Hydrogeochemistry of the Animas River Alluvial Aquifer in New Mexico after the Gold King Mine Spill

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ABSTRACT

In response to the Gold King Mine (GKM) spill in August, 2015, researchers from the New Mexico Bureau of Geology and Mineral Resources conducted a groundwater investigation with the objectives of characterizing the hydrogeologic system, investigating groundwater/surface water interactions, and assessing the possible impacts of the GKM spill to shallow groundwater in the Animas Valley, New Mexico. We collected water samples from up to 26 wells four times per year between January 2016 and June 2017. Water chemistry data indicate that shallow groundwater is primarily comprised of young river water with a small regional groundwater component. As the river is mostly a gaining system in the study area, the seepage of irrigation water to the subsurface through ditches and agricultural fields is the main potential pathway for contaminants in the river to enter the aquifer. While some groundwater samples exhibited high concentrations of manganese and iron, there is no evidence that the GKM spill impacted groundwater quality. Continued monitoring of groundwater quality is recommended.

INTRODUCTION

On August 5, 2015, the accidental breech of the Gold King Mine (GKM), located in Colorado, resulted in the movement of millions of gallons of bright orange water through the Animas River in northwestern New Mexico. This water, which was loaded with dissolved metals and contaminated sediments, posed a potential risk to groundwater quality in the Animas Valley. In response to the spill, researchers at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), a research and service division of New Mexico Institute of Mining and Technology (NM Tech), began a hydrologic assessment of the Animas River focused on the alluvial aquifer in New Mexico, from the Colorado state line to Farmington, NM (Figure 1). The purpose of this project was to evaluate possible effects from the mine release on the shallow groundwater near the Animas River. Accomplishing this required an understanding of the seasonal changes to the surface water-groundwater system and long-term monitoring of the groundwater quality conditions along this reach of the Animas River. Local domestic wells were utilized to measure groundwater levels and

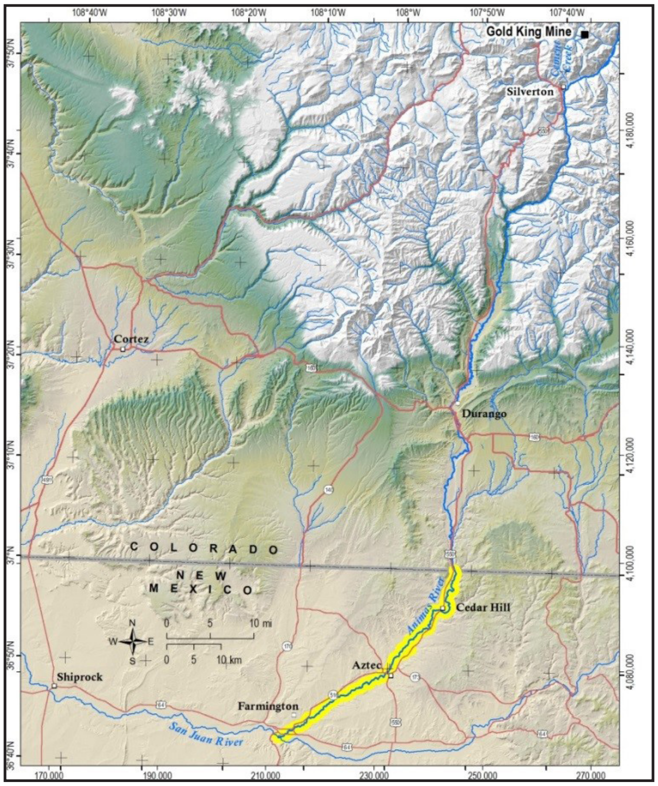

Figure 1.The study focused on the reach of the Animas River outlined in yellow, from the Colorado-New Mexico state line to Farmington. The location of the Gold King Mine, the source of the contaminant spill is also shown.

to collect water samples for geochemical analyses. This paper describes this study and presents results and conclusions, primarily focusing on the geochemical analyses.

THE GOLD KING MINE SPILL AND RESPONSE

There is a long history of natural acid rock and acid mine drainage in the headwater region of the Animas River, along the western San Juan Mountains near Silverton, Colorado. For at least 9,000 years, acidic and metal-laden waters have drained into mountain streams, including Cement Creek and the upper Animas River (Church et al., 2007; Yager and et al., 2016). On August 5, 2015, in an attempt to repair drainage issues in the Level 7 adit of the Gold King Mine, workers accidentally breached the earthen plug holding back acidic water in the vertical mine workings. As the mine workings rapidly drained, the released water also gained an estimated 490,000 kg (~540 tons) of metals and sediment from waste rock piles below the mine (U.S. Environmental Protection Agency, 2017). Cement Creek was soon flooded with yellow-orange, sediment laden water from the Gold King Mine and surrounding area. This water-sediment mixture contained high concentrations of iron, aluminum, manganese, lead, copper, arsenic, zinc, cadmium, and some mercury (U.S. Environmental Protection Agency, 2017). Within about 3 days, the yellow water had flowed down the Animas River to Farmington, New Mexico where it entered the San Juan River.

Immediately following the Gold King Mine spill, many questions were asked about the connection of the Animas River to the surrounding groundwater. Could there be contamination of the groundwater aquifer along the river? How exactly do the groundwater and surface water interact? How might Gold King Mine spill sediments deposited in the river bed or irrigation ditches affect groundwater?

In August 2015, in collaboration with the U.S. Geological Survey, New Mexico Office of the State Engineer, and New Mexico Environment Department, the New Mexico Bureau of Geology and Mineral Resources collected groundwater level measurements at over 100 locations along the Animas River. The goal of these measurements was to identify gaining or losing reaches of the river system. Water quality samples were initially collected by the U.S. Environmental Protection Agency and their contractors in August 2015. Using the network of private domestic wells established in August 2015, we developed a repeat sampling program for groundwater quality and groundwater levels along the Animas River valley. While long-term research continues in 2018 and 2019, the summary of this paper is focused on data collected from this well network during several sampling events between January 2016 and June 2017.

REGIONAL GEOLOGY

The geology of the area described here is summarized from Craigg (2001), which is part of a larger review of the geology found in the San Juan Basin. The Animas River in northwest New Mexico flows through the northwestern margin of the San Juan Basin, which is an asymmetric structural depression in the Colorado Plateau province. Below and surrounding the alluvial aquifer, the geology along the Animas River from Durango to Farmington consists of sedimentary rocks of late Cretaceous to Paleogene age. The Nacimiento Formation, which underlies the alluvial aquifer throughout most of the study area, consists of interbedded gray shale, with discontinuous lenses of sandstone, and it interfingers with the Paleocene Ojo Alamo Sandstone, which consists of arkosic sandstone and conglomerate. The Nacimiento Formation is a known aquifer to the north in La Plata County, CO (Robson and Wright, 1995) and in other areas in the San Juan Basin (Phillips et al., 1986). Along the river in the proximity of Farmington, outcrops of late Cretaceous (~75 Ma) Kirtland Shale are found. The Kirtland Shale consists of interbedded repetitive sequences of sandstone, siltstone, shale and claystone and is likely an aquitard, which water cannot easily flow through.

The Animas River from the Colorado-New Mexico border flows through Quaternary alluvial deposits, which comprises the alluvial aquifer of primary interest for this study. The Quaternary alluvium is largely made up of sediment eroded from Paleogene rocks into which the Animas River has incised. While municipal or regional drinking water is largely sourced from the Animas River, most private domestic wells in the valley rely on this alluvial aquifer, with well depths of about 30 to 60 feet.

THE ANIMAS RIVER

The headwaters of the Animas River originate high in the San Juan Mountains, in the Silverton Mining District. Two large tributaries, Cement Creek and Mineral Creek drain water from this mineral rich region and join the Animas River in Silverton. These streams account for roughly one-third of the observed flow measured in Farmington, NM. The Animas flows through the Animas Canyon, between Silverton and Durango (roughly 50 miles), where it receives flow from numerous smaller streams. By the time the river reaches Durango, it has more than doubled in volume. Just north of the New Mexico-Colorado border, the Florida River joins the Animas River. By the time the Animas enters New Mexico the river discharge is roughly equal to the flow measured at Farmington, NM, (~300 cfs at baseflow). The Animas River meanders roughly 40 miles from the New Mexico border, to Farmington, where it joins the San Juan River. The San Juan River flows an additional ~180 miles through New Mexico and Utah before discharging into Lake Powell.

The discharge of the Animas River fluctuates with the seasons. In Farmington, just upstream of where the Animas River joins the San Juan River, the U.S. Geological Survey has recorded over 90 years of river discharge measurements. The median daily discharge varies from 208 cfs at its lowest, to nearly 3000 cfs at its peak. In general, the river discharge begins to rise slowly in April as early snow melt enters the river. Discharge continues to increase throughout May as temperatures in the mountains feeding the headwaters rises, melting more snow. The river typically reaches peak discharge between late May and mid-June as the main pulse of snowmelt moves through the river. The discharge declines through late summer as the snowpack diminishes. Throughout the late summer, river discharge often rises rapidly as result of monsoon storms, before ebbing back to previous levels. By late August the river has returned to a baseflow. The river is often lowest during early fall as result of diversions for water supply and irrigation, and higher evapotranspiration rates. Moving into fall and winter the river remains relatively steady at roughly 300 cfs.

GROUNDWATER FLOW CONDITIONS

Groundwater flow conditions discussed in this section are based on groundwater level measurements from this study. A more detailed discussion about groundwater levels is provided by Newton et al. (2017). The general groundwater flow direction along this reach of the Animas River is from northeast to southwest and toward the river. Groundwater level fluctuations in the majority of measured wells were observed to be controlled by either river stage or irrigation. Water level fluctuations in many wells in close proximity to the river showed a strong correlation to river stage fluctuations, with peak water level elevations occurring in June when river stage is high due to snowmelt from the high mountains. Groundwater level fluctuations in many other wells throughout the area correlated with the timing of irrigation. When the irrigation ditches are first filled in late March, the groundwater level begins to rapidly rise and continues to rise through June, and generally doesn’t reach its maximum until late July. Groundwater levels typically remain elevated in these wells until the end of the irrigation season, when the ditches are shut off. At this point, there is a sharp drop in groundwater levels as the ditches are no longer supplying water to the alluvial aquifer. The declining leg of these hydrographs flattens as the groundwater level approaches equilibrium before the irrigation season begins again. These data indicate that river water that is diverted to irrigation ditches and agricultural land recharges the aquifer, resulting in an increase in groundwater levels during irrigation season. When irrigation ends, groundwater gradually drains back into the river.

This reach of the Animas River largely is a gaining river where groundwater discharges to the river. However, in some localized areas, the water table gradient is nearly flat in close proximity to the river, and the gradient between groundwater and the river reversed, causing the river to lose water to the aquifer (Figure 2). This gradient reversal was observed during winter months (non-irrigation period). The observed gradient reversal suggests that these localized areas may be potential pathways for contaminants in river to enter the aquifer. Simple Darcy's Law calculations indicate that during non-irrigation periods, in losing reaches of the river, the river water that recharges the aquifer could potentially flow a little over 30 meters away from the river before the gradient switches back to gaining conditions (Newton et al., 2017). Throughout the Animas Valley, seepage of irrigation water into the subsurface is the main source of groundwater recharge and a potential pathway by which contaminants in the river may enter the groundwater system.

METHODS

Protocols used by NMBGMR for collecting groundwater samples and preventing contamination during sampling are described in more detail by Timmons et al. (2013), and Newton et al. (2017). The goal was to collect water samples that were chemically representative of local groundwater using existing domestic and irrigation wells that were equipped with pumps. Water sampling procedures include purging the well until field parameters (pH, dissolved oxygen, specific conductivity, oxidation-reduction potential (ORP), and temperature) stabilize before collecting the sample

All groundwater samples were analyzed for major cations and anions, trace metals, and the stable isotopes of oxygen and hydrogen. For trace metals and major cations, total and dissolved concentrations were determined. For a small subset of wells, extra samples were collected for the analysis of the environmental tracers, carbon-14 and tritium. All water samples were tracked using chain-of-custody documentation. Analyses for trace metals, major ions and stable isotopes of oxygen and hydrogen were performed at the Chemistry Lab at New Mexico Bureau of Geology and Mineral Resources. Samples to be analyzed for environmental tracers were sent to Beta Analytic (carbon-14) and Miami Tritium Lab (tritium).

For this study, groundwater samples for geochemical analysis were collected during base flow (January), the onset of irrigation (March), high flows or snowmelt runoff (June), and toward the end of irrigation (October). Sampling events occurred at the following time periods: January 26 – 27, 2016; March 14 – 17, 2016; May 31 – June 10; October 17 – 21, 2016; January 23 – February 3, 2017; March 13 – 24, 2017; and May 29 – June 9, 2017.

GEOCHEMISTRY OF THE ANIMAS RIVER ALLUVIAL AQUIFER

Geochemical data collected for this study have helped provided important information about recharge sources, mixing processes, and other important geochemical processes that affect groundwater quality. In this section we will discuss some key findings from the geochemical analyses. A more detailed description of these analyses is provided by Newton et al. (2017).

Groundwater Recharge Assessment

Mineral/water interactions largely control the concentrations and relative distribution of dissolved constituents in groundwater. The types of minerals present in the aquifer, their solubility, and the residence time of the water determines the relative amount of major ions in solution. Therefore, the geochemical composition of groundwater can help to identify different recharge sources. For most water samples, the major ions present were calcium, bicarbonate, and sulfate, indicating the dissolution of calcium carbonate (limestone, dolomite, or calcite cements) and calcium sulfate (gypsum). The left map panel on Figure 3 shows the different water types observed for water produced by wells in the study area. Groundwater in the northern portion of the valley exhibited a calcium-bicarbonate water type while

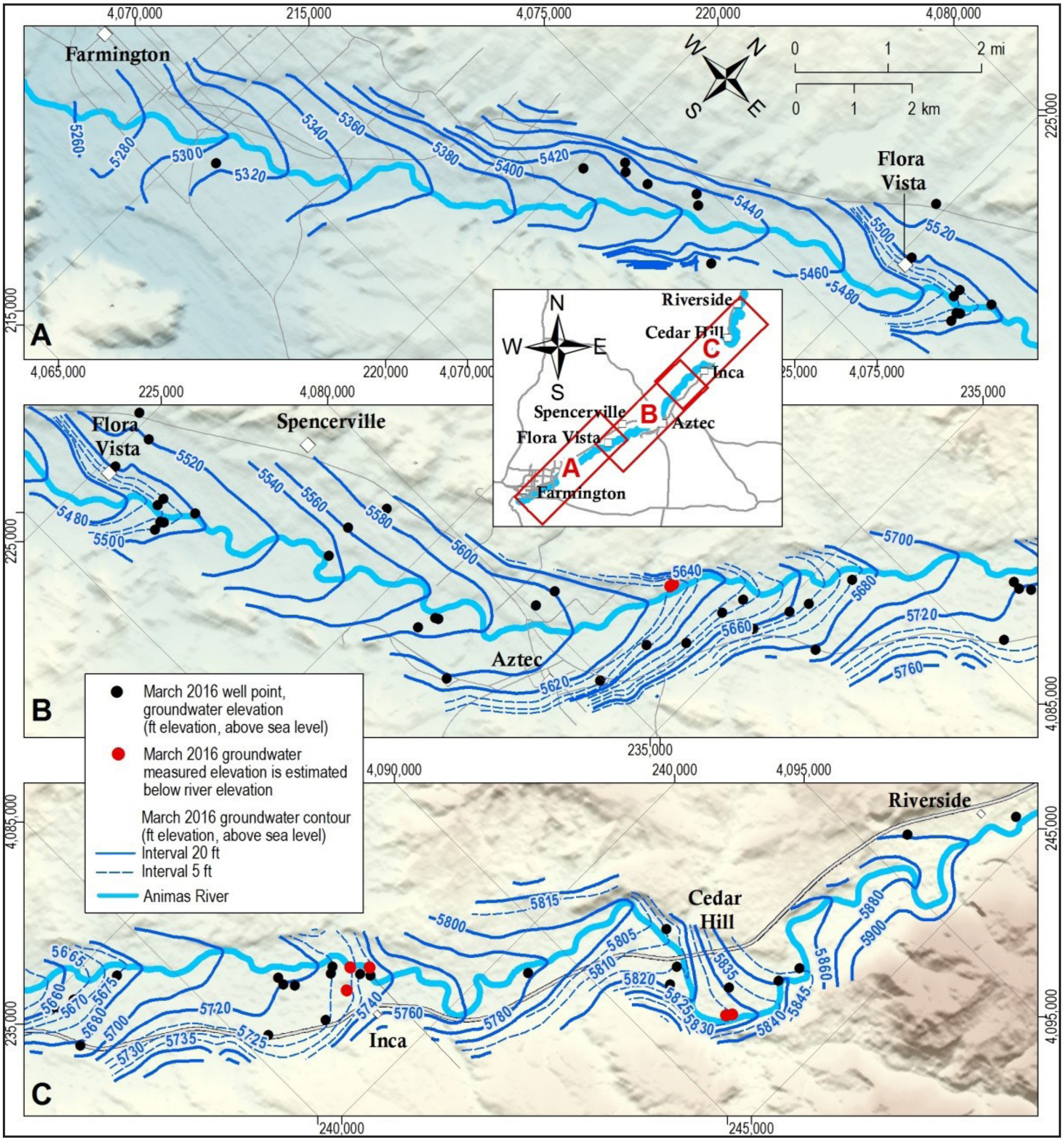

Figure 2. Water table map based on water level measurements during March 2016. Red points designate wells that exhibited water level elevations below the estimated river stage elevation at the time, indicating that in these areas the river water is recharging the alluvial aquifer. The losing stream condition only occurs in certain areas during the winter months.

groundwater to the south showed a water type of calcium-sulfate. The spatial distribution of water types in the Animas Valley correlates to observed spatial trends for total dissolved solids (TDS) (Figure 3, center panel) and sulfate (SO_4) (Figure 3, right panel), where concentrations increase from northeast to southwest (down-gradient). The samples collected from the two wells outside of the valley to the west (AR-0213 and AR-0214) stand apart from other samples with a sodium sulfate water type and the highest observed TDS and sulfate concentrations. In addition, water produced from these two wells were geochemically distinct from groundwater in the alluvial valley based on their water age and stable isotopic compositions (data not shown, see Newton et al., 2017).

The spatial geochemical trends shown in Figure 3 can be explained largely by the mixing of young and relatively fresh river water and older brackish regional groundwater that likely discharges from the underlying Nacimiento Formation as seen in Figure 4. River water is by far the largest recharge component and enters the system during irrigation season as described above, resulting in rising groundwater levels between late March and October. Newton et al. (2017) shows multiple lines of evidence for these recharge and mixing mechanisms.

Groundwater Contaminants

The U.S. EPA water quality standards discussed in this section are provided simply for comparison of privately owned domestic well water samples and are not enforceable for private wells. According to water chemistry data for the measured constituents, all water samples exhibited chemical concentrations below the "maximum contaminant levels" (MCLs) as defined by the U.S. EPA National Primary Drinking Water Regulations that were established to protect against consumption of drinking water contaminants that present a risk to human health. For the following discussion, we evaluate groundwater quality by comparing water chemistry results to secondary maximum contaminant levels (SMCLs) as defined by the U.S. EPA secondary drinking water regulation, which is a non-enforceable guideline regarding cosmetic or

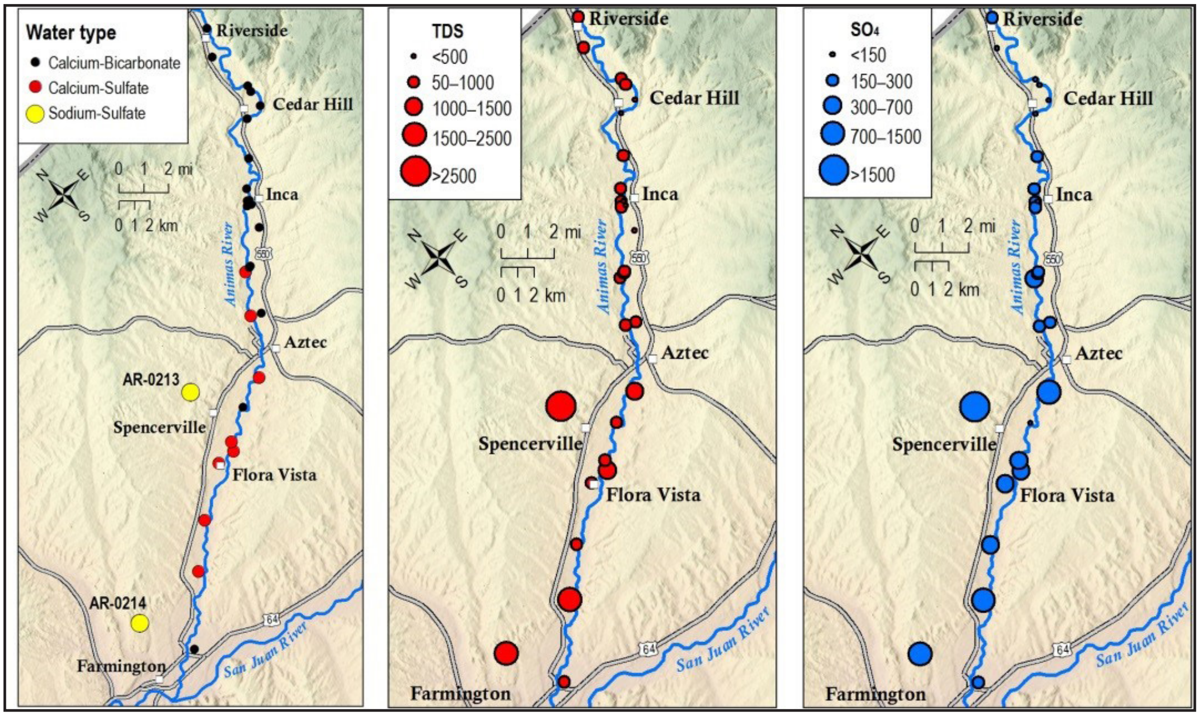

Figure 3. Trends for water type, total dissolve solids, and sulfate concentrations. Left panel: Water type as defined by relative cation and anion concentrations. Center panel: Average total dissolved solids concentrations show a general trend of increasing in the downstream (southwest) direction. Right panel: Average SO_4 concentrations show a general trend of increasing in the downstream (southwest) direction.

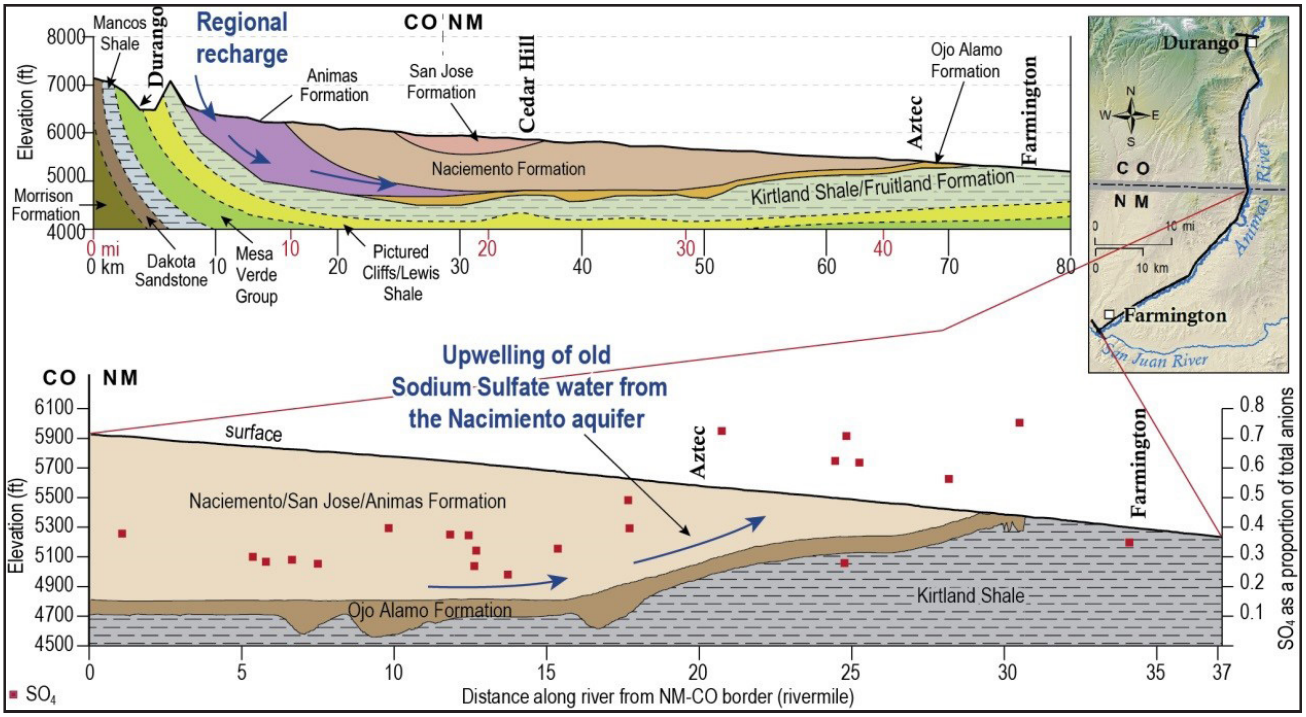

Figure 4. Schematic regional cross-sections showing groundwater flow paths in regional bedrock. Regional groundwater recharge to the Nacimiento/Ojo Alamo/San Jose aquifer occurs in the San Juan Mountains near Durango, at the northern edge of the San Juan Basin. Increased sulfate (red data points and right y-axis) and total dissolved solids concentrations in shallow groundwater south of Aztec are due to the upwelling of old sodium-sulfate regional groundwater from the Nacimiento/Ojo Alamo aquifer as a result of the structure of the San Juan Basin. The thinning of this deeper aquifer forces regional groundwater into the shallow alluvial aquifer (which overlies the bedrock, but is not shown on this image). It should be noted that the horizontal distances shown on the NM cross-section (bottom) are river miles, resulting in a larger relative distance than is shown in the larger-scale cross-section (top).

aesthetic effects. While these contaminants are not health threatening, if present at levels above the SMCLs, these constituents may cause the water to appear cloudy or colored, or to taste or smell bad.

Figure 5 shows the locations of wells that produced water that exceeded groundwater SMCLs for TDS, sulfate, total iron, total manganese, and total aluminum. Groundwater with TDS concentrations exceeding the SMCL of 500 mg/L is common in New Mexico due to the dissolution of soluble minerals such as calcite and gypsum. Most of the wells that produce water with sulfate concentrations exceeding the SMCL are located south of Aztec mostly due to mixing process described above (Figure 4).

Potential groundwater contaminants identified in water and sediments associated with the Gold King Mine spill include iron, aluminum, manganese, lead, copper, arsenic, zinc, cadmium, and mercury. All of the metals mentioned above were either below U.S. EPA MCLs, or were below the reporting limit of the analysis. One well produced water that slightly exceeded the U.S. EPA SMCL for total aluminum. Several wells in the shallow alluvial aquifer produced water that exceeds U.S. EPA SMCLs for dissolved iron and manganese (Figure 5). It is difficult to determine the source of these trace metals. While iron and manganese were observed at high concentrations in the Gold King Mine spill plume and water in the Animas River has relatively high iron and manganese total concentrations (most is likely adsorbed onto colloids and other particulates), these metals are also present in the aquifer sediments. Therefore, the spatial distribution of water that is high in iron and manganese may be controlled by the location where these minerals were dominantly deposited within the alluvial aquifer. The ability of water to dissolve iron and manganese is controlled by electro-chemical or redox conditions. The presence of dissolved iron and manganese and the observed range of oxidation-reduction-potential (ORP) values (data not shown, see Newton et al., 2017) suggest that these metals are redox buffers that control redox conditions in the aquifer. More research is needed to understand redox processes in the shallow aquifer to explain the spatial distribution these metals.

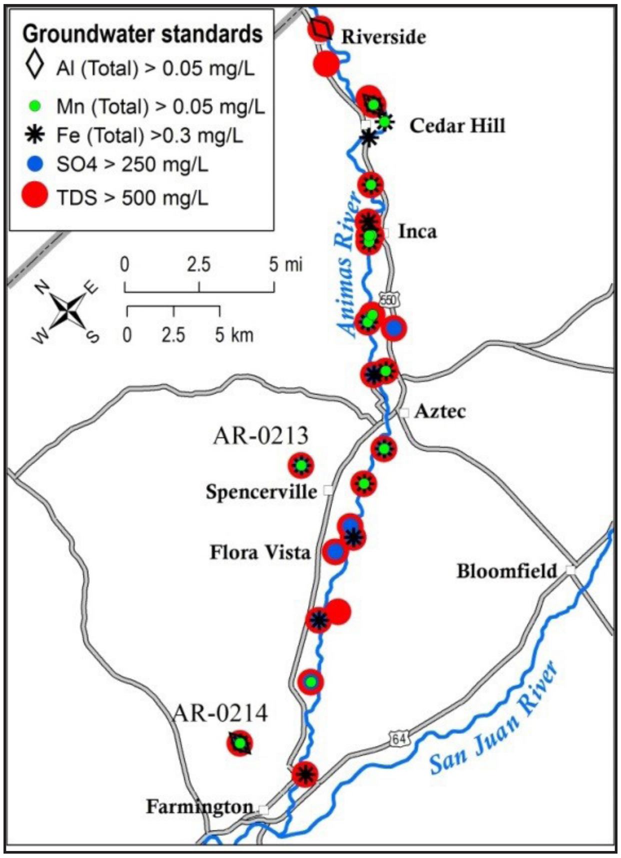

Figure 5. Location of wells that produced water exceeding US EPA secondary contaminant levels for total dissolved solids, total iron, total manganese, and total aluminum.

CONCLUSIONS

Results from this study within the Animas Valley has helped us to better understand the hydrogeologic system with implications for assessing potential impacts to the shallow aquifer by the GKM spill or similar accidents that may occur in the future. The primary recharge source is river water via irrigation, where water infiltrates through the bottoms of irrigation ditches and through soils in agricultural fields to the water table, which is usually less than 20 feet below the surface. This is an important consideration with regard to the Gold King Mine spill and possible impacts to groundwater quality. Contaminated sediment associated with the Gold King Mine spill that was possibly deposited in irrigation ditches during or after the release, can possibly result in the contamination of the shallow aquifer. So far, the groundwater quality does not appear to have been impacted through this recharge mechanism.

The water-sediment mixture from the Gold King Mine spill contained high concentrations of iron, aluminum, manganese, lead, copper, arsenic, zinc, cadmium, and some mercury (U.S. Environmental Protection Agency, 2017). There is no evidence that groundwater quality in the Animas Valley was impacted by the GKM spill. With the exception of aluminum (one well), iron, and manganese, all of the metals from the GKM spill are either observed in groundwater at levels well below set maximum contaminant levels or were below the reporting limit of the analysis. With groundwater pH being fairly constant between 6.7 and 8.3, and with manganese and iron buffering the redox conditions, it is unlikely that these metals will be contaminants of concern in this groundwater system. However, continued long-term monitoring of groundwater quality and additional research to better understand redox processes in the aquifer is recommended and underway.

ACKNOWLEDGMENTS

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