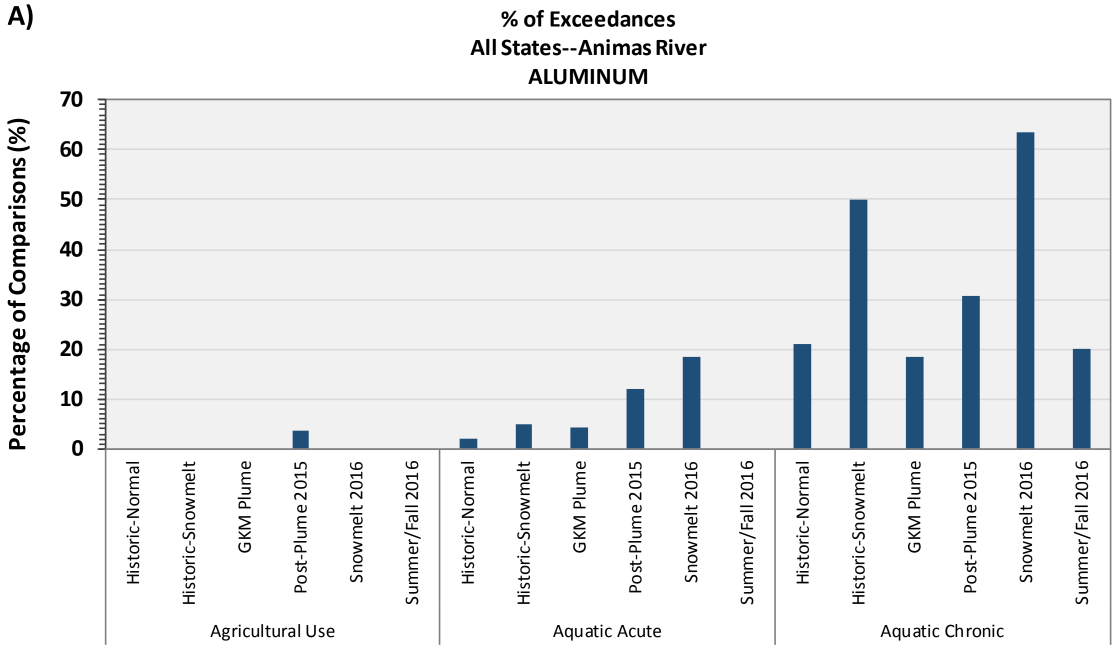


Figure 9-59. Percentage of exceedances of water quality criteria relative to the number of comparisons of metal concentrations to all appropriate state water quality criteria by designated use in the San Juan River: A) lead and B) arsenic. Data are organized by time periods defined for the Gold King release in Figure 9-48.

A)



B)

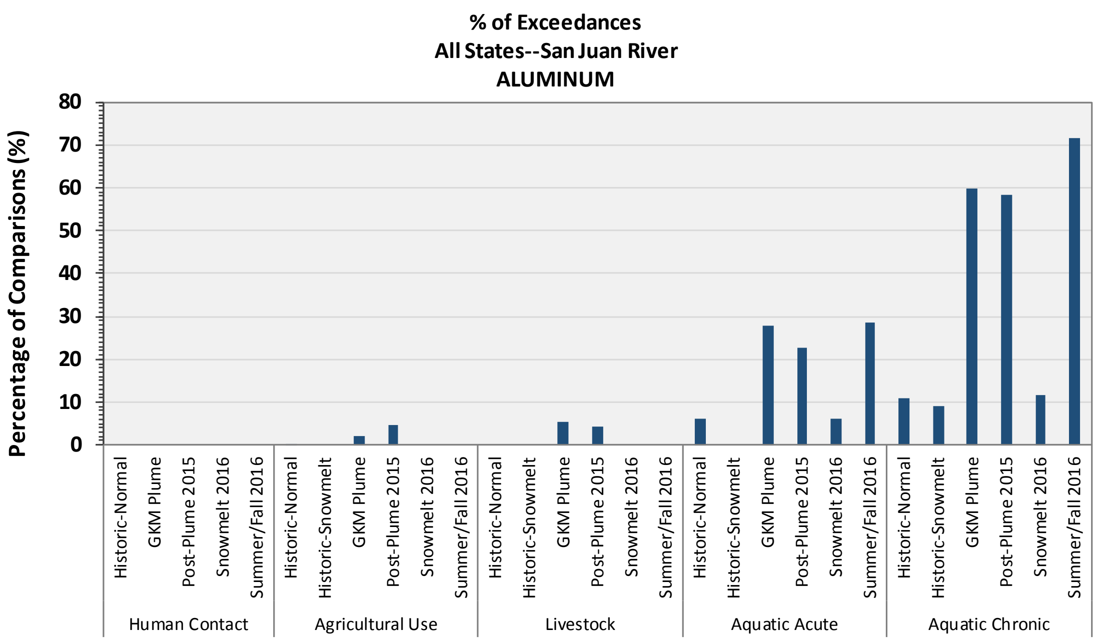


Figure 9-60. Percentage of exceedances of water quality criteria relative to the number of comparisons of the concentration of aluminum to all appropriate state water quality criteria by designated use in A) the Animas River, and B) the San Juan River. Data are organized by time periods defined for the Gold King release in Figure 9-48.

In the San Juan River, exceedances of domestic water criteria for lead and arsenic were more common than in the Animas River (Figure 5-59). The frequency domestic water criteria exceedances increased due to lead and arsenic during the GKM-plume and in the Post-plume 2015 period. Rates returned to historically observed levels in 2016. Agricultural use exceedances due to lead were infrequent but were somewhat elevated relative to historic rates in the Post-plume 2015 period. There were no exceedances in agricultural, livestock or aquatic habitat criteria due to lead in 2016. Arsenic has not historically exceeded agricultural, livestock and aquatic habitat use criteria and the GKM release did not cause any arsenic-related exceedances. No exceedances due to lead or arsenic for any state designated use was observed in the San Juan River.

Aluminum was a major component of the Gold King Mine release and states and tribes have criteria for many of the designated uses for either dissolved or total aluminum. Patterns of dissolved aluminum were shown earlier in this chapter to have changed in the lower Animas River following the August 27 storm (Section 9-5). The aluminum increase in the Animas River also affected concentrations in the San Juan River. This effect was strong enough to have statistically increased concentrations in the Post-plume 2015 period in the Animas and San Juan Rivers. The rate of aluminum-related exceedances in the Animas and San Juan Rivers are shown in Figure 9-60.

The rate of exceedances in agricultural use criteria in the Animas River increased somewhat in this period (Figure 9-60A). The rate of aquatic acute exceedances increased to a greater degree, while the rate of aquatic chronic exceedances increased a relatively smaller amount. Exceedances of aquatic criteria have historically spiked during snowmelt. Exceedances due to aluminum also increased during snowmelt 2016 and to a greater degree than observed historically. Exceedance rate due to aluminum in the Animas River returned to historic levels in Summer/Fall 2016.

Exceedances of state aluminum-related criteria for domestic and human contact were not exceeded in the San Juan River historically and the Gold King release did not affect those designated uses (Figure 9-60B). The Gold King release caused infrequent exceedances of aluminum-related agricultural and livestock criteria in 2015 but not in 2016. Historically, aquatic habitat acute and chronic criteria for the San Juan River were exceeded infrequently due to aluminum. The rate of exceedance of both acute and chronic criteria increased in the San Juan River in the GKM-plume and Post-plume 2015 periods. Exceedance rates for aquatic chronic habitat were at historic levels during snowmelt but have remained elevated in Summer/Fall 2016.

9.10 Summary of Post Gold King Release Water Quality

In this chapter, water concentration data were displayed in spatial and temporal detail, statistical comparisons of pre- and post-event metals concentrations were performed where possible, and trends in the rate of water quality exceedances were reviewed at a river segment level, largely defined by state or tribal boundaries. Earlier analyses highlighted the inherent differences between the Animas and San Juan Rivers, and discussed flow and weather factors that influenced the deposition and mobilization of Gold King release materials during and following the event that initially occurred early in August 2015 but affected the river system through the Snowmelt 2016 period.

Review of the effects of the Gold King release on metals concentrations from the perspective of water quality criteria reflects the differences in the background characteristics of the Animas and San Juan Rivers and the jurisdictional differences in individual state and tribal water quality criteria. The overall pattern in water quality followed the patterns in metals concentrations identified in earlier sections of the chapter. Some analyses highlighted the importance of natural river processes and some demonstrated the role of the Gold King release. Because the rivers vary in many characteristics, and because the state and tribal jurisdictions have different water quality criteria, the same rivers have varying patterns of water quality response when viewed from a designated use perspective. Overall, exceedances during the Gold King plume and Post-plume 2015 periods due to metals associated with the plume could be identified. Some

Gold King-associated metals were evident in April 2016 as GKM release deposits were transported with the snowmelt runoff. Exceedance rate of most designated uses criteria have returned to pre-event conditions in 2016.

The dominant metals in the Gold King release (larger relative mass) tended to be the metals associated with elevated water quality exceedance rates during the Gold King plume and Post-plume 2015 periods. The Gold King release primarily contained colloidal/particulate metals. Water quality criteria that target total metal concentration tended to be exceeded more frequently, especially during the immediate period during and following the release. This included lead and aluminum, and to a much more limited extent, arsenic. Iron made up most of the GKM release mass but there are very few water quality criteria for iron so this metal did not impact water quality for designated uses. Other metals were locally important depending on the state or tribal criteria. For example, manganese was involved in agricultural criteria exceedances in Colorado.

Once the Gold King plume passed out of the rivers nine days after the initial release event, 95% of the released mass was left behind as deposits in the streambed spread through the river system. This material affected water quality for a period of time after the release event that varied with location. Most of the material was deposited in the Animas River within Colorado. Data displays showed that water concentrations returned to pre-event conditions within the first several weeks after the release in this portion of the river despite the deposits, and statistical tests found the post GKM event water concentrations of many of the trace metals were actually lower than historic levels. The sorptive capacity of fresh iron and aluminum (hydr)oxide deposits was a possible explanation for this pattern. Water quality exceedances followed this pattern in that there was little change from historical exceedance rates once the Gold King plume passed. Gold King deposits were mobilized during snowmelt 2016 and infrequent exceedances of domestic water use criteria were observed in Colorado during snowmelt runoff. Water quality patterns in the Animas River within Colorado were at or lower than historical conditions for most of the period after the Gold King release. Mass estimates during snowmelt suggested that all of the Gold King release deposits were resuspended and removed from the Animas River.

The lower Animas River in New Mexico experienced lower metals concentrations during passage of the Gold King plume than the upper Animas, but metals were deposited within the New Mexico segment as well. A storm on August 27, 2015 about 20 days after the plume passed mobilized what appeared to be all of the deposited metals within the New Mexico segment of the Animas and the San Juan River and probably transported them to Lake Powell given the strength of the storm. Without the sorptive capacity of the deposits, water quality changed in the months after the release. Concentrations of dissolved aluminum and iron along with other trace metals increased during the Post-plume period in 2015. The change was statistically significant and sufficient to increase the rate of exceedances of some aluminum-related water quality criteria. Exceedances were rare and there no exceedances observed in Summer/Fall 2016. The lower Animas River also appears to have returned to pre-event conditions in 2016.

By the time the Gold King plume reached the San Juan River, most of the mass of metals had been deposited in the Animas River. However, the passage of the plume could be detected the San Juan River at least as far as Four Corners, New Mexico and possibly as far as Bluff, Utah before the signature was difficult to detect within the background sediment load. The San Juan River has higher background concentrations of metals due to the amount of sediment carried in the river and had high levels of sediment when the Gold King plume passed through due to a release of water from the Navajo Dam. The background metals concentrations in the San Juan sediments reflect those in the soils and geology that produce them. Background metals in the sediments help to cause higher rates of metals-related criteria exceedances in the San Juan River generally. Nevertheless, the Gold King release infrequently increased the rate of exceedances of various designated uses during the GKM plume and Post-Plume 2015 periods, including domestic and agricultural uses.

Analyses indicated that most, and more likely all, of the Gold King mass that had been deposited within the upper and middle reaches of the Animas River was mobilized and transported through the San Juan River to Lake Powell during snowmelt runoff in 2016. There was evidence in the water concentrations of Gold King metals during this time, but the passage of the Gold King deposits through the San Juan River did not trigger water quality exceedances. Water quality exceedance rates in the San Juan River have returned to pre-event conditions.

The results from this report will be added to the Conceptual Monitoring Plan Report being prepared by EPA's Office of Water and EPA Regions and analyzed along with the biological community, fish and physical habitat data collected since fall 2015. That report is expected to be released in Spring 2017. In addition, EPA is working with USGS under a Cooperative Agreement to attempt to develop a correlation between particulates that may be detected by USGS sondes that were deployed during 2016 and metals concentrations. This work has the potential to use the sondes to detect elevated metals levels during storm events and snowmelt.

CHAPTER 10 SUMMARY AND SYNTHESIS

On August 5, 2015, an EPA team was investigating Gold King Mine (GKM) as one of hundreds of mines that is a source of metals contamination in the Animas River, in preparation for remediation. Drainage within the mine was dammed behind the collapsed mine structure and rock that blocked the opening of the mine and pressurized the water dammed behind it. While the EPA team was excavating above the main GKM adit, the blockage was destabilized and water began leaking from the mine. The small leak quickly turned into a significant breach that suddenly released 11.33 million liters (approximately 3 million gallons) of mine water into the North Fork of Cement Creek, which joins the Animas River 12.5 kilometers (7.8 miles) downstream. The mine water flooded the North Fork of Cement Creek, and over a nine-day period, the plume from the release flowed down the Animas River to the San Juan River and into Lake Powell. The majority of the mine drained in about 6 hours.

The release traveled as a coherent plume, or slug, of metals over an eight-day period and through 550 kilometers (342 miles) of the Animas and San Juan Rivers before ultimately reaching Lake Powell. The release crossed three states (i.e., Colorado, New Mexico, and Utah), three Indian reservations (i.e., Southern Ute Indian Tribe, Ute Mountain Ute Tribe, and Navajo Nation), and multiple communities. EPA worked with state agencies, tribes, and local communities, through its Area Command Center in Durango, Colorado, to curb withdrawals from the Animas and San Juan Rivers for domestic water supply (e.g., consumption), agricultural use, and recreation and to provide alternative water supplies during the weeks following the release.

EPA, the states, and tribes initiated an extensive monitoring program through the entire river system, from the headwaters of the Animas River, through the San Juan River, and into Lake Powell. EPA collected samples over varying intervals, beginning at six-hour intervals early in the response and continuing weekly during later phases of the response. EPA, the states, and tribes continued to monitor water quality on a less frequent basis throughout the affected river system through the fall of 2015 and in the following year from snowmelt through summer 2016. Figures 10-1 through 10-6 show photographs of the Animas and San Juan Rivers in August 2016 one year after the Gold King Mine release.

In March 2016 EPA released the Post-Gold King Mine Release Incident: Conceptual Monitoring plan for Surface Water, Sediments, and Biology (U.S. EPA 2016a). This monitoring plan is designed to gather scientific data to evaluate river conditions over the course of the year and to identify any potential impacts to public health and the environment from the release. EPA's Conceptual Monitoring Plan (CMP) is designed to assess physiochemical and biological parameters downstream of the GKM Release Incident.

EPA’s Office of Research and Development (ORD) scientists have supported EPA efforts by investigating the transport and fate of metals introduced to the Animas and San Juan Rivers from the Gold King Mine release and assessing what has happened to sediment deposits and water quality following the event. The objectives of the research described in this report were to:

- Quantify the release from the GKM source (including what and how much was released);
- Quantify transport and fate of metals in the Animas and San Juan Rivers (including the receiving waters and streambed);
- Characterize potential exposure to metal concentrations as the plume traveled through the system;
- Assess the status of metals in water and sediments in the year after the event; and
- Evaluate the mobilization of metals deposited in the streambed during high flows in storms or seasonal snowmelt.

Over 1,400 water quality and 700 sediment samples collected by EPA, states, tribes, and others were analyzed and used to quantify the source, transport, and fate of the GKM plume (i.e., where it went and what happened to it along the way). Water quality, groundwater, and geochemical modeling with existing software-based process models was employed to better understand the physical and chemical processes that determined the release characteristics and its impact over this large area.

Figure 10-1. Cement Creek (near RK 13) in Silverton, Colorado in August 2016.

The headwaters of the Animas River are located in the San Juan Mountains, where contamination from past mining has been a concern for decades. Beginning in the 1870s, southwest Colorado, near the town of Silverton, was home to hundreds of mines that produced gold, silver, lead, zinc, and copper from ores extracted from the highly mineralized geologic formations and hardrock mines. Mining operations in this area ceased in the early 1990s and left hundreds of abandoned mines that have historically discharged an average of 5.4 million gallons of acidic mine drainage (AMD) per day to the headwaters of the Animas River (Church *et al.* 2007). AMD contains high concentrations of heavy metals, such as zinc, lead, cadmium, copper, and aluminum. The USGS focused considerable research activity in the upper Animas watershed from 1995 to 2007 as part of the national research initiative to study and abate AMD. Information generated in that comprehensive and integrated set of studies was informative to this Gold King Mine Release Transport and Fate Study.

The release of three million gallons of Gold King Mine effluent was equivalent to four to seven days of current acid mine drainage, and the total metals mass in the plume was comparable to a mass of metals carried in one to two days of high spring runoff, varying by metal.

10.1 How much mine waste was released and what was its composition?

The Gold King Mine released 11.33 million liters (approximately 3 million gallons) of low pH (~3) acid mine drainage containing 490,000 kg of dissolved and colloidal/particulate metals into the Animas River. Colloidal metals are small solids, less than 10 µm in size. A relatively small amount of the mass of metals that was released to the Animas River actually came from inside the mine (i.e., 2,900 kg). Most of the mass was entrained between the mine entrance and Cement Creek before reaching the Animas River in Silverton, Colorado. The majority of the additional mass was eroded from an old mine waste pile that made up most of the hillslope between the mine and the North Fork Cement Creek ,70 meters below. The flood from the mine could have also entrained or dissolved metals in the contaminated sediments of Cement Creek, which receives large quantities of ongoing AMD.

Figure 10-2. Animas River at Bakers Bridge near RK 64 in August 2016.

The Gold King Mine plume delivered very high concentrations of a number of metals to the Animas River where Cement Creek joins it at Silverton, Colorado, with most draining over a period of 8 hours but continuing for up to 24 hours. The majority of the released mass was colloidal/particulate aluminum, iron, and manganese, with significant quantities of lead, copper, arsenic, zinc, and cadmium. The release contained a minute quantity of mercury. Of the 490,000-kg metals mass in the GKM plume, approximately 15,000 kg were dissolved forms of these metals, as the plume traveled through Cement Creek. Both dissolved and colloidal/particulate metals can be toxic, varying by designated uses, organisms, and length of exposure, and were a concern as the Gold King plume migrated through the rivers.

10.2 What happened to the metals released from the Gold King Mine?

The GKM release traveled downstream through the Animas River and joined the San Juan River on August 8. The plume traveled for an additional 4 days when it reached Lake Powell in Utah, nearly 550 kilometers from the Gold King Mine source. The metals in the GKM plume traveled as a coherent plume mass over a period of 9 days, traveling at approximately 3 kilometers per hour (2 miles per hour).

For most of the metals mass in the plume to pass a single location required between 24 hours near the Gold King Mine source and 50 hours in the lower Animas River; this time interval lengthened due to the drag forces of the river bed. However, the majority of the metals mass, and highest concentrations of metals, traveled within a core 12-hour period a length of time that persisted through much of the length of the river. Evidence suggests that there was a front of dissolved metals, and as chemical reactions occurred within the acidic core of the plume, a trail of colloidal/particulate material was left, including precipitated iron and aluminum oxides, which created the intense yellow color witnessed in the Animas and San Juan Rivers.

Once the acidic plume entered the larger and more alkaline Animas River, both dissolved and colloidal/particulate metals concentrations began to decline rapidly, as chemical reactions and hydraulic processes transformed, diluted, and deposited material.

Dilution from incoming flow to the river from the upper Animas and other tributaries diluted metals concentrations in the plume almost as soon as they entered the Animas River. Upon joining the Animas 13 kilometers from the Gold King Mine, flow was diluted by 50%, and by the time the plume traveled an additional 4 kilometers, it was diluted to 10% of its original strength by the incoming flow of Mineral Creek and the mainstem of the Animas River in the vicinity of Silverton, Colorado. The plume was diluted to just 1% of original strength by the time it reached Durango, 95 kilometers from its source.

The acidity of the plume was neutralized as it mixed with the alkaline waters of the Animas River. Increasing pH triggered formation of iron and aluminum oxides and other incipient minerals through chemical reactions that produced the intense yellow color of the river during this event. Aluminum and iron (hydr)oxides primarily formed as the plume moved from Silverton to below Durango until the plume's acidity was largely exhausted. Geochemical calculations of neutralization were supported by observations of pH along the river, and reduction of dissolved metals was observed in water samples collected as the plume passed. Geochemical reactions neutralized the low pH and transformed dissolved metals to iron and aluminum oxides, among other minerals. These materials were probably initially colloidal particles suspended in the river's water.

A)

B)

Figure 10-3. Animas River at A) 32nd Street Bridge at RK 93 in Durango, Colorado, and B) north of Durango at approximately RK 91 in August 2016.

The volume of acidity in the release carried dissolved metal ions much farther downstream in dissolved form than typically occurs with the ongoing mining contamination. The aluminum and iron oxides scavenged dissolved trace metals into their structures, removing them from solution. Dissolved metals concentrations were at background levels by the time the Animas joined the San Juan River, 192 kilometers from the Gold King Mine.

Metals concentrations in the water also declined as colloidal/particulate metals, including entrained particulates and aggregated iron and aluminum oxides, were deposited in the river bed. Metals mass was deposited along the entire length of the Animas River at channel margins, side channels, and behind flow obstructions. Initially, 89 percent of the plume deposited in the Animas River, 6% deposited in the San Juan River, and 5% was delivered to Lake Powell during the movement of the plume.

Much of the metals mass deposited in the upper Animas River was in the approximately 80-kilometer reach between Silverton and Durango, Colorado, with a majority depositing where the river exits the constrained channel reach through the San Juan Forest at Baker's Bridge (i.e., 64 kilometers from the GKM source). More metals deposited through the next 30 kilometers of braided and meandering river segments north of Durango. Another depositional area was between 132 and 164 kilometers from the Gold King Mine source in the lower Animas River near Cedar Hill, Colorado and Aztec, New Mexico.

The GKM plume continued to flow from the Animas River into the sediment-rich San Juan River at Farmington, New Mexico. Modeling estimated that 55,000 kilograms of colloidal/particulate metals mass was carried from the Animas River into the San Juan River at Farmington. The plume that entered the San Juan was largely iron and aluminum, but still carried a relatively high mass of lead, copper, and zinc compared to background in the San Juan.

Although Animas River metals concentrations were measurably high with the Gold King Mine release, the plume became difficult to visibly distinguish and measure after it traveled through the San Juan River. The two rivers were about equal in flow where they joined, but the San Juan had a high amount of sediment with commensurately high background loads of metals naturally present in the sediment.

A mineralogical fingerprinting technique was developed that could be applied to data routinely collected in monitoring programs as a signature of the Gold King Mine release trace metals. This technique involved associating the concentration of trace metals to that of aluminum or iron as representative of the dominant metals in the geologic substrate and the soils and sediments that weather from them. The technique was effective in identifying metals associated with the release within background concentrations during the plume and in post-event samples. This technique highlighted the prominence of lead, and to a more limited degree, copper and zinc, as metals generated in the plume and enabled the presence of these metals to be detected in the San Juan River within the background sediment load.

When the Gold King plume mixed with the large existing sediment load in the San Juan River, the metals concentrations in the plume became largely comparable to those in the San Juan. Metals that were notably elevated included lead and to a lesser extent, zinc. Although background levels of metals in the San Juan River sediment are generally low, the river carries large quantities of sediment during storms in which metal concentrations are elevated. Rocks and soils that weather from those sediments have natural levels of major and trace metals. In the San Juan River, trace metals occur in proportion to their elemental makeup in the Mancos Shale, which dominates the geology of much of the area and is the source of much of the sediment in the river. Overall metal concentrations in the streambed of the San Juan River are much lower than they are in the Animas River and increase proportionately with mobile sediments in high flows.

Modeling estimated that 5% of the original Gold King Mine mass was initially deposited in the 360 km of the San Juan River before the remaining mass (approximately 24,000 to 45,000 kg, depending on model) flowed into Lake Powell in Utah. Measurements of streambed sediments suggested that metals tended to increase in the streambed sediments relative to background. Deposition of some metals, such as lead, were detected within 10 km of the confluence of the Animas and San Juan Rivers.

Figure 10-4. Animas River near Aztec, New Mexico at approximately RK 162 in August 2016.

10.3 How was water and sediment quality affected by the Gold King Mine release?

10.3.1 Metals in the Surface Water During the Gold King Plume

Metals are natural components of soils and present in minute quantities in water. High levels of metals can be detrimental to human, terrestrial, and aquatic life. States and tribes have adopted water quality criteria that protect human life by identifying metals concentrations at which it is safe ingest or come into contact with water; the criteria address the various designated uses through which humans can be exposed to metals in water, such as in domestic water supply (e.g., consumption), agricultural use, and recreation. Criteria also specify safe levels for aquatic life.

Generally, dissolved trace metals are considered more toxic, more reactive, and more mobile than particulate metals. While dissolved metals initially increased in Cement Creek and were high in the first 100 kilometers of the Animas River, dissolved metals decreased to pre-event conditions within the upper Animas in the months after the release. Some dissolved metals concentrations increased after the plume in the lower Animas and San Juan Rivers as deposited materials chemically adjusted to new equilibriums. Most of the metals in the plume was colloidal/particulate solids, dominated by iron and aluminum. These particulate solids can also have adverse effects, and water quality criteria for some designated uses reference total metals concentrations (i.e., dissolved + particulates passing a 45-micron filter), such as in the case of aluminum, a very abundant metal in the Gold King plume and is a dominant constituent of the soils and sediments in the area. Total metals are also the basis for domestic supply and recreational contact criteria. Trace metals were sorbed into these precipitates, making them available.

Potential adverse impacts from exposure to high metals concentrations in water were assessed by comparing modeled plume concentrations to appropriate state or tribal water quality standards as the plume moved through the length of the river.

Water quality criteria defined for various water uses were exceeded in some locations as the plume passed, especially in the upper Animas River closer to the mine source. The duration of water quality exceedances was short, as the core of the plume, which contained the highest metals concentrations, moved past a location in 12-hours, varying by metal. Most metals did not exceed any criteria at any location. Agricultural criteria for copper, lead, and manganese were exceeded for 132 kilometers downstream from the mine, including the town of Durango and the Southern Ute Indian Tribe reservation. However, lead and aluminum criteria were exceeded in the San Juan River.

EPA coordinated with states, tribes, and local municipalities to curtail the use of water for drinking, irrigation, and recreation for a number of days as the plume passed to prevent exposures to adverse levels of metals. Dilution and chemical reactions largely limited the spatial extent of significantly elevated concentrations to the upper Animas River during the plume.

Because of the short duration of the plume, aquatic life was more vulnerable to acute, shorter-term concentrations during movement of the plume itself. Acute criteria for aquatic life for aluminum were exceeded for up to six hours in the Animas River from source to near the Colorado/New Mexico border a distance of about 140 kilometers; the duration of these exceedances was less than the 96-hour exposure built into the criteria. There were no reported GKM-related fish kills during or after the release, and post-event surveys by a variety of organizations have indicated other aquatic life did not appear to have suffered harmful effects from the plume.

Monitoring continues to evaluate potential chronic impacts from deposited metals beyond the effects of acid mine drainage from the historic mining activity known to impair parts of the watershed (EPA 2016). Concentrations of aluminum and iron exceeded Colorado water quality standards to protect aquatic life from persistent, long-term exposure. High levels of these metals have occurred in the Animas River during spring runoff in previous years, as well. The Mountain Study Institute, located in Durango, Colorado, has studied the aquatic life in the Animas River since the Gold King plume. A 2016 report found no substantial impacts to aquatic communities that signal degrading water quality.

The metals that may have had the largest effect on water quality were aluminum, lead, and iron due to their predominance in the release load. These metals were particularly abundant in the plume and triggered exceedances of one or more water quality criteria along the rivers. Variation in exceedances reflect differences in criteria among states and tribes. Particulate (total) lead was detected most frequently.

10.3.2 Bed Sediments

The Gold King Mine plume mass deposited throughout the length of affected rivers, and there were many reports and photographs of residue, especially along the length of the Animas River. Although a large amount of GKM material was deposited, the metals deposits were not different in content or mass from those already in the streambed that store the legacy of mining and ongoing AMD contamination, and could not be statistically distinguished from pre-event conditions in the headwaters of the Animas, where there were sufficient data for comparison. However, metals concentrations in streambed sediments were higher than historic in a number of locations throughout the Animas, including the segment from RK 140 to 190. Data suggest that aluminum deposits were highest in this reach.

Post-plume adjustments to the chemistry of the deposited minerals were to be expected. The deposited precipitates were likely a mix of incipient and more stable minerals with different degrees of chemical stability. Deposits were not sampled for their geochemistry and mineralogy, which would have provided this study a more complete understanding of the post-event chemistry. The majority of the deposits were likely iron and aluminum oxides. Once deposited, these would undergo “aging” and ripening, as their structure internally organized toward long-term chemical stability. Incipient amorphous minerals would have been “active” in the months after the release. Some of the minerals that probably formed, such as gypsum (a calcium sulfate mineral), would be likely to dissolve under different pH conditions.

10.3.3 Groundwater Effects

Figure 10-5. Animas River near RK 190 in Farmington, New Mexico in August 2016.

There are hundreds of water supply wells in the floodplain aquifers of the Animas River, ranging from continuous, larger pumping wells (e.g., the community wells) to the small pumpers (e.g., the domestic/household wells). There are also intermittent intermediate pumpers (e.g., the irrigation wells). Groundwater modeling suggests only a handful of these wells potentially source from the Animas River and were potentially vulnerable to exposure to the GKM river plume. Given their low pumping rates, the domestic/household wells would most likely need to be located in proximity to a “losing” reach of the river (water flows from the river into the sediments of the floodplain). The Animas River is expected to be a gently gaining stream under most conditions, with periods of losing water to the shallow aquifer during periods of high river stage, such as during the annual late spring-early summer snowmelt or strong rain events. The complication in determining whether any given stretch of the Animas River is either gaining or losing is site-specific and temporal. One community well located within 35 m of the mid Animas River floodplain (near Baker’s Bridge) had a chemical signal of some dissolved metals soon after the plume the concentrations were well below drinking water action levels. Modeling studies could neither confirm nor reject the hypothesis that this signal may have been associated with the GKM plume.

10.4 Have Water and Sediment Concentrations Returned to Pre-Event Levels?

Water concentrations in the Animas River declined towards background conditions within hours to days after the Gold King plume passed, as documented by monitoring during the plume period. The time required for concentrations to decline towards pre-event varied from days to weeks. It has been an ongoing concern that deposited metals would degrade water quality after the plume passed, or that deposited plume sediments would remobilize during higher flows and generate a second wave of contamination through the system. EPA, states, and tribes monitored water and sediments intensively in the months following the release (from August through October) to evaluate post-event effects.

An intensive monitoring program for sampling water and sediment of the Animas and San Juan Rivers began during passage of the Gold King Mine plume and has continued in the year following the release to understand its long-term impacts. Over 1,400 water quality samples have been collected to date. Most of the post-event samples were collected from August through October 2015 with a hiatus during the winter.

Sampling resumed in February 2016 and included focused efforts to sample spring snowmelt from April through June 2016. Various studies, monitoring programs, and routine sampling at USGS gages have generated historic data for metals concentrations in water and sediment in the Animas and San Juan Rivers prior to the Gold King Mine release. These data allowed for pre- and post-event comparisons to assess the effect and recovery of the system to pre-existing conditions.

Water concentrations declined from the elevated levels in the plume toward background conditions for many metals of interest in all reaches of the Animas River south of Silverton and in the San Juan River, in the days after the Gold King plume passed. In the headwaters of the Animas River, water quality continued to be impaired by acid mine drainage in the watershed above Silverton, including Cement Creek where the Gold King Mine is located. Water chemistry has changed since the GKM plume and treatment began, but high concentrations of metals continue to flow from Cement Creek into the Animas River.

Iron and aluminum concentrations have historically been high in the headwaters of the Animas as evident in pre-event data. Most of the Gold King Mine release mass that flowed through the rivers was iron and aluminum (88.3 and 8.4%, respectively) occurring predominantly as colloidal/particulates but with a dissolved fraction as well. There have been persistent changes in iron and aluminum that manifested in dissolved and total concentrations at various locations within the Animas and San Juan Rivers in both surface water and bed sediments.

In the mid Animas, metals in the streambed and water are the same as historical levels, suggesting that deposited aluminum and iron oxides continue to scavenge metals from the water. Concentrations of some trace metals in the Durango area have declined relative to historic levels. In this area, metals in water and sediments were also statistically the same as pre-event conditions, which have been historically impacted by mining in the watershed.

In the lower Animas, between Durango and Farmington, Gold King Mine deposits appeared to shed low, but elevated concentrations of dissolved aluminum and iron into the Animas River as concentrations in the water column were elevated relative to pre-event conditions. Adjustments were small, but statistically detectable. These increases did increase the rate of exceedance of some water quality based on dissolved aluminum.

The dissolved metals from the lower Animas subsequently moved into the San Juan River, where they decreased in concentration in proportion to incoming San Juan flow. Once in the San Juan River, the dissolved aluminum and iron appeared to have passed through the length of the San Juan River without depositing to the sediment layer. On average, iron and aluminum changes have not increased metals to adverse levels relative to the water quality criteria applicable to the San Juan River. They have not affected the concentrations of other trace metals to a detectable level. There are not sufficient pre-release data on water concentrations of total metals to compare pre- and post-release conditions in the San Juan River. Aluminum and iron were the only dissolved metals with a statistically significant increase in concentration in pre- versus post-release sampling. These increases did increase the rate of exceedance of some water quality based on dissolved aluminum.

Post-event adjustments in and/or mobilization of plume deposits and related effects on water chemistry contributed to exceedances of water quality criteria after the Gold King Mine release. Some exceedances occurred during storm events and snowmelt, when background metals concentrations were slightly elevated and contributed to, or were the primary cause, of higher metals concentrations. Background and GKM-related exceedances could often not be reliably distinguished. Nevertheless, the Gold King Mine release contributed to episodic or repeated exceedances of state criteria for a variety of designated uses associated with aluminum, lead, zinc and copper, predominantly. Criteria for aluminum, lead, copper, zinc, and arsenic adopted by the Navajo Nation and the Ute Mountain Ute Tribe were frequently exceeded in the San Juan River. The frequency of the exceedances appears to be primarily related to the sediment loads carried in the river.

Figure 10-6. San Juan River near RK 196 in Farmington, New Mexico in August 2016

10.5 Remobilization of Gold King Deposits

Gold King Mine metals deposited throughout the Animas River, with most settling in the mid and upper Animas, although deposition also occurred in the lower Animas, especially between RK Verify RK. Water and sediment concentrations were elevated in the lower Animas, and post event adjustments immediately following the plume showed elevated concentrations in water and sediments that declined in the first several weeks after the release. A large storm three weeks after the GKM release effectively swept the deposits from the lower Animas, which then maintained low sediment concentrations until the following spring snowmelt. Water concentrations in the lower Animas were responsive to a series of storms through the fall, but declined to low levels between storms as is the historic pattern as metal concentrations respond to mobilization of river sediments during high flows (Church *et al.* 1997).

The middle and upper Animas did not have storms of sufficient magnitude to mobilize the Gold King Mine deposits until the 2016 spring snowmelt. Water and sediment was sampled over a 3-month period from April to June of 2016, capturing the effect of the snowmelt hydrograph at many locations along the Animas and San Juan Rivers. Flow was particularly high in the headwaters of the Animas River where preliminary gage data suggested that peak runoff was the second highest recorded since the gages records began in 1991 and the largest since 1995.

Field measurements of water and sediment during the 2016 snowmelt hydrograph indicated that Gold King Mine deposits were mobile throughout the Animas and San Juan Rivers during the 2016 snowmelt. Elevated metals concentrations were much smaller than what occurred during the plume, but were detectable in the water and sediments at most locations during the 2016 snowmelt. Metals concentrations would naturally be elevated during peak runoff, as particulates are mobilized in the high flow. The metals concentrations seen at Durango during snowmelt, for example, were close to what would be predicted from historical data. Concentrations of many metals should be expected to be elevated during snowmelt as established in previous USGS studies. The increases in metal concentrations in the middle Animas is not as large as observed during the GKM plume, but can be sufficient to exceed some water quality criteria, including domestic and agricultural water supply. Such exceedances can be expected each year.

However, field evidence and modeling suggest that at least some of the increase observed in the 2016 snowmelt period was resuspended Gold King Mine deposits. Evidence suggests that the Gold King release deposits were mobilized early in the snowmelt period (mostly April) and were transported through the Animas and San Juan Rivers to the receiving water in Lake Powell. Latter patterns of metals mobility appeared to reflect normal high flow transport that occurs in snowmelt and storms. Small increases in metals concentrations, when factored over the duration of snowmelt runoff, accounted for mobilization of most if not all of the mass deposited in the Gold King Mine plume.

Gold King Mine deposits appeared to mobilize from the upper and mid Animas River relatively early on the rising limb of the six-week snowmelt hydrograph. This was especially evident at the sampling location at Baker's Bridge (RK 64), which received some of the heaviest deposits during the plume. Metals increased in sediments for a time at Durango, and GKM metals appeared to be mobile as soon as flow increased above the level it had been during the plume.

Deposited plume mass may have been removed in the weeks prior to the peak of the hydrograph, as the signature of Gold King Mine metals declined near the peak of the 2016 hydrograph. The amount of metals transported during the 2016 snowmelt hydrograph was far greater than the mass deposited during the plume, suggesting that there is little if any residual from the Gold King mass still stored within the rivers.

Water and sediment samples collected throughout the Animas and San Juan Rivers during snowmelt showed elevated levels of metals that rose and fell with the snowmelt hydrography. Concentrations in the San Juan River were commensurately lower than in the Animas River, but could be detected. It is not known whether the San Juan River normally sees elevated snowmelt concentrations, as there were no well-timed historic samples.

Water and sediment samples collected through the summer and fall of 2016 showed that metals in samples at all locations had returned to pre-event levels. Post-snowmelt samples and mass balance calculations of metals transported suggest the Gold King Mine plume deposits have been carried from the rivers to the final receiving waters. Continued monitoring through an additional snowmelt season will allow assessment of this hypothesis.

REFERENCES

Ambrose, R. B., Wool, T. A., Connolly, J. P., and Schanz, R. W. (1988). *WASP4, a hydrodynamic and water-quality model-model theory, user's manual, and programmer's guide*. (PB-88-185095 /XAB; EPA/600/3-87/039). Athens, GA: U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory.

Amorosi, A., Guermandi, M., Marchi, N., and Sammartino, I. (2014). Fingerprinting sedimentary and soil units by their natural metal contents: A new approach to assess metal contamination. *Science of The Total Environment*, 500, 361-372.

Aquaveo, GMS. (2016) (Version 10.1.) [Software]. Available from: www.aquaveo.com/software/gms-groundwater-modeling-system.

Berger, A. C., Bethke, C. M., and Krumhans, J. L. (2000). A process model of natural attenuation in drainage from a historic mining district. *Applied Geochemistry*, 15(5), 655-666.

Besser, J. M., Brumbaugh, W. G., May, T. W., Church, S. E., and Kimball, B. A. (2001). Bioavailability of metals in stream food webs and hazards to brook trout (Salvelinus fontinalis) in the upper Animas River watershed, Colorado. *Archives of Environmental Contamination and Toxicology*, 40(1), 48-59.

Besser, M., and Leib, K. J. (1999). *Modeling frequency of occurrence of toxic concentrations of zinc and copper in the upper Animas River.* In D.W. Morganwalp, and H.T. Buxton (Eds.), *U.S. Geological Survey Toxic Substances Hydrology Program–Proc. Technical Meeting, Charleston, South Carolina, March 8-12,1999--Volume 1 of 3--Contamination From Hard-Rock Mining* (Water-Resources Investigation Report 99-4018A). Reston, VA: U.S. Geological Services, Toxic Substances Hydrology Program.

Besser, J. M., Brumbaugh, W.G, May, T.W., Church, S.E., and Kimball, B.A. (2001). Bioavailability of metals in stream food webs and hazards to brook trout (Salvelinus fontinalis) in the upper Animas River watershed, Colorado. *Archives of Environmental Contamination and Toxicology* 40:49-59.

Besser, J. M., and Leib, K.J. (2007). *Toxicity of metals in water and sediment to aquatic biota*. In S.E. Church, P.B. von Guerard, and S.E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. (Professional Paper 1651), 837-849. Reston VA: U.S. Department of the Interior, U.S. Geological Survey.

Besser, J. M., Finger, S. E., & Church, S. E. (2007). *Impacts of historical mining on aquatic ecosystems: An ecological risk assessment.* In S.E. Church, P.B. von Guerard, and S.E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado.* (Professional Paper 1651), 87-106. Reston, VA: U.S. Geological Services, Toxic Substances Hydrology Program.

Bethke, C. M. (1998). *The Geochemist's Workbench (Release 3.0): A users software guide toRxn, Act2, Tact, React, and Gtplot.* Hydrogeology Program, University of Illinois, (Urbana-Champaign).

Bureau of Land Management (BLM) and U.S.D.A. Forest Service (2007). *Abandoned Mine Lands: A Decade of Progress Reclaiming Hardrock Mines*. (BLM Publication Number: BLM-WO-GI-07-013-3720/Forest Service Publication Number: FS-891). Washington, DC: Department of the Interior, Bureau of Land Management and U.S. Department of Agriculture, Forest Service.

Bureau of Reclamation (BOR) (2015). *Technical Evaluation of the Gold King Mine Incident.* Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center.

Bureau of Reclamation (BOR) (2016). *San Juan River water quality before, during and after the Gold King Mine spill.* Prepared by the Water Treatment Group, Technical Services Center. U.S. Department of the Interior, Bureau of Reclamation.

Bove, D.J., Mast, M.A., Dalton, J.B., Wright, W.G., and Yager, D.B. (2007). *Major styles of mineralization and hydrothermal alteration and related solid and aqueous phase geochemical signatures*. In S.E. Church, P.B. von Guerard, and S.E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado.* (Professional Paper 1651), 161-230. Reston, VA: U.S. Geological Services, Toxic Substances Hydrology Program.

CDPHE. (2015). *Laboratory Services Division, Colorado Department of Public Health & Environment, Animas River spill incident – FINAL Drinking Water sample results* [Data file]. Retrieved from https://www.colorado.gov/pacific/sites/default/files/WQ-Animas-DW-Data-FINAL-Update-12-08-15.pdf

CDPHE. (2016). *Gold King Mine Spill Animas River Basin - Southwest Colorado - August 2015.* Denver, CO: Colorado Department of Public Health and Environment.

CH2MHILL. (2015). *Appendix E. Summary of Literature-Derived Fish Tissue Toxicity Data, Baseline Ecological Risk Assessment Halaco Superfund Site, Oxnard, California Remedial Investigation, EPA Contract No. EP-S9-08-04, Task Order No. 015-RIRI-09X6, CH2M HILL Project No. 385135.* Thousand Oaks, California: CH2M HILL.

Chapman, B. M., Jones, D. R., and Jung, R. (1983). Processes controlling metal ion attenuation in acid mine drainage streams. *Geochimica et Cosmochimica Acta*, 47(11), 1957-1973.

Church, S. E., Kimball, B. A., Fey, D. L., Ferderer, D. A., Yager, T. J., and Vaughn, R. B. (1997). *Source, transport, and partitioning of metals between water, colloids, and bed sediments of the Animas River, Colorado.* (Report 97-151). Denver, CO: U.S. Geological Survey.

Church, S.E., von Guerard, Paul, and Finger, S.E. (2007). *Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado*. (Professional Paper 1651). Reston, VA: U.S. Geological Services, Toxic Substances Hydrology Program.

Covelli, S. and Fontolan, G. (1997). Application of a normalization procedure in determining regional geochemical baselines, Gulf of Trieste, Italy. *Environmental Geology,* 30(1-2): 34-45.

Creed, J.T., Brockhoff, C.A., and Martin, T.D. (1994) *Method 200.8, Revision 5.4: Determination of trace elements in waters and wastes by inductively coupled plasma-mass spectrometry.* Cincinnati, Ohio: U.S. Environmental Protection Agency.

Desborough, G. A. and Yager, D. B. (2000). *Acid-neutralizing potential of igneous bedrocks in the Animas River headwaters, San Juan County, Colorado*. (Open-File Report 2000-165). Denver, CO: U.S. Department of the Interior, U. S. Geological Survey.

Dripps, W. R., Hunt, R. J., and Anderson, M. P. (2006). Estimating recharge rates with analytic element models and parameter estimation. *Ground Water,* 44(1), 47-55.

Fitts, C. R. (2010). Modeling Aquifer Systems with Analytic Elements and Subdomains, *Water Resources Research*, 46, W07521, doi:10.1029/2009WR008331.

Haitjema, H. M. (1995). *Analytic element modeling of groundwater flow.* San Diego, CA: Academic Press, Inc.

Haitjema Software (2016). GFLOW. (Version 2.2.2.) [Software]. Available from: http://www.haitjema.com/.

Harbaugh, A. W. (2005). *MODFLOW-2005, The U.S. Geological Survey modular ground-water model — the ground-water flow process. USGS Techniques and Methods 6-A16.* Reston, VA: U.S. Department of the Interior, U.S. Geological Survey

Hasbrouck Geophysics Inc. (2003). *Animas Valley Gravity Survey for Animas Water Company, Final Report.* Durango, Colorado: Hasbrouck Geophysics, Inc.

Hornewer, N. J. (2014). *Sediment and water chemistry of the San Juan River and Escalante River Deltas of Lake Powell, Utah, 2010-2011.* U.S. Geological Survey Open-File Report 2014-1096. 7 p. http://dx.doi.org/10.3133/ofr20141096

Hunt, R. J. (2006). Ground water modeling applications using the analytic element method. *Ground Water* 44(1), 5-15.

Johnson, C. and Mifflin, M. (2006). The AEM and regional carbonate aquifer modeling. *Ground Water* 44(1), 24-34.

Johnson, D. B. and Hallberg, K.B. (2005). Acid mine drainage remediation options: a review. *Science of the Total Environment*. 338, 3-14.

Jones, W.R. (2007). *History of mining and milling practices and production in San Juan County, Colorado, 1871-1991.* In S.E. Church, P.B. von Guerard, and S.E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. (Professional Paper 1651), 39-86. Reston, VA: U.S. Geological Services, Toxic Substances Hydrology Program.

Juckem, P. F. (2009). *Simulation of the regional ground-water-flow system and ground-water/surface-water interaction in the Rock River Basin, Wisconsin*. (Scientific Investigations Report 2009-5094). Reston, VA: U.S. Geological Survey

Kimball, B. A., Walton-Day, K, and Runkel, R.L. (2007). *Quantification of Metal Loading by Tracer Injection and Synoptic Sampling, 1996–2000*. Chapter E9 of Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. Ed. Church, S. E. von Guerard, P. Finger, S. E. U.S. Geological Survey Professional Paper 1651. 423-495.

Kvanli, A., Pavur, R., Keeling, K. (2006). *Concise managerial statistics.* Engage Learning. South-Western/Thomson Learning, Australia and United Kingdom. ISBN 9780324223880.

Luedke, R. G. and Burbank, W. S. (2000). *Geologic map of the Silverton and Howardsville quadrangles, southwestern Colorado: U.S. Geological Survey Map I-2681.* [map]. (ca. 1:24,000). Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

Mountain Studies Institute (MSI). (2016). *Animas River water quality at Rotary Park, Durango, CO, Gold King Mine Release Monitoring.* Durango, CO: Mountain Studies Institute.

New Mexico Environment Department. (2015). *New Mexico Environment Department Surface Water Quality Bureau Sonde Sampling Provisional Results Gold King Mine Spill.* [Data file]. Retrieved from https://www.env.nm.gov/river-water-safety/animas-river-data-documents-page/

Nordstrom, D. K. (1982). The effect of sulfate on aluminum concentrations in natural waters: some stability relations in the system Al_20_3-SO_3-H_2O at 298 K. *Geochimica et Cosmochimica Acta*, 46(4), 681-692.

Nordstrom, D. K. (2011). Hydrogeochemical processes governing the origin, transport and fate of major and trace elements from mine wastes and mineralized rock to surface waters. *Applied Geochemistry* 26 (11), 1777-1791.

Nordstrom, D. K., Valentine, S. D., Ball, J. W., Plummer, L. N., and Jones, B. F. (1984). *Partial compilation and revision of basic data in the WATEQ programs*. (Water-Resources Investigation Report 84-4186). Menlo Park, CA: Department of the Interior, U.S. Geological Survey.

Parizek, R. R., White, W.B., and Langmuir, D. (1971). *Hydrogeology and geochemistry of folded and faulted rocks of the central Appalachian type and related land use problems.* Penn State University, University Park, PA.

Rampe, J. J., and Runnells, D.D. (1989). Contamination of water and sediment in a desert stream by metals from an abandoned gold mine and mill, Eureka District, Arizona, U.S.A. *Applied Geochemistry* 4:445-454.

Ransome, F. L. (1901). *A report on the economic geology of the Silverton quadrangle, Colorado*. (Bulletin No.182). Washington, DC: Department of the Interior, U.S. Geological Survey.

R Core Team. (2016). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. [Software]. Available from: (https://www.R-project.org.)

Reimann, C. and Garrett, R.G. (2005). Geochemical background—concept and reality. *Science of the Total Environment*, 350(1), 12-27.

Sánchez-España, J., Yusta, I., and Diez-Ercilla, M. (2011). Schwertmannite and hydrobasaluminite: A re-evaluation of their solubility and control on the iron and aluminium concentration in acidic pit lakes. *Applied Geochemistry* 26(9), 1752-1774.

Schemel, L. E. and Cox, M.H. (2005*). Descriptions of the Animas River-Cement Creek confluence and mixing zone near Silverton, Colorado, during the late summers of 1996 and 1997.* (Open File Report 2005-1064) Washington, DC: U.S. Department of the Interior, U.S. Geological Survey.

Schemel, L. E., Kimball, B. A., and Bencala, K. E. (2000). Colloid formation and metal transport through two mixing zones affected by acid mine drainage near Silverton, Colorado. *Applied Geochemistry*, 15(7), 1003-1018.

Schemel, L. E., Kimball, B. A., Runkel, R. L., and Cox, M. H. (2007). Formation of mixed Al-Fe colloidal sorbent and dissolved-colloidal partitioning of Cu and Zn in the Cement Creek - Animas River Confluence, Silverton, Colorado. *Applied Geochemistry*, 22(7), 1467-1484.

Schnoor, J.L. (1996). *Environmental Modeling: Fate and Transport of Pollutants in Water, Air, and Soil*. J Wiley & Sons. New York.

Shacklette, H. T. and Boerngen, J.G. (1984). *Element concentrations in soils and other surficial materials of the conterminous United States.* U.S. Geological Survey Professional Paper 1270. Dept. of Interior, Washington D.C.

Singer, P. C., and Stumm, W. (1970). Acidic mine drainage: the rate-determining step. *Science,* 167(3921), 1121-1123.

Smith, K. (1999). Metal sorption on mineral surfaces: an overview with examples relating to mineral deposits. In G.S. Plumlee and M.J. Logsdon (Eds.), *The Environmental Geochemistry of Mineral Deposits. Part B, Case Studies and Research Topics. Reviews in Economic Geology 6A*, 161-182.

Spruill, T. (1987). A*ssessment of Water Resources in Lead-Zinc Mined Areas in Cherokee County, Kansas, and Adjacent Areas*. (Water Supply Paper 2268) Lawrence, KS: U.S. Department of the Interior, U.S. Geological Survey and Kansas Department of Health and the Environment.

Steefel, C. I., and Van Cappellen, P. (1990). *A new kinetic approach to modeling water-rock interaction: The role of nucleation, precursors, and Ostwald ripening*. Geochimica et Cosmochimica Acta 54:2657-2677.

Stumm, W., and Morgan, J.J. (1996, 1981). *Aquatic chemistry; an introduction emphasizing chemical equilibria in natural waters.* John Wiley & Sons, New York.

SUIT. (2015). *Metal Survey of Animas River Fishes*. Ignacio, CO: Southern Ute Indian Tribe.

Theobald, P. K., Lakin, H.W., and Hawkins, D.B. (1963). The precipitation of aluminum, iron and manganese at the junction of Deer Creek with the Snake River in Summit County, Colorado. *Geochimica et Cosmochimica Acta* 27:121-132.

Timmons, S., Mamer, E., and C. Pokorny. (2016). *Animas River Long-term Monitoring: Hydraulics and chemistry from March 2016*. Socorro, New Mexico: New Mexico Bureau of Geology and Mineral Resources.

Tuttle, M. L., Fahy, J., Grauch, R. I., Ball, B. A., Chong, G. W., Elliott, J. G., Kosovich, J.J., Livo, K.E., and Stillings, L.L. (2007). *Results of chemical analyses of soil, shale and soil/shale extract from the Mancos Shale Formation in the Gunnison Gorge National Conservation area, Southwestern Colorado, and at Hanksville, Utah.* (Open-File Report 2007-1002-D). Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

U.S. EPA. (1983). *Method 305.1. Acidity (Titrimetric) Technical revision 1974 in Methods for the Chemical Analysis of Water and Wastes (MCAWW).* U.S. Environmental Protection Agency, Cincinnati, Ohio. (EPA/600/4-79/020).

U.S. EPA. (1994a). *Method 200.8. Determination of trace elements in waters and wastes by inductively coupled plasma-mass spectrometry.* Revision 5.4. U.S. Environmental Protection Agency, Cincinnati, Ohio.

U.S. EPA. (1994b). *Method 245.1, Revision 3.0: Determination of Mercury in Water by Cold Vapor Atomic Absorption Spectrometry.* U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. EPA. (1994c). *Method 7471A, Revision 1. Final Update II to the Third Edition of the Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA publication SW-846.

U.S. EPA. (1996). *Method 3050B (SW-846): Acid Digestion of Sediments, Sludges, and Soils. Revision 2*.

U.S. EPA. (2001). *Method 200.7. Trace elements in water, solids, and biosolids by inductively coupled plasma-atomic emission spectrometry. Revision 5.0*. U.S. Environmental Protection Agency, Washington, D.C.

U.S. EPA. (2007a). *Method 6010C, Revision 1. Final Update IV to the Third Edition of the Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA publication SW-846.

U.S. EPA. (2007b). *Method 6020A, Revision 1. Final Update IV to the Third Edition of the Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA publication SW-846.

U.S. EPA. STOrage and RETreival (STORET) for Water Quality Data. Washington, DC: U.S. Environmental Protection Agency, Office of Water, Office of Wetlands, Oceans, and Watersheds. https://www.epa.gov/waterdata/storage-and-retrieval-and-water-quality-exchange. Accessed multiple dates 2016.

U. S. EPA. (2001). *Method 200.7 Trace elements in water, solids, and biosolids by inductively coupled plasma-atomic emission spectrometry. Revision 5.0.* (EPA-821-R-01-010). Washington, D.C.: U.S. Environmental Protection Agency.

U.S. EPA and USGS. (2012). *National Hydrography Dataset Plus – NHDPlus. Version 2.* [Data file]. Washington, DC: U.S. Environmental Protection Agency and Reston, VA: U.S. Geological Survey. Retrieved from https://www.epa.gov/waterdata/nhdplus-national-hydrography-dataset-plus.

U.S. EPA. (2013). Water Quality Analysis Simulation Program (WASP). (Version 7.5.2) [Software]. Washington, DC: U.S. Environmental Protection Agency. Available from https://www.epa.gov/exposure-assessment-models/water-quality-analysis-simulation-program-wasp.

USGS. (2013). N*ational Hydrography Geodatabase*. U.S. Geological Survey. [Data file]. Available from The National Map viewer. **http://viewer.nationalmap.gov/viewer/nhd.html?p=nhd**.

U.S. EPA. (2015). *BASINS (Better Assessment Science Integrating Point & Non-point Sources) Modeling Framework.* (Version 4.1) [Software]. Research Triangle Park, NC: U.S. Environmental Protection Agency, National Exposure Research Laboratory. Available from https://www.epa.gov/exposure-assessment-models/basins.

U.S. EPA. (2016a). *Post-Gold King Mine Release Incident: Conceptual Monitoring Plan for Surface Water, Sediments, and Biology.* Washington, DC: U.S. Environmental Protection Agency.

U.S. EPA (2016b). *EPA Gold King Mine Analysis of Fate and Transport in the Animas and San Juan Rivers: Response to Peer Review Comments.* (EPA/600/R-16/113). Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development.

U.S. EPA. (2016c). *One year after the Gold King Mine Incident: A retrospective of EPA's efforts to restore and protect impacted communities.* Washington, DC: U.S. Environmental Protection Agency.

U.S. EPA. (2016d). *Wellhead Analytic Element Model (WhAEM).* (Version 3.2.1) [Software]. Athens, GA: U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling. Available from https://www.epa.gov/exposure-assessment-models/whaem2000.

U.S. EPA. (2016e). *Emergency Response to August 2015 Release from Gold King Mine.* [Internet]. Washington, DC: U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/goldkingmine.

U.S. EPA. (2016f). *Gold King Mine Videos: Emergency Response to August 2015 Release from Gold King Mine.* [Video files]. Retrieved from https://www.epa.gov/goldkingmine/gold-king-mine-videos.

USGS. (2007*). Summary and conclusions from the investigation of the effects of historical mining in the Animas River watershed, San Juan County, Colorado.* In S.E. Church, P.B. von Guerard, and S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado.* (Professional Paper 1651). Reston, VA: U.S. Geological Survey.

USGS. (2016). Gold King Mine Release Database [Internet]. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

UDEQ. (2015). *Preliminary analysis of immediate effects of Gold King Mine release on water quality in the San Juan River, Utah.* Salt Lake City, UT: Department of Environmental Quality, Division of Water Quality.

UDEQ. (2016b). *Evaluation of UDEQ Water Quality Data Collected during Spring Runoff following the Gold King Mine Release.* Salt Lake City, UT: Utah Department of Environmental Quality, Division of Water Quality.

UDEQ. (2016a). *Utah's long-term monitoring and assessment plan for the San Juan River and Lake Powell, Utah.* Salt Lake City, UT: Utah Department of Environmental Quality, Division of Water Quality.

Vincent, K.R. and Elliott, J.G. (2007). *Stratigraphy of late Holocene channel and floodplain deposits exposed in a trench excavated across the Animas River valley floor 1.4 kilometers downstream of Eureka Townsite, San Juan County, Colorado, Plate 6.* In S.E. Church, P.B. von Guerard, and S.E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. (Professional Paper 1651).

von Guerard, P., Church, S. E., Yager, D. B., and Besser, J. M. (2007). *The Animas River Watershed, San Juan County, Colorado.* In S. E. Church, P. von Guerard, and S. E. Finger (Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado.* (Professional Paper 1651), 17-38.

Yager, B. B. and Bove, D. J. (2002). *Generalized geologic map of part of the upper Animas River watershed and vicinity, Silverton, Colorado: Miscellaneous Field Studies Map 2377* [map]. (ca. 1:48,000). Reston, VA: U.S. Department of the Interior, U.S. Geological Survey.

White, J. (2016). *Animas River Fish Inventory Report*. Colorado Parks and Wildlife Department Report.

Wirt, L., K. R. Vincent, P. L. Verplanck, D. B. Yager, S. E. Church, and D. L. Fey. (2007). Chapter E17. *Geochemical and hydrologic processes controlling formation of ferricrete*. Pages 779-822 in S. E. Church, P. von Guerard, and S. E. Finger, editors. Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. U.S. Geological Survey.

Yager, D.B. and Bove, D.J. (2007). *Geologic framework.* In S.E. Church, P.B. von Guerard, and S.E. Finger(Eds.), *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado.* (Professional Paper 1651), 107-140.

Yager, R. M., and Neville, C. J. (2002). GFLOW 2000: An analytic element ground water flow modeling system. *Ground Water* 40(6), 574-576.

GLOSSARY

(numbers in parentheses are references at end of glossary)

Acid mine drainage (AMD): Drainage of water from areas that have been mined for coal of other mineral ores. The water has a low pH because of its contact with sulfur-bearing material and is harmful to aquatic organisms. (2)

Adit: A horizontal or gently-inclined excavation made into the side of a hill or mountain to provide underground access. Adits commonly are driven with an uphill slope (about 1%) to provide drainage such that groundwater seepage will readily flow out of the excavation and discharge to the surface. An adit is only open to the ground surface on one end; the other end may be a dead end or it may connect to a shaft, raise, or other type of mine passage that could eventually reach the ground surface. (4)

Advection: Movement of mass resulting from unidirectional flow; moves mass from one position in space to another. (5)

Alluvium: Relating to and/or sediment (clay, silt, sand, and gravel) deposited by flowing water. (2)

Analysis of existing data: The process of gathering and summarizing existing data from various sources to provide current information on mining activities. (8)

Analyte: The element, ion, or compound that an analysis seeks to identify; the compound of interest. (2)

Anisotropy: The property of being directionally dependent, as in anisotropic hydraulic conductivity in having different values in the horizontal direction than in the vertical direction.

Aquifer: An underground geological formation, or group of formations, containing water. A source of groundwater for wells and springs. (2)

Blowout: A sudden, violent, release of gas or liquid due to the reservoir pressure in a drill hole or mine. (4)

Caldera: A large depression formed in volcanic rock with an approximately circular shape. (4)

Contaminant: A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful (adverse) health effects. (2)

Colloid: A homogenous, non-crystalline substance consisting of large molecules or ultramicroscopic particles of one substance dispersed through a second substance. Colloids include gels, sols, and emulsions; the particles do not settle and cannot be separated out by ordinary filtering or centrifuging like those in suspension. Range in size from 10^{-6} to 10^{-3} cm. (6)

Diffusion: Movement of mass due to random water motion or mixing; moves mass from regions of high concentration to low concentration. (5)

Dispersion: The spreading of mass due to velocity differences in space. (5)

Dissolved analyte: The concentration of analyte in an aqueous sample that will pass through a 0.45-µm membrane filter assembly prior to sample acidification. (1)

Domestic water supply: Water used for indoor household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and outdoor purposes such as watering lawns and gardens. Domestic water use includes water provided to households by a public water supply (domestic deliveries) and self-supplied water. (3)

Drinking water resource: Any body of water, ground or surface, that could (now or in the future) serve as a source of drinking water for public or private water supplies. (8)

Dupuit-Forchheimer assumption: The DF assumption neglects resistance to vertical flow in shallow groundwater systems, meaning that hydraulic heads are constant with depth, and flow essentially horizontal.

Equilibrium: The state of dynamic balance attained in a reversible chemical reaction when the velocities (of reaction progress) in both directions are equal. (7)

Empirical: Based on observations.

Formation: A geological formation is a body of earth material with distinctive and characteristic properties and a degree of homogeneity in its physical properties. (2)

Freshwater: Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids. Generally, water with more than 500 mg/L of dissolved solids is undesirable for drinking and many industrial uses. (3)

ft^3/s: An abbreviation for cubic feet per second, a unit of measure for rate of flow. One cubic foot per second of flow is equal to 448.83 gallons per minute. (4)

gpm: An abbreviation for gallons per minute, a unit of measure for rate of flow. (4)

Geographic information system (GIS): A computer system designed for storing, manipulating, analyzing, and displaying data in a geographic context, usually as maps. (2)

Groundwater: All water found beneath the surface of the land. Groundwater is the source of water found in wells and springs and is used frequently for drinking. (2)

Hydraulic Bulkhead: A structural barrier placed in a mine or tunnel for the purpose of impounding water to flood the mine openings and re-establish the pre-mining groundwater levels. The terms adit plug, mine plug, mine seal, and bulkhead seal also have been used to describe this type of impounding structure. (4)

Hydraulic gradient: Slope of a water table or potentiometric surface. More specifically, change in the hydraulic head per unit of distance in the direction of the maximum rate of decrease. (2)

Hyporheic zone: A region beneath and alongside a stream bed where there is missing of shallow groundwater and surface water.

Industrial water use: Water used for fabrication, processing, washing, and cooling. Includes industries such as chemical and allied products, food, paper and allied products, petroleum refining, wood products, and steel. (3)

Instream use: Water that is used, but not withdrawn, from a surface water source for such purposes as hydroelectric power generation, navigation, water quality improvement, fish propagation, and recreation. (3)

Irrigation water use: Water that is applied by an irrigation system to assist crop and pasture growth, or to maintain vegetation on recreational lands such as parks and golf courses. Irrigation includes water that is applied for pre-irrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, leaching of salts from the root zone, and conveyance losses. (3)

Iron-oxide: A general term for a group of oxidized minerals and amorphous compounds that form in nature due to the weathering of iron-containing rocks and minerals and due to the oxidation of iron-rich waters. It can include minerals such as goethite, lepidocrocite, ferrihydrite, schwertmannite, jarosite, and colloids such as limonite. In mine workings it commonly precipitates out, forming sediment composed of orange-brown colloidal-sized particles. These iron minerals have a strong affinity for absorbing metals such as cadmium, lead, arsenic, and other elements when they form. The terms “yellowboy” and “ochre” commonly used in reports about abandoned mines refer to the same material. (4)

Livestock water use: Water used for livestock watering, feedlots, dairy operations, and other on-farm needs. Types of livestock include dairy cows and heifers, beef cattle and calves, sheep and lambs, goats, hogs and pigs, horses and poultry. (3)

Major cations: For purposes of this report includes calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na).

Mechanistic: Based on physical processes.

Method blank: An aliquot of reagent water or other blank matrix that is treated exactly as a sample including exposure to all glassware, equipment, solvents, reagents, and internal standards that are used with other samples. The method blank is used to determine if method analytes or other interferences are present in the laboratory environment, reagents, or apparatus (1).

Method detection limit (MDL): The minimum concentration of an analyte that can be identified, measured, and reported with 99% confidence. The MDL is determined according to procedures described in 40 CFR Part 136, Appendix B. (1)

Mine: A surface or underground excavation made for the purpose of extracting a valuable mineral commodity such as coal or metal ore. (4)

Mine Waste Dump: A pile of rock and soil placed onto the ground surface immediately outside of a mine entrance as a means of disposal of unwanted material that must be broken and excavated to gain access to the ore in the mine. (4)

Partition Coefficient: The ratio of concentrations of a constituent (e.g., metal) between two phases (e.g., solid phase and water) (5).

Partitioning: The tendency for a constituent to attach to particles. (5)

Permeability: Ability of rock to transmit fluid through pore spaces. (1)

Porosity: Percentage of the rock volume that can be occupied by water. (1)

Portal: A structure constructed at the entrance to an adit or tunnel for the purpose of providing support to the surrounding soil and weathered rock in order to allow safe passage into the underground mine opening. (4)

Precipitate: An insoluble solid that emerges from a liquid solution.

Public supply water use: Water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 connections. Public suppliers provide water for a variety of uses, such as domestic, commercial, industrial, thermoelectric power, and public water use. (3)

Public water system (PWS): A system that provides water to the public for human consumption through pipes or other constructed conveyances. A PWS, per EPA's definition, must have at least 15 service connections or regularly serve at least 25 people. (2)

Public water use: Water supplied from a public supplier and used for such purposes as firefighting, street washing, flushing of water lines, and maintaining municipal parks and swimming pools. Generally, public-use water is not billed by the public supplier. (3)

Resuspension: The velocity of particles leaving the sediment layer and entering the water column.

Saturation: The state of a solution when it holds the maximum equilibrium quantity of dissolved matter at a given temperature. (6)

Settling: The velocity of particles moving down the water column towards the sediment layer.

Shaft: A vertical or steeply-inclined excavation from the surface extending down into the ground for the purpose of providing underground access. Related terms are winze and raise. A winze is a similar downward extending excavation, but it is initiated from within an underground mine working and therefore is not open to the ground surface. A raise is an upward extending excavation initiated from within an underground mine working. A raise may or may not extend to the ground surface. (4)

Solid sample: A sample taken from material classified as either soil, sediment, or industrial sludge. (1)

Species: Actual form in which a molecule or ion is present in solution. (9)

Specific conductance: Specific conductance (SC) is a measure of how well water can conduct an electrical current and is measured using a sensor that measures resistance. SC is reported in "mhos" or "siemens" in the International System of Units (8).

Statistical analysis: Analyzing collected data for the purposes of summarizing information to make it more usable and/or making generalizations about a population based on a sample drawn from that population. (2)

Stope: An underground excavation from which ore has been removed. (4)

Surface water: All water naturally open to the atmosphere (rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries). (2)

Total dissolved solids: The quantity of dissolved material in a given volume of water. (2)

Total recoverable analyte: The concentration of analyte determined either by "direct analysis" of an unfiltered acid preserved drinking water sample with turbidity of <1 NTU, or by analysis of the solution extract of a sludge, solid, or unfiltered aqueous sample following digestion by refluxing with hot dilute mineral acid(s) as specified in the method. (1)

Tuff: A volcanic rock formed of consolidated or cemented volcanic ash. (4)

Tunnel: A horizontal or gently-inclined excavation that penetrates a hill or mountain and is open to the surface on both ends such as a highway tunnel or railroad tunnel. The term tunnel is commonly misused in mining to refer to long adits. For example, the American Tunnel is actually an adit, because it does not extend to the opposite side of the mountain. (4)

Water use: Pertains to the interaction of humans with and influence on the hydrologic cycle; includes elements such as water withdrawal, delivery, consumptive use, wastewater release, reclaimed wastewater, return flow, and instream use. (3)

Water sample: A sample taken from one of the following sources: drinking, surface, ground, storm runoff, industrial, or domestic wastewater. (1)

Watershed: An area of land that drains to a particular stream or river. (4)

Water withdrawal: Water removed from the ground or diverted from a surface water source for use. (3)

Glossary References

1. U.S. EPA (2001). Method 200.7 *Trace elements in water, solids, and biosolids by inductively coupled plasma-atomic emission spectrometry.* Revision 5.0. EPA Report EPA-821-R-01-010. 68 p.

2. U.S. EPA (2006). *Terminology services: Terms and acronyms*. Available at: https://iaspub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do

3. Kenny, J. F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelance, J.K., and Maupin, M.A. (2009). *Estimated use of water in the United States in 2005*. USGS Circular 1344. 52 pp. Available at: http://pubs.usgs.gov/circ/1344/

4. Bureau of Reclamation (BOR) (2015). *Technical Evaluation of the Gold King Mine Incident.* Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center.

5. Chapra, Steven C. (1997). *Surface Water-Quality Modeling*. McGraw-Hill, Boston.

6. Rose, A. and Rose, E. (1966). *The Condensed Chemical Dictionary*. Reinhold Publishing Company. New York, NY. 104,,,,4 pp.

7. Gove, P.B. (1986). *Webster's Third New International Dictionary*. Merriam Webster, Inc. Springfield, MA. 2662 pp.)

8. American Public Health Association (1998). *Standard Methods for the Examination of Water and Wastewater*. 20th edition.

9. Stumm, Werner and Morgan, James J. (1996). *Aquatic chemistry. An introduction emphasizing chemical equilibria in natural waters*. John Wiley & Sons. New York. 780 pp.

10. Colorado Geological Survey. Org. http://coloradogeologicalsurvey.org/mineral-resources/what-are-minerals/