The Influence of Shallow and Deep Ground-Water Discharge on Stream-Water Quality in a Watershed with Historical Mining, Prospect Gulch, Colorado, USA[1]

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ABSTRACT

Stream-water quality in Prospect Gulch, a watershed in southwestern Colorado near Silverton, is affected by acid-mine drainage (AMD) from historical mining and acid-rock drainage (ARD) from hydrothermally-altered bedrock. Sampling of stream-water quality, throughout the year at the mouth of Prospect Gulch and a detailed one-time sampling within the watershed at base-flow conditions, indicates the presence of shallow and deep ground-water discharge. The shallow and deep ground waters are confirmed by geochemistry and age dating in multilevel monitoring wells. Stream geochemistry indicates that shallow ground-water discharge in the upper part of Prospect Gulch is affected by AMD and ARD. The AMD has very high concentrations of iron (Fe, up to 700 mg/L) and copper (Cu, up to 32,000 µg/L) that result from shallow ground water flowing through mine-waste rock. In contrast, the ARD flows through shallow, weathered rocks and soils, producing much lower Fe and Cu concentrations (up to 0.7 mg/L and 700 µg/L, respectively). The lower part of Prospect Gulch is largely influenced by deep ground water that has interacted with acid-generating bedrock and has an unknown percentage of AMD. Ground water from these longer, deeper flow paths has very low Cu concentrations (<2 µg/L), but high Fe concentrations (up to 100 mg/L). During the year, deep ground-water discharge is relatively constant, but shallow ground-water discharge increases after snow melt and large rain events. Transient changes are reflected in the stream-water quality, with an increase in Cu concentrations (up to 300 µg/L) and a decrease in Fe concentrations (as low as 3 mg/L) during higher flows. During the winter, when the shallow ground-water discharge diminishes, the deep ground water dominates the stream-water quality at the mouth of Prospect Gulch with higher Fe (up to 52 mg/L) and lower Cu (as low as 30 µg/L) concentrations. Spatial and temporal monitoring of Prospect Gulch provides a better understanding of the interaction between AMD, ARD, and shallow versus deep ground-water flow, with eventual discharge and effects on surface-water quality. This information will provide baseline data for quantifying post-remediation effectiveness and/or effects from possible future mining.

Additional Key Words: acid-rock drainage, acid-mine drainage, geochemistry, historical mining, stream-water quality.

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INTRODUCTION

In the late nineteenth century, San Juan County, southwestern Colorado, USA, was the center of a metal mining boom in the San Juan Mountains. Although most mining activity ceased by the 1990s, the effects of historical mining continue to contribute metals to ground and surface water. These increased metal concentrations degrade stream-water quality and are toxic to fish and other aquatic organisms. As a result, viable fish and aquatic habitat is now more limited than what existed before mining (Besser et al., 2007). Since the 1990s, the local economic base has shifted away from hard-rock mining toward tourism with a focus on recreational opportunities. This shift toward tourism and increased population downstream has enhanced the demand for clean water. Streams in this area have naturally low pH values and elevated metal loads due to acid-rock drainage (ARD), but the influence of acid-mine drainage (AMD) from historical mining activity has degraded preexisting ground-water and surface-water quality (Church et al., 2007).

Much of the San Juan Mountains are influenced by historical mining, and many surface-water samples (along with other data) were collected in the upper Animas River watershed (Figure 1) by the U.S. Geological Survey as part of the Abandoned Mine Lands Initiative (AMLI) (Church et al., 2007; *http://amli.usgs.gov/reports/*). Three goals of the upper Animas AMLI program were to (1) characterize the surface-water quality, (2) identify abandoned mines that contribute the greatest metal loads to surrounding surface waters, and (3) determine premining water quality. The ultimate objective of the AMLI is to provide the necessary scientific information for public land managers to select effective remedial approaches that would improve water quality in a watershed.

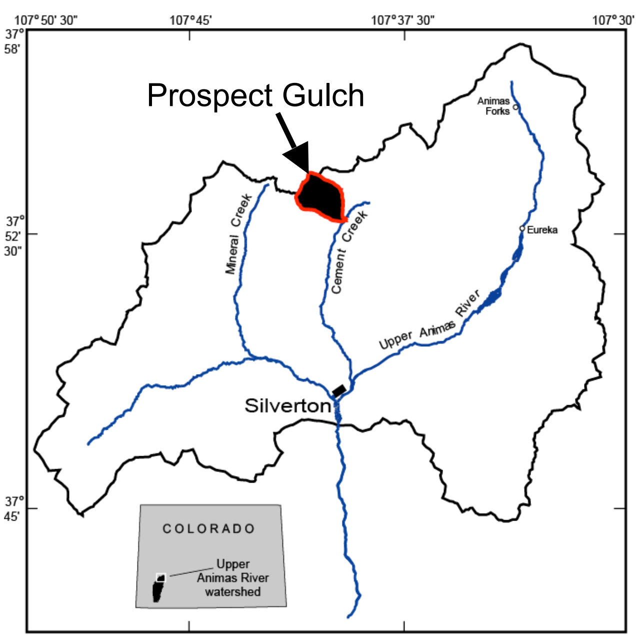

Figure 1. Location of Prospect Gulch in the upper Animas River watershed in southwestern Colorado.

Ground-water discharge has been identified as a significant pathway for the loading of metals to surface water from both AMD and from ARD (Mast et al., 2007; Kimball et al., 2002; Kimball et al., 2007; Paschke et al., 2005). Understanding the ground-water flow and dissolved metal transport is essential in determining whether sampled metal loads to streams are related to AMD or ARD, and thus, whether or not an identified source of metal loading should be remediated.

In an effort to understand the ground-water flow system in the upper Animas River watershed, Prospect Gulch (Figure 1) was selected for further study because of the amount of data provided in and around that particular watershed (Church et al., 2007). This includes stream tracer-dilution studies (Kimball et al., 2002; Wirt et al., 1999, 2001) and detailed maps of hydrothermal alteration (Bove et al., 2007b). In addition, many of the inactive mines within Prospect Gulch are on land managed by the U.S. Bureau of Land Management

(BLM). An understanding of the ground-water flow system is critical in assisting the BLM with their remedial efforts. An integrated-science approach was taken to address surface-water metal contributions from mining and the interaction of hydrothermally-altered, sulfide-rich, volcanic rock with ground water.

The objective of this research is to integrate multiple datasets to help understand the transport of metals through ground water in Prospect Gulch, San Juan County, Colorado, and its impact on surface-water quality. The sources of metals in this area are AMD and ARD related to the recharge area of the watershed. The subsequent transport of metals through ground water was monitored through sampling of springs, monitoring wells, and piezometers. In addition, surface-water quality was measured during base-flow conditions and throughout the year, to understand the metal loading from the ground water to the surface water.

FIELD INVESTIGATIONS

Bedrock in Prospect Gulch is composed of volcanic rocks that have been hydrothermally altered (Figure 2). These rocks contain pyrite as a result of this alteration, which oxidizes and generates acidic ground water that can have high concentrations of iron (Fe) and sulfate (SO_4). A combination of impurities in the pyrite, oxidation of other sulfide minerals, and dissolution of buffering minerals also provide a source of other metals, such as copper (Cu), zinc (Zn), and aluminum (Al), which are all toxic to fish at low concentrations. Sulfide oxidation occurs naturally in the mountain block (ARD) and can be enhanced via mining activities through underground shafts and adits and the placement of sulfide-rich waste rock at the surface (AMD). To monitor the resulting metal transport processes in Prospect Gulch, an intensive field investigation was initiated.

Multilevel ground-water monitoring wells with sampling points at several depths were drilled in three locations (Figure 2) to determine: 1) ground-water quality, 2) ground-water flow conditions, and 3) geology/mineralogy with depth. Bedrock cores were collected to a depth of 150 to 200 feet below land surface. Pyrite content up to 20 weight percent was measured in these cores (Bove et al., 2007a), indicating a large capacity for ARD and an exiting natural source of acidity and metals. The monitoring wells were located at upper, middle, and lower elevations (Figure 2) to capture ground water above, near, and below the mining-affected areas, which occur in the middle elevations of Prospect Gulch. Water levels in the monitoring wells were measured year-round, when accessible. Additional geochemistry data were provided from sampling springs and the

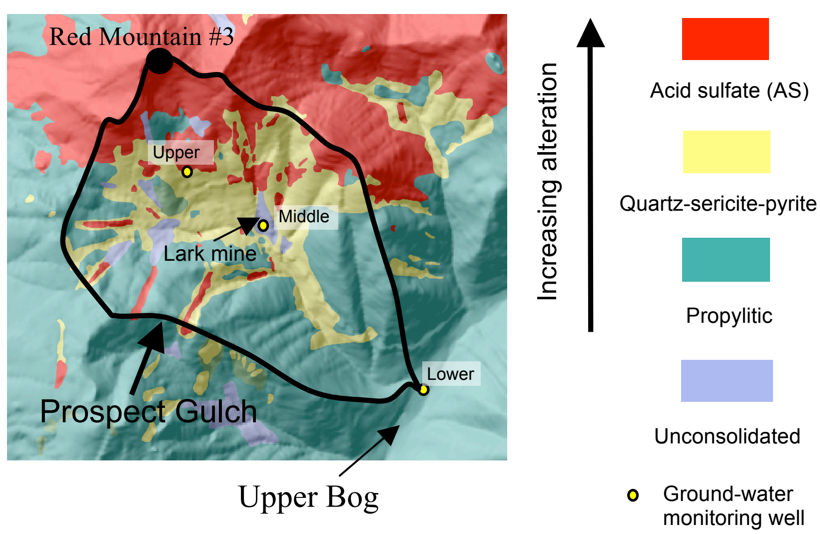

Figure 2. Map of altered bedrock in Prospect Gulch with the location of three ground-water monitoring wells.

installation of shallow ground-water sampling points. Detailed sampling of surface-water quantity and quality using stream-tracer dilution studies provided a companion data to the ground-water sampling. In addition to the detailed snapshot of surface-water data provided by the stream-tracer dilution studies, data on surface-water quality and quantity were collected at the mouth of Prospect Gulch for several months. The complete details on methods and data collected during this project are summarized in three USGS Open-File Reports (Johnson and Yager, 2006; Johnson et al., 2007, and Bove et al., 2007a). Additional data collected before this project as part of the USGS AMLI (Church et al., 2007) were also used as needed to assist in interpretations.

GEOCHEMISTRY

Pyrite oxidation in the hydrothermally-altered bedrock in Prospect Gulch is the ultimate source of Fe, SO_4, and trace metals. The most altered bedrock occurs in the higher and middle elevations (Figure 2), in an area with active ground-water recharge. This area is also the locus for historical mining activity, which followed mineralized veins associated with the hydrothermal alteration. Ground water sampled at the base of Prospect Gulch in the lower well and many of the piezometers are high in Fe (up to 123 mg/L), Al (up to 27 mg/L), and SO_4 (up to 638 mg/L), with no dissolved oxygen. All concentration values are for filtered samples (< 0.45 microns). The pyrite oxidation process releases Fe and SO_4, while consuming oxygen and lowering the pH. Aluminum is dissolved from existing feldspar minerals along the ground-water flow path under these low-pH conditions. Due to access limitations and the expense of drilling, data on ground-water geochemistry at depth (> 230 ft.) within the mountain block are not available. However, the water sampling data from streams, springs, wells, and piezometers provide good indicators of the overall geochemical reactions that are occurring within the watershed.

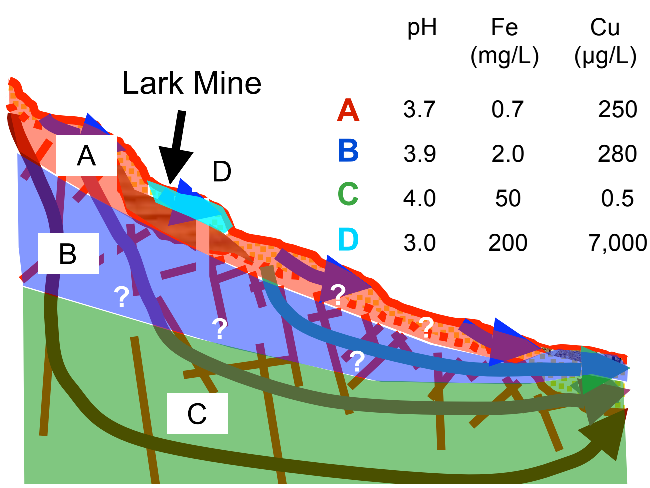

Figure 3. Conceptual cross section with ground-water flow lines along Prospect Gulch.

Data from geophysics, monitoring-well installations, and hydraulic and geochemical testing were used to develop a conceptual model of the hydrogeology at Prospect Gulch (Johnson et al., 2007). A conceptual cross-section from the top of Red Mountain #3 to the base of Prospect Gulch, with an elevation drop of 2,500 feet is shown in Figure 3. The conceptual model of the ground-water flow is characterized by shallow, intermediate, and deep ground-water flow lines. These ground-water flow paths have longer residence times with depth as confirmed by helium/tritium age dating (Johnson et al., 2007). The interaction of the ground-water flow with the geology produces distinct zones of geochemistry (Figure 3, with representative pH, Fe, and Cu concentrations). The shallow ground water is zone A, has low pH, elevated Cu concentrations, and low Fe concentrations. Zone B represents an intermediate flow path with little geochemical difference from the shallower zone, except for slightly higher Fe concentrations. In zones A and B, sulfide oxidation is releasing Fe and Cu, but the oxygenated system allows for the precipitation of Fe oxyhydroxides, whereas the

Cu remains in solution. As ground water moves with depth (zone C), sulfide oxidation continues to release Fe and Cu and consume oxygen. The consumption of oxygen allows for Fe to remain in solution, but Cu is removed from solution. These oxidation-reduction controls are also seen with other metal concentrations (Johnson et al., 2007). The ground-water geochemistry created by mine-waste rock (AMD) is characterized by distinct ground-water plumes with even lower pH and very high concentrations of Fe, Cu, and other metals (above background) that generally occur only in the shallow ground water (zone D).

Discharge of ground water to the surface creates distinct geochemistry in stream water. A snapshot of surface-water geochemistry is shown in Figures 4 and 5, where detailed

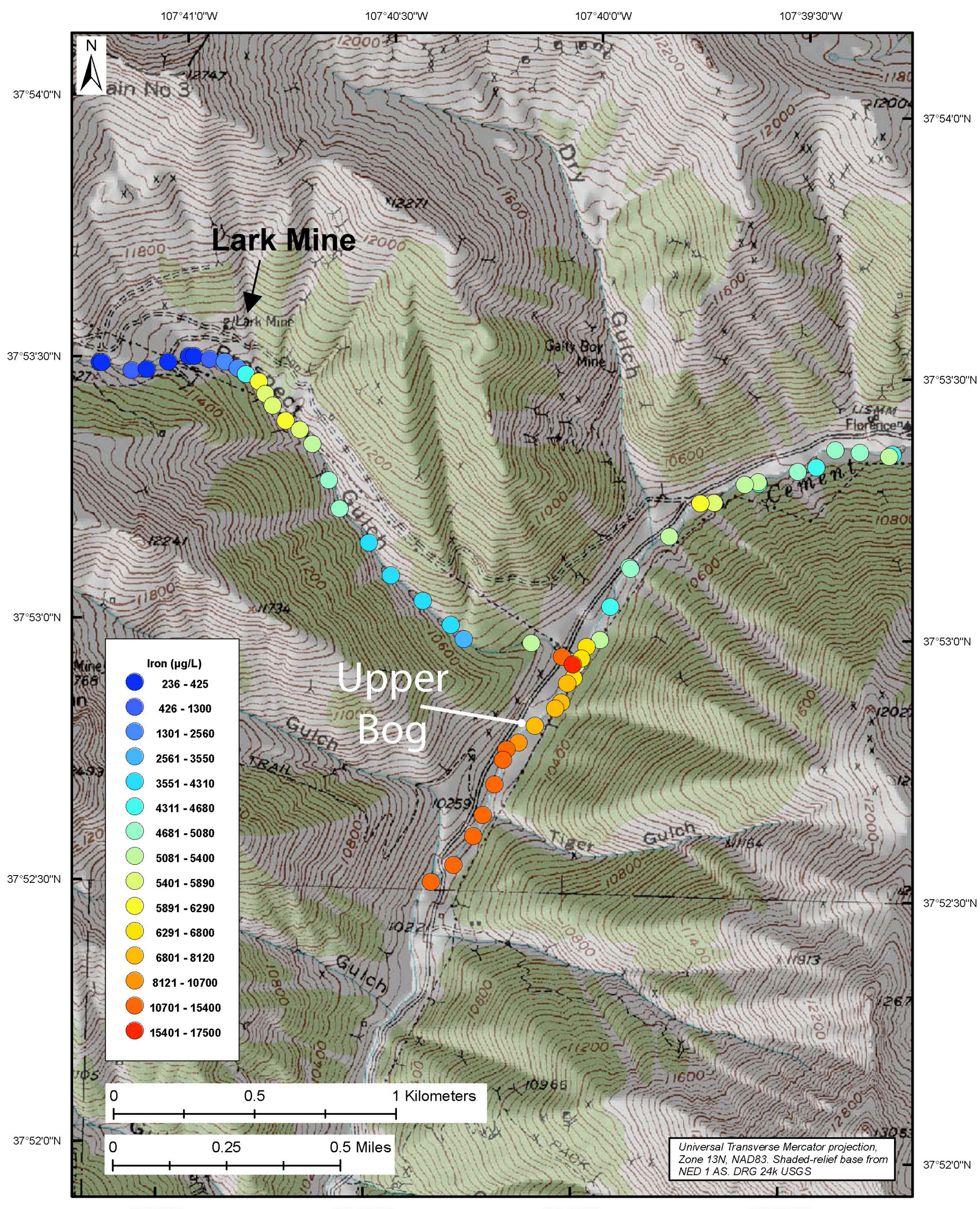

Figure 4. Instream iron concentrations in µg/L.

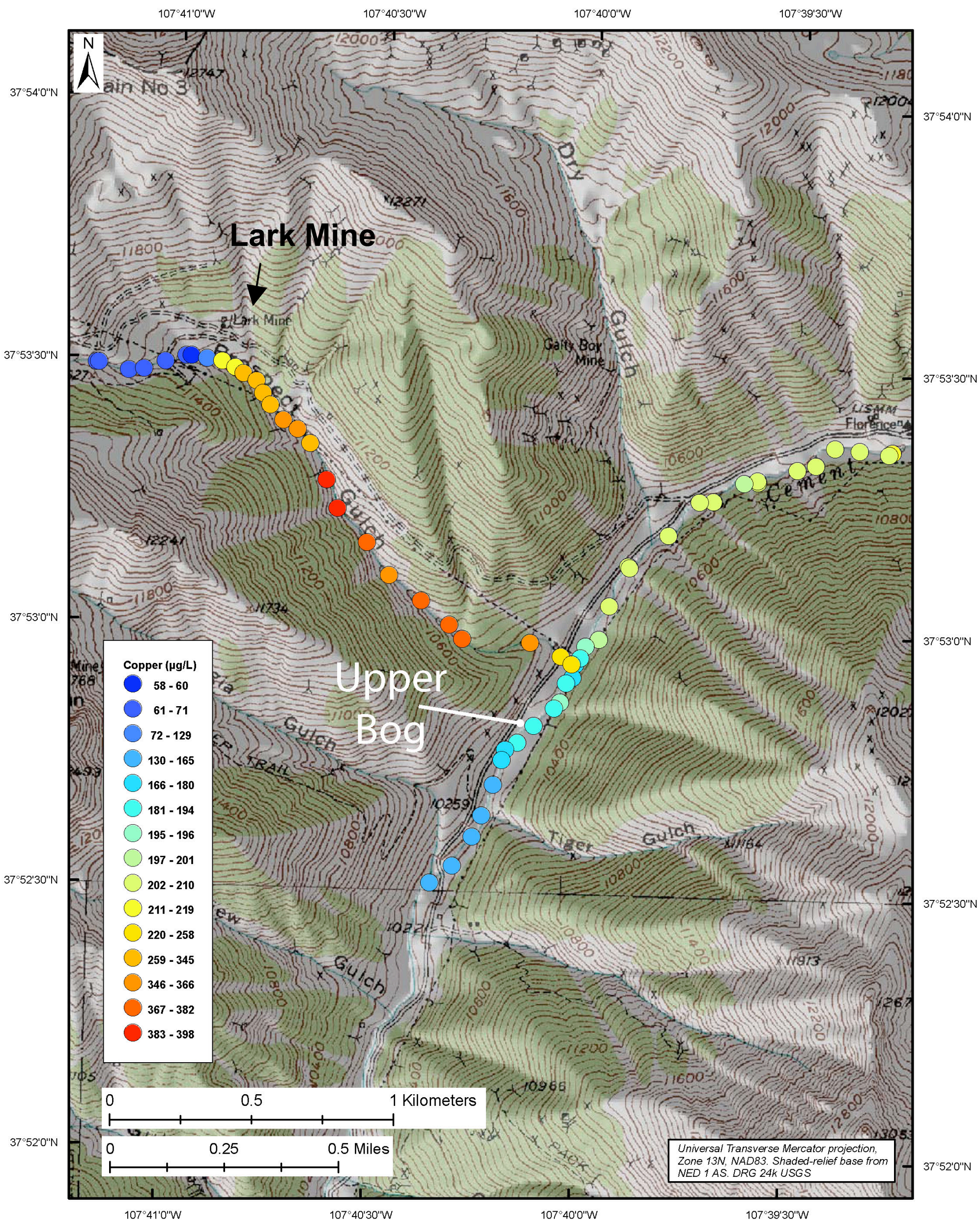

Figure 5. Instream copper concentrations in µg/L.

geochemistry of the stream water was collected at low-flow conditions (October 2004). These figures highlight the deep and shallow ground-water flow, plus the influence of mine-affected shallow ground waters. The mine-affected waters result in Fe and Cu loading to Prospect Gulch near the Lark Mine. Near the Lark Mine, on June 27, 2005 at the middle well, the Cu concentration was 5,410 μg/L compared to a background piezometer (represents zone A in Figure 3) with 630 μg/L. Likewise, the Fe concentrations at the middle well compared to background were 187 mg/L and 0.389 mg/L, respectively. Maximum Fe and Cu in mine-affected ground water in this area were up to 700 mg/L and 32,000 μg/L, respectively. In the shallow ground water, mine-affected waters are relatively distinct from background sulfide oxidation due to the very large concentration of dissolved metals (Johnson et al., 2006 and Mast et al., 2007). Downstream from the central portion of Prospect Gulch, the non-mine affected shallow and intermediate depth ground water discharges to the stream with low Fe and high Cu concentration (similar to background values listed above and zone A and B in Figure 3); hence, the dilution of Fe and maintenance of high Cu concentrations within the stream. At the base of Prospect Gulch and in Cement Creek downstream from the confluence with Prospect Gulch, the discharge of the deep ground water to surface water dramatically increases Fe and decreases Cu concentrations. In this area (similar to zone C in Figure 3), the Cu concentrations are generally less than 2 μg/L and Fe concentrations are as high as 100 mg/L. While the majority of this deep ground water appears to be influenced by ARD, a component of AMD that gets into the system through mine shafts and adits is a possibility. A quantification of any deep AMD was beyond the scope of this research.

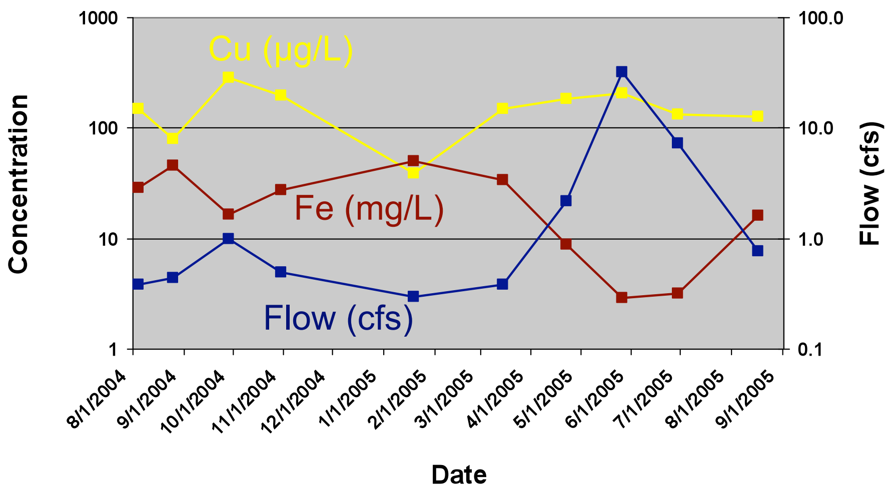

Figure 6. Temporal instream geochemistry and stream flow.

The results of stream monitoring at the mouth of Prospect Gulch indicate how the shallow and deep ground water affects the seasonal surface-water geochemistry (Figure 6). After recharge events, such as spring snowmelt or late summer rains, the larger contribution of shallow ground water creates a higher concentration of Cu (up to 300 μg/L) at the mouth of Prospect Gulch and a dilution of Fe down to 3 mg/L. In contrast, during the winter months, when stream flow is supported by deep ground-water discharge, the highest Fe concentrations and lowest Cu concentrations occur (52 mg/L and 30 μg/L, respectively). These temporal surface-water data are valuable in understanding the seasonal complexity of ground-water flow and geochemistry within Prospect Gulch.

SUMMARY AND CONCLUSIONS

In Prospect Gulch, an interdisciplinary approach has demonstrated the occurrence of shallow and deep ground-water flow with distinct pathways, residence times, and geochemistry. The distinct geochemistry of the ground water is created by changing oxidation-reduction conditions, local geology, and mining effects. The discharge of ground water to nearby streams influences the concentrations of metals observed in the surface water in spatial and temporal patterns. These patterns highlight the discharge of shallow, deep, and mine-affected ground water because of their unique geochemical signatures.

The shallow ground water is generally controlled by topography and flows directly to the surface water through the alluvium and colluvium overlying the bedrock on a seasonal basis (very little shallow flow in the winter). Water in the shallow ground water is generally of good water quality (low Fe and slightly elevated Cu concentrations) due to a short rock/water interaction time, except in areas with mine-waste rock where active sulfide oxidation adds Fe, SO_4, and other metals to the ground water. The deeper ground water flows through the fractured bedrock and does not have distinct seasonal variations. The water quality in the deeper ground water is influenced by the geology, where high sulfide content at higher elevations (recharge zones) increases the Fe, SO_4, and trace-metal content (including Cu). Subsequent flow through propylitically-altered bedrock with a lack of buffering and the depletion of oxygen through pyrite oxidation produces discharging deep ground water with high Al and Fe content, a pH near 4, no dissolved oxygen, and low Cu concentrations.

Because of the seasonal variations in surface-water quality, the measurement of water-quality improvement after remedial efforts must be characterized carefully. Adequate representation of remedial success or failure will require a comparison of future data to the pre-remediation seasonal data.

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