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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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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.

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.

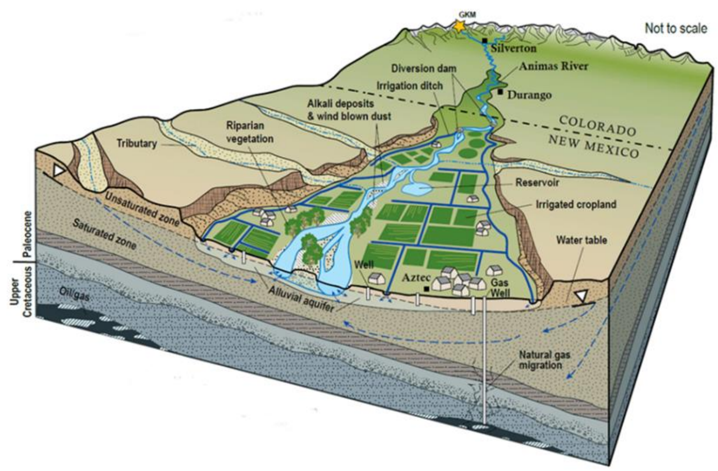


Figure 8-1. The shallow alluvial floodplain aquifer of the Animas River, with emphasis between Aztec and Farmington, New Mexico. (**Image from Timmons *et al*. 2016.)**

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)

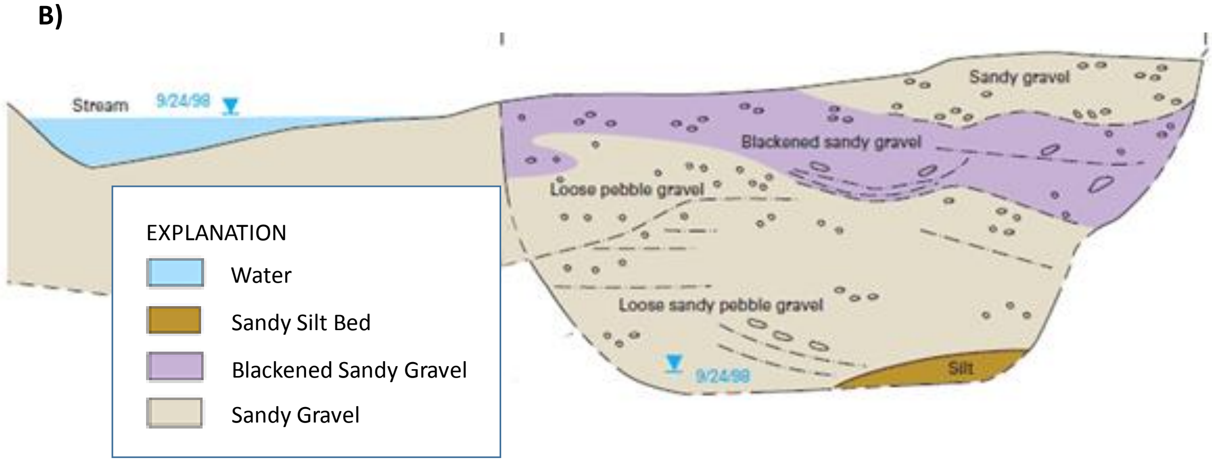


Figure 8-2. Animas River in floodplain near Eureka above Silverton, Colorado. A) GoogleEarth image showing braided dry channels and the approximate location of the geologic cross section. B) Generalized geologic cross section of the shallow floodplain deposits of the Animas River above Silverton modified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

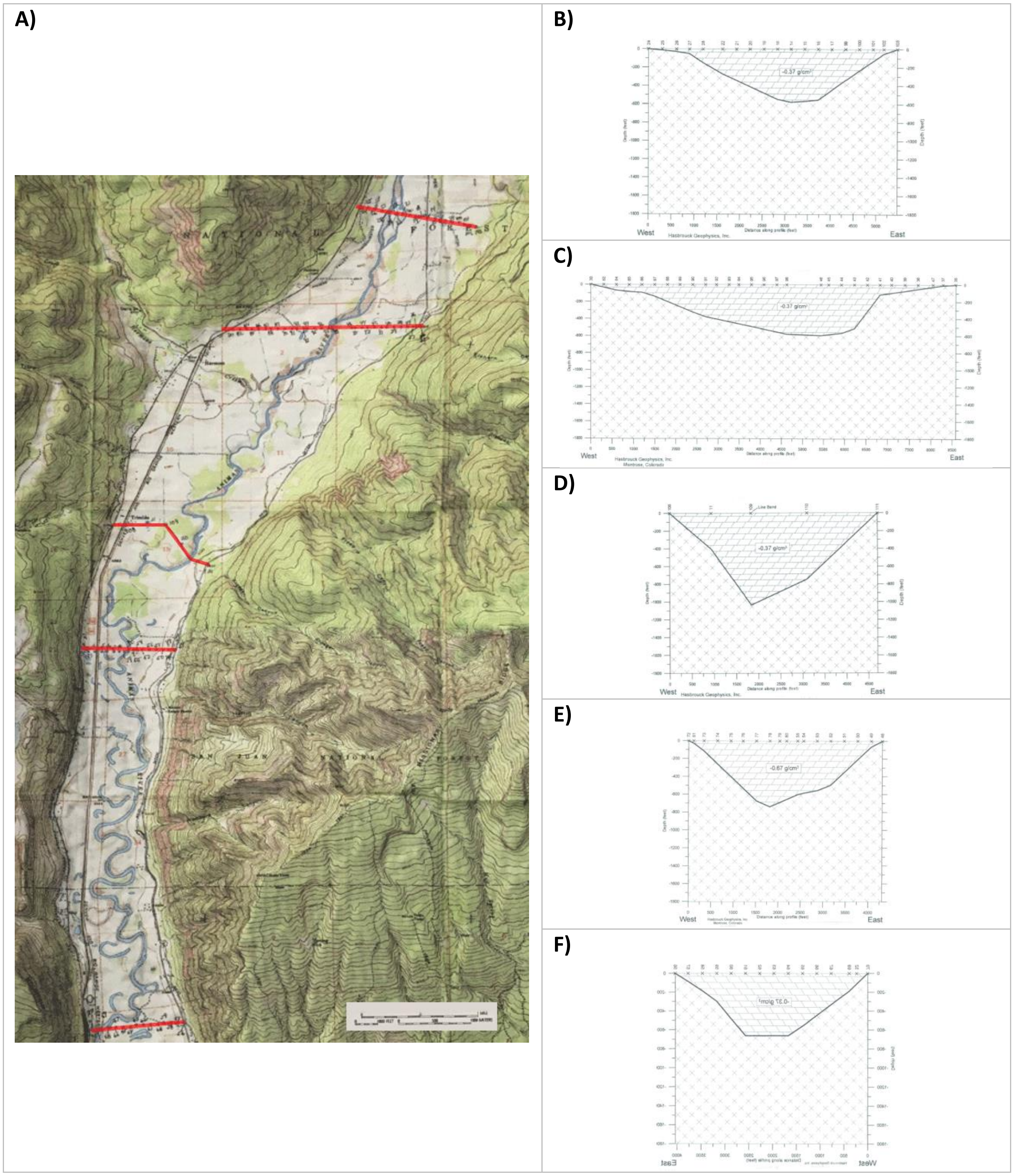


Figure 8-3. Geophysics modeling of the shallow floodplain aquifer base elevation based on a gravity survey: A) map of the five gravity survey lines; B) line 1 gravity and depth profile – 2-layer model; C) line 2; D) line 5; E) line 3; and F) line 4. Data source: Hasbrouck Geophysics (2003).

A)

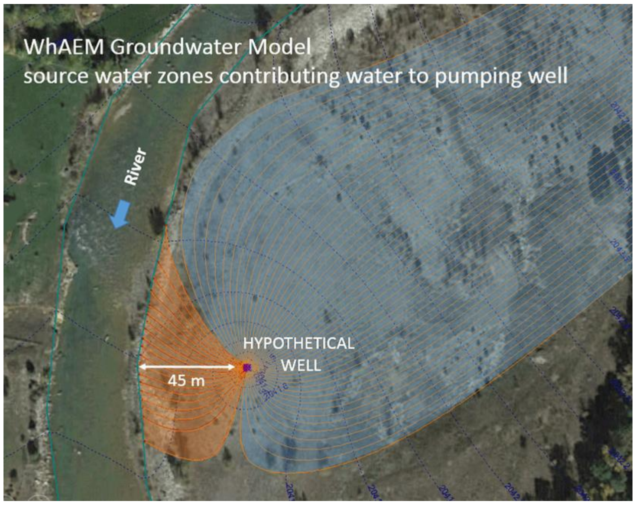


Image: GoogleEarth

B)

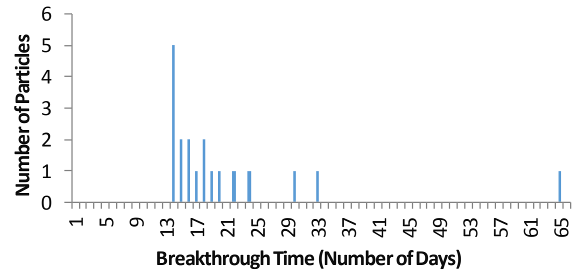


Figure 8-4. Demonstration of a pumping well capture zone and particle tracking breakthrough histogram using the Wellhead Analytic Element Model (WhAEM) of a hypothetical groundwater scenario. A) The well sources some of its water from the river (orange zone) and some from aquifer recharge and storage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

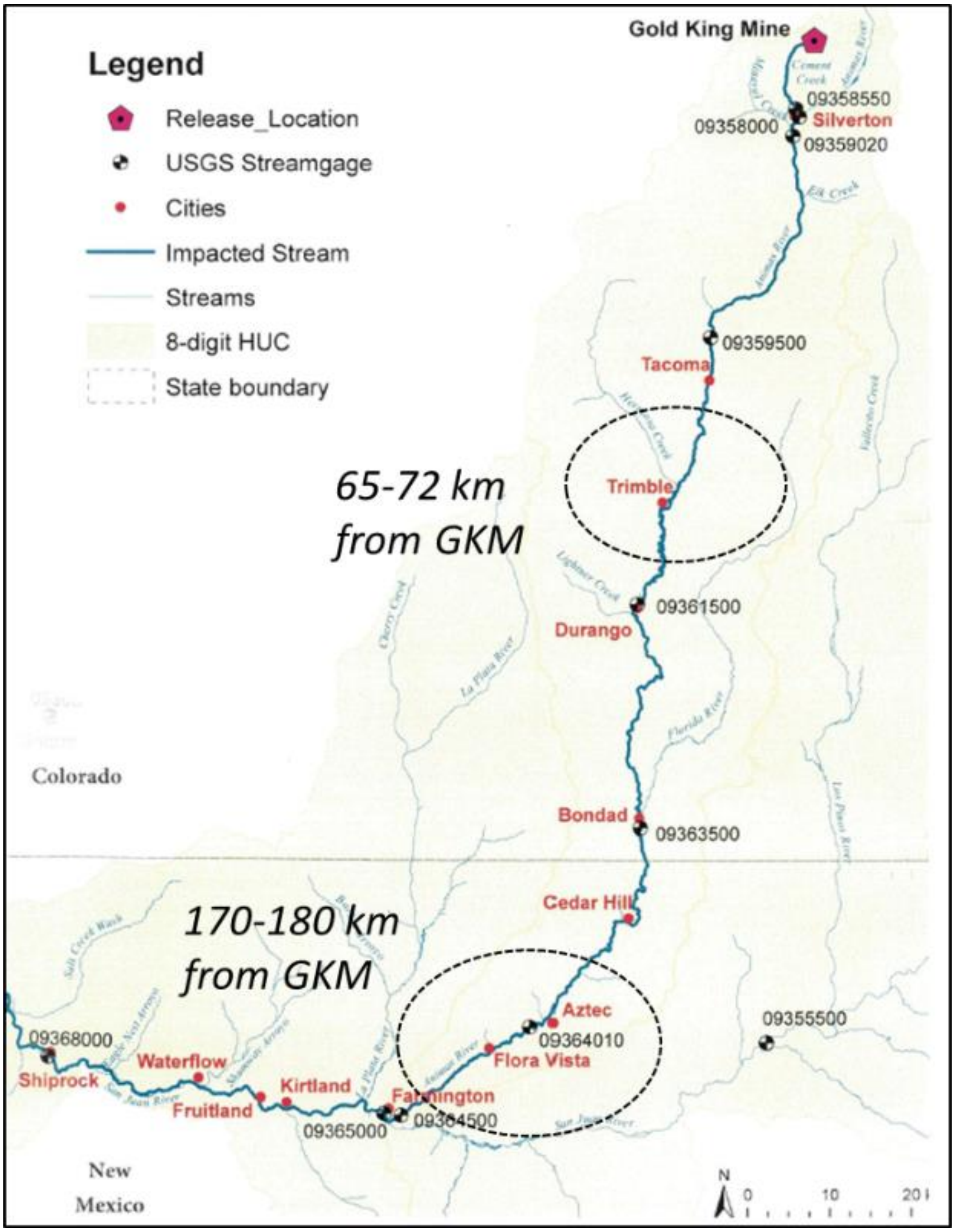


Figure 8-5. The mid Animas and lower Animas River clusters of community and private wells selected for groundwater modeling analyses. The mid Animas River groundwater study area is between Tacoma and Durango, Colorado, 65-72 km downstream of the Gold King Mine (GKM) release site. The lower Animas River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

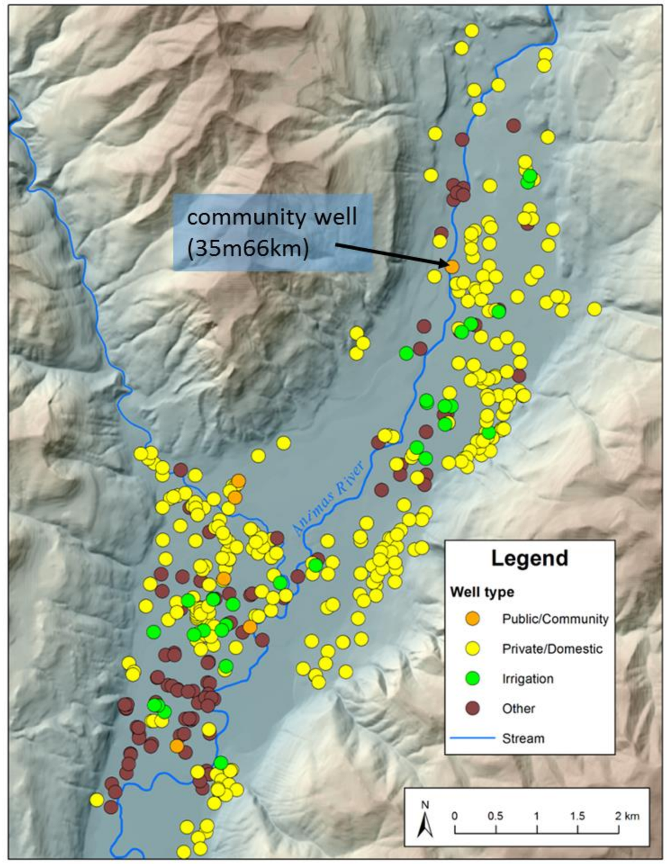


Figure 8-6. Water supply wells of the floodplain of the mid Animas River of Colorado (RK 65-72). The background is the topographic digital elevation model (DEM) and the hydrography of the USGS Hermosa Quad. Well data available from the Colorado Division of Water Resources (DWR) well permit search database.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

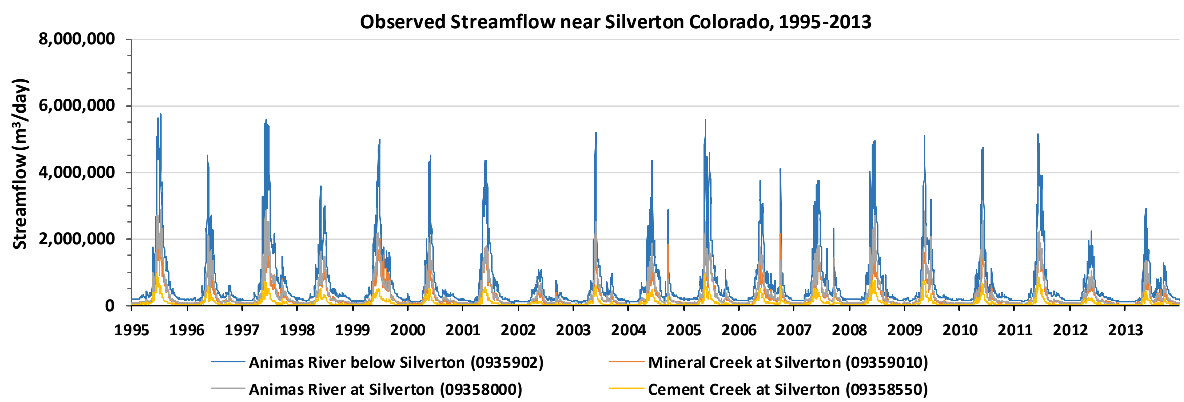
The analytic element computer program GFLOW (v.2.2.2; www.haitjema.com) was used to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). The GFLOW program is well documented and accepted within the groundwater modeling community (Hunt 2006; Yager and Neville 2002), 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)



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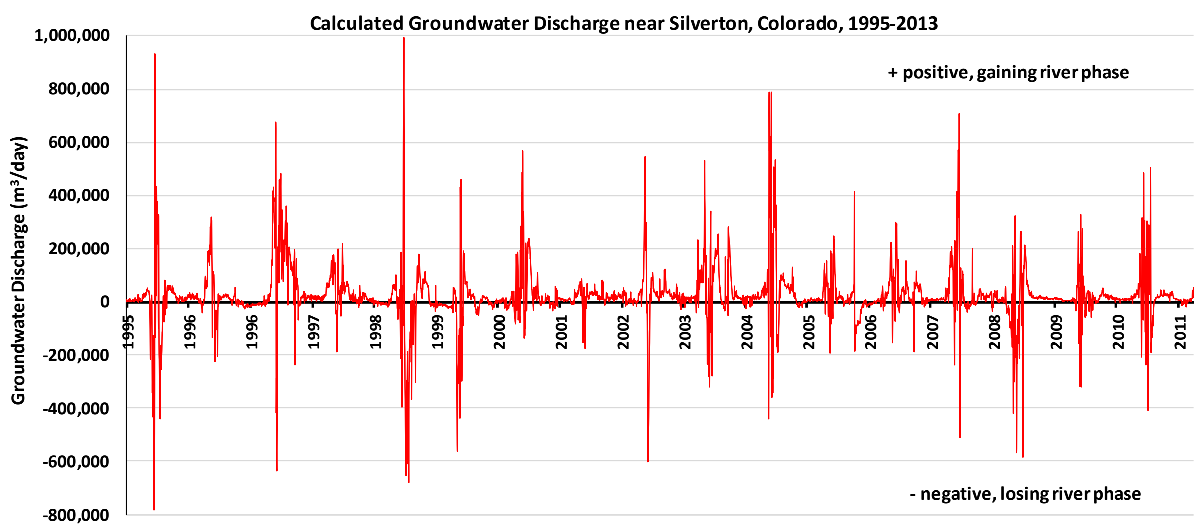


Figure 8-7. Streamflow analysis of the upper Animas River near Silverton, Colorado. A) Streamflow hydrographs of measured discharge (Q) in cubic meters per day of the Animas River and tributaries near Silverton, Colorado. B) Inferred groundwater inflows along the section of the Animas River near Silverton,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

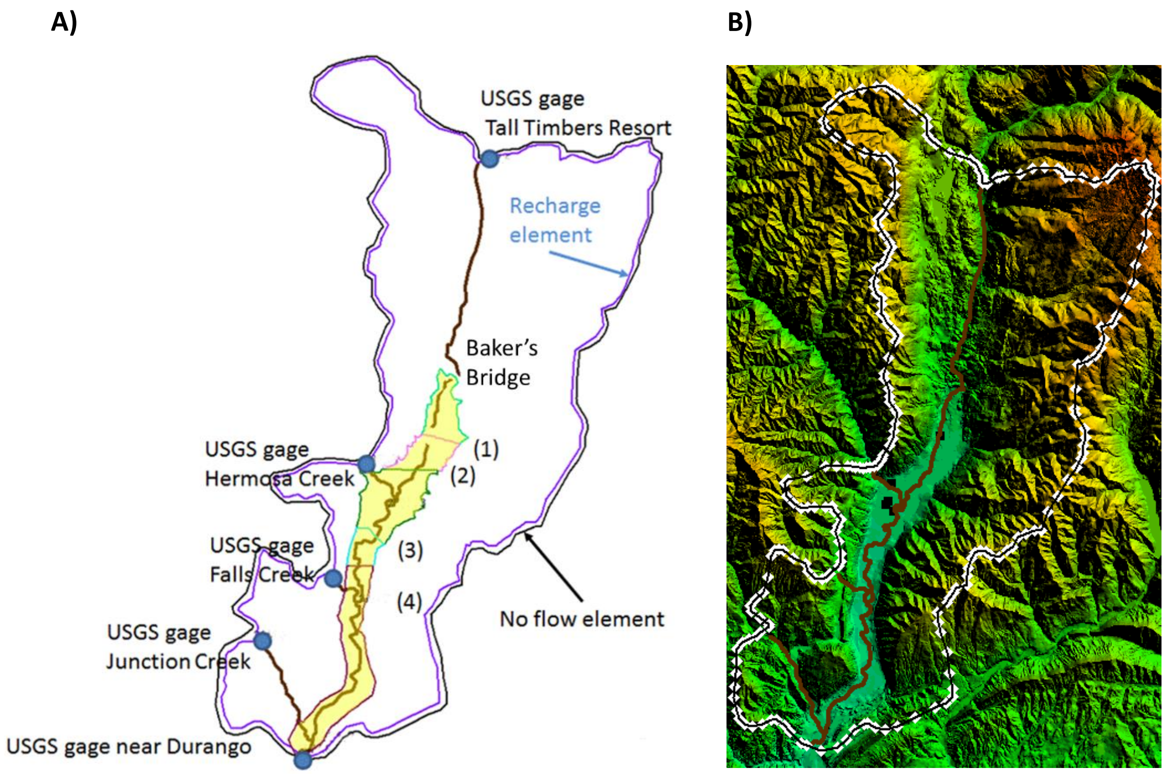


Figure 8-8. GFLOW analytic element groundwater model for the mid Animas River floodplain. A) Layout of analytic elements. B) The USGS digital elevation model (National Elevation Dataset 10m resolution) was used to define the catchment between USGS gages.

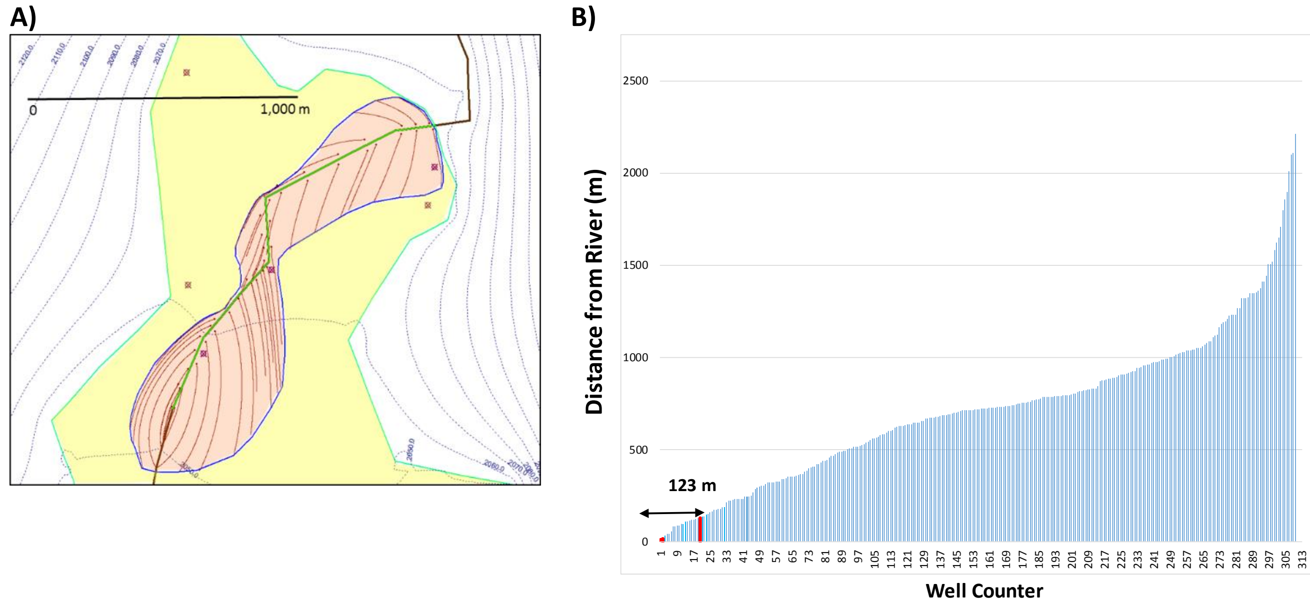


Figure 8-9. GFLOW model of the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015. A) Solution showing hydraulic head contours (m) and forward streamlines with respect to pumping wells (points). B) The 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.

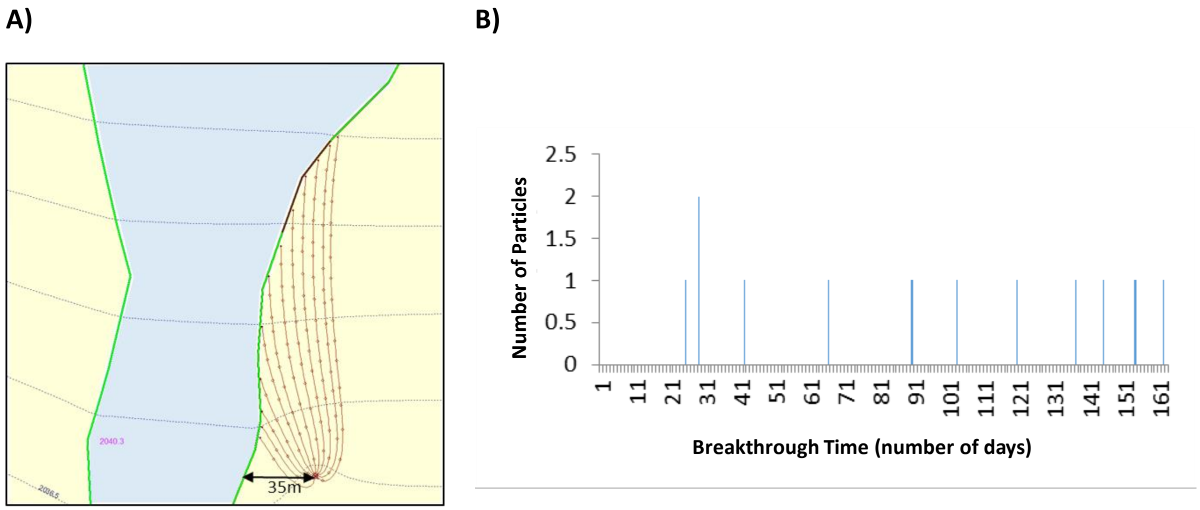


Figure 8-10. GFLOW capture zone and solute breakthrough histogram for a mid-Animas River community well. GFLOW analysis of mid Animas River community well (35m-66km), high pumping (Qw= 2,616.5 m^3/d) and low porosity (n=0.2). A) Particle tracking with 12 forward pathlines, and B) predicted time of arrival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

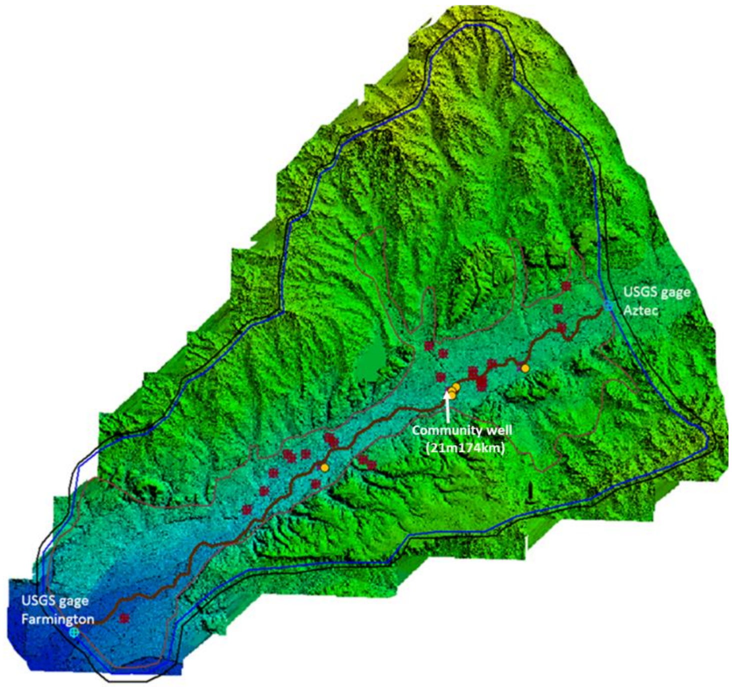


Figure 8-11. Community wells (orange) and select private wells (red) for the Lower Animas River floodplain study area. The catchment draining between the USGS gages at Aztec and Farmington was delineated as guided by the light detection and ranging (LiDAR) digital elevation model (DEM). Note the 21m174km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

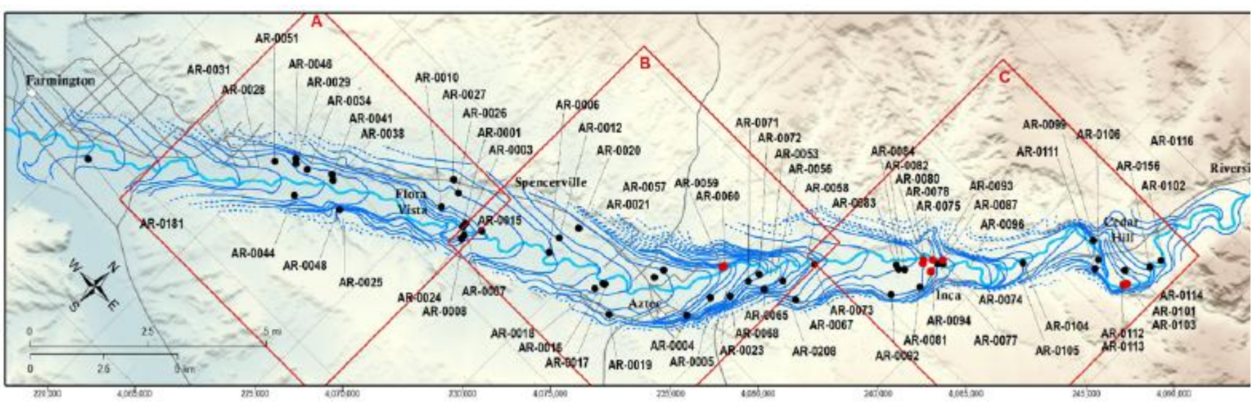


Figure 8-12. High-resolution synoptic survey of the river water levels and well water levels in the lower Animas River floodplain, January 2016, between Riverside and Farmington, New Mexico. The wells were geospatially located using hand-held global positioning system (GPS). A high-resolution light detection 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.

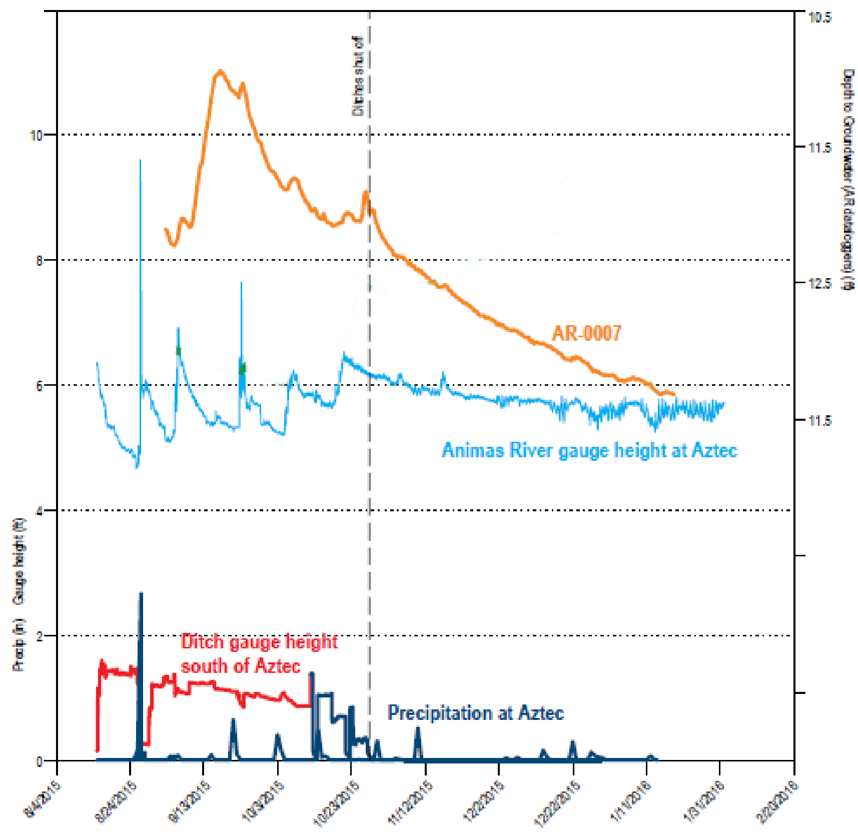


Figure 8-13. Hydrographs from the Aztec, New Mexico area including a well with continuous data recorder plotted with influences from precipitation, Animas River stage, and ditch gage height. Well AR-0007 is located on the south side of Aztec, is 32 feet deep, and is located on the east side of the river.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

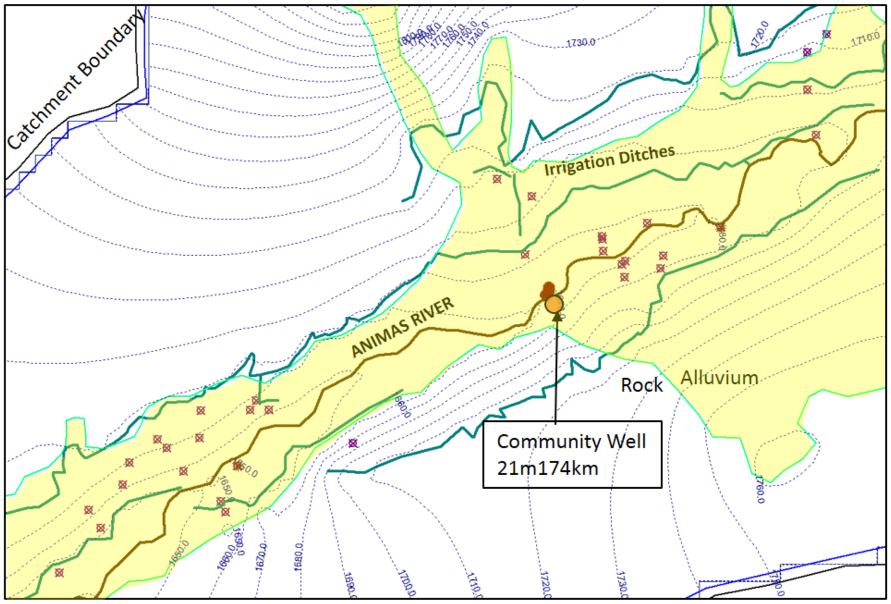
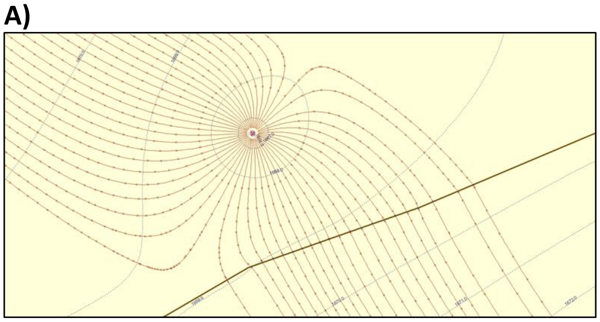
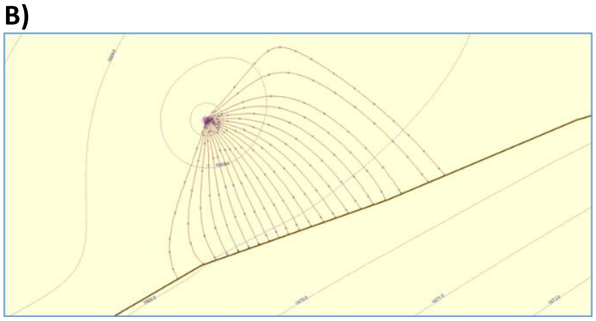


Figure 8-14. GFLOW model of groundwater-surface water interactions in the lower Animas River floodplain between Aztec and Farmington, New Mexico (RK 170-180) for the averaging period August to October 2015.

A)



B)



C)

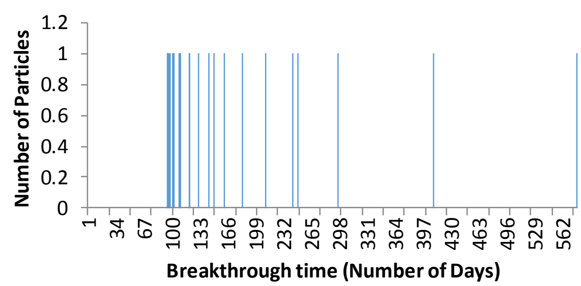


Figure 8-15. GFLOW capture zone and solute breakthrough histogram for lower Animas community well. GFLOW analysis of Lower Animas River community well (21m-174km), high pumping (Qw=817.6 m^3/d) and low porosity (n=0.25): A) capture zone delineation with 48 reverse streamlines; B) particle tracking with 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.

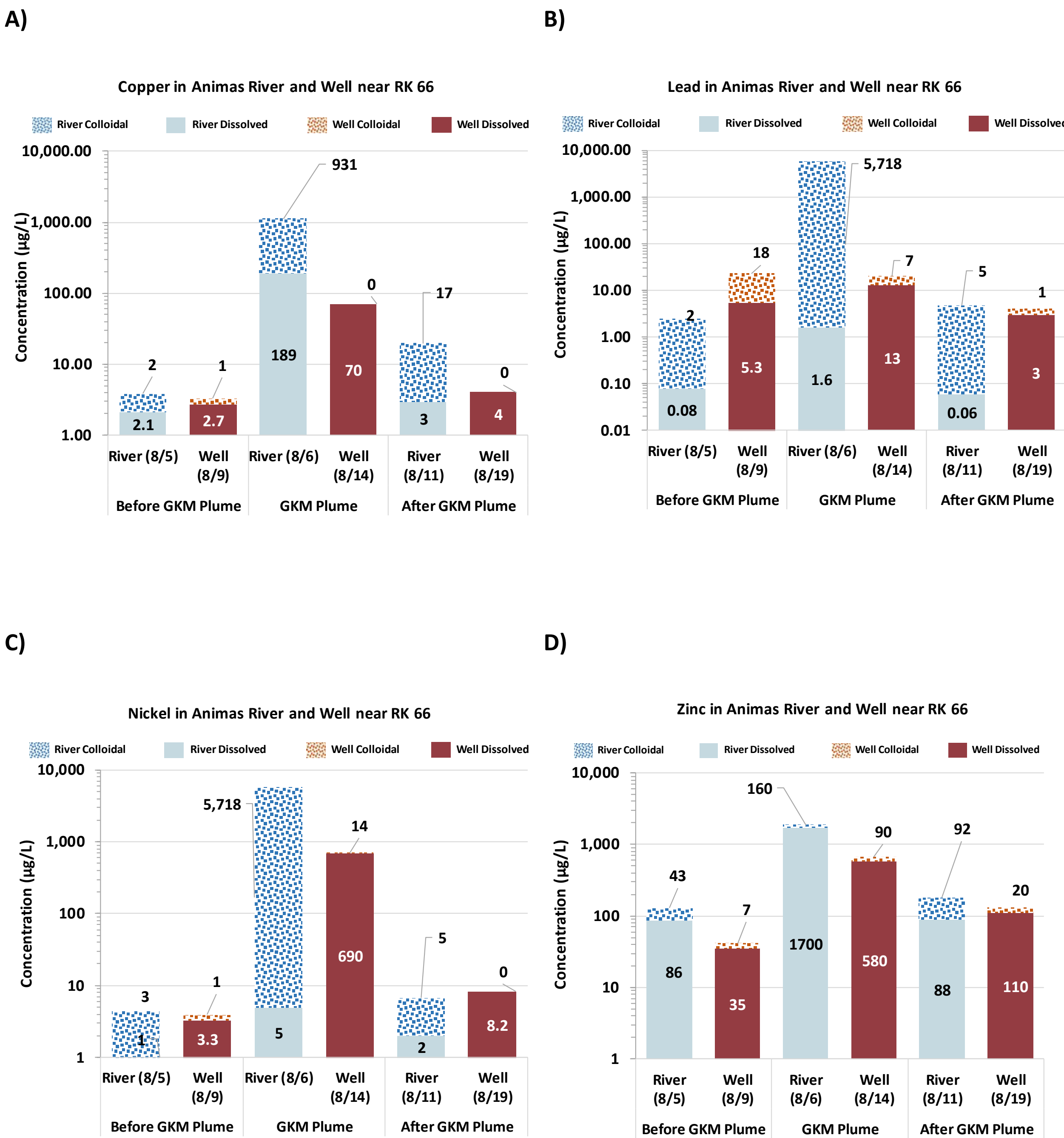


Figure 8-16. River and well dissolved and colloidal metals concentrations of A) copper, B) lead, C) nickel, and D) zinc around RK 66 of the mid-Animas River. The data are organized into before, during, and after plume time windows assuming the peak river plume passed the location on August 6 and a potential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

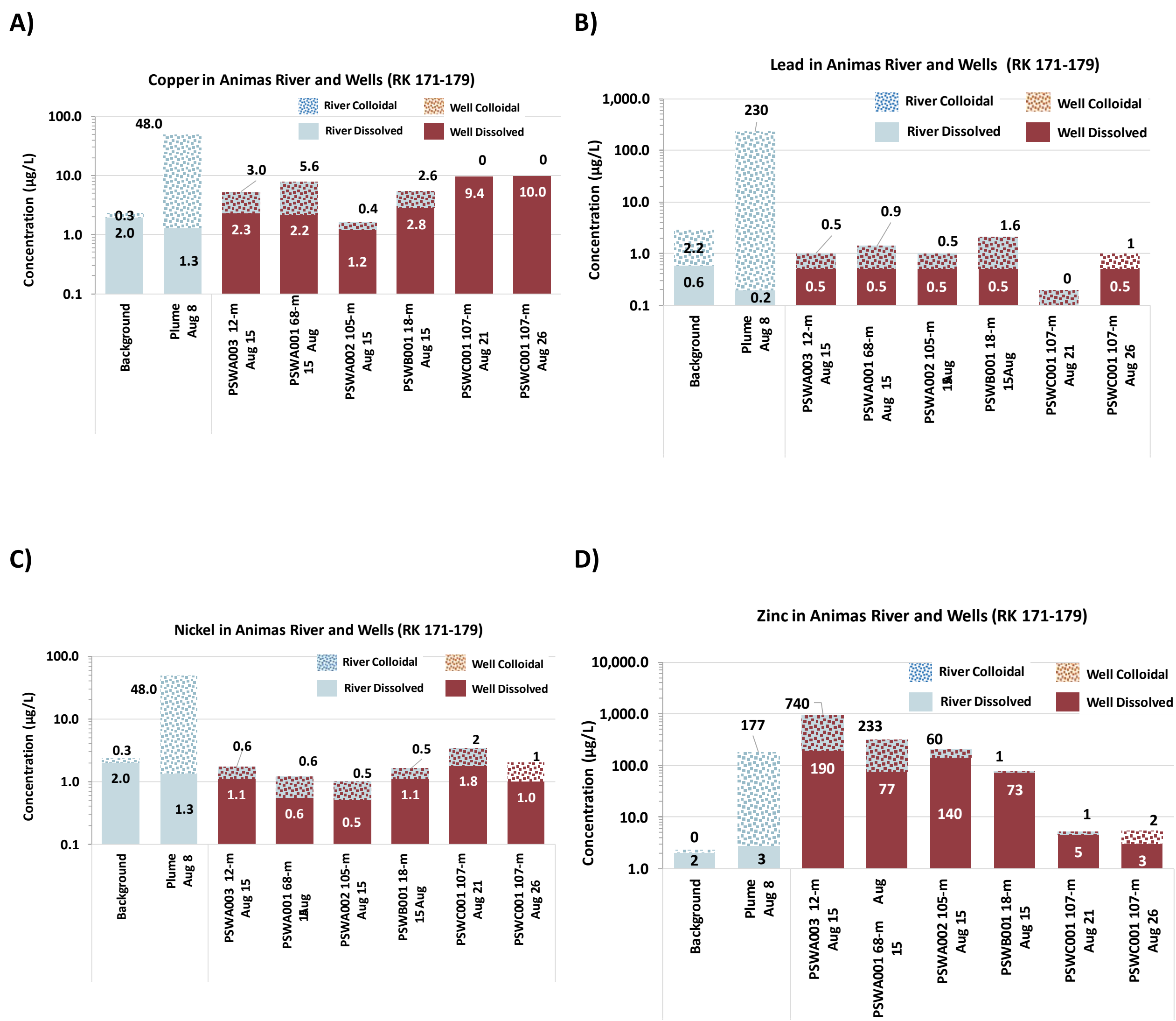


Figure 8-17. River and well dissolved and colloidal metals concentrations of A) copper, B) lead, C) nickel, and D) zinc around RK 171-179 of the lower Animas River in New Mexico.

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.

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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

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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

APPENDICES

Appendix D.

Groundwater Data and Methods

Contents

Overview

A groundwater analysis was conducted to investigate the potential for impact of the Gold King Mine (GKM) surface water release on downstream floodplain water supply wells. The accidental release of about 3 million gallons of acid mine drainage to Cement Creek above Silverton, Colorado, on August 5, 2015, resulted in a plume of dissolved and colloidal metals that flowed downstream to enter the Animas River near Silverton, Colorado, and joined with the San Juan River in New Mexico, continuing on through Utah before reaching the Lake Powell reservoir around August 12. At any point along the river, the measurable dissolved plume flowed past within 48 hours. The legacy of deposited colloidal and particulate metals remained in the bed sediment. There are hundreds of active pumping wells located in the floodplain deposits of these rivers, including community wells, and private irrigation and household wells. This investigation was limited to the wells in the Animas River floodplain of Colorado and New Mexico (See Figure D-1).

A) **B)**

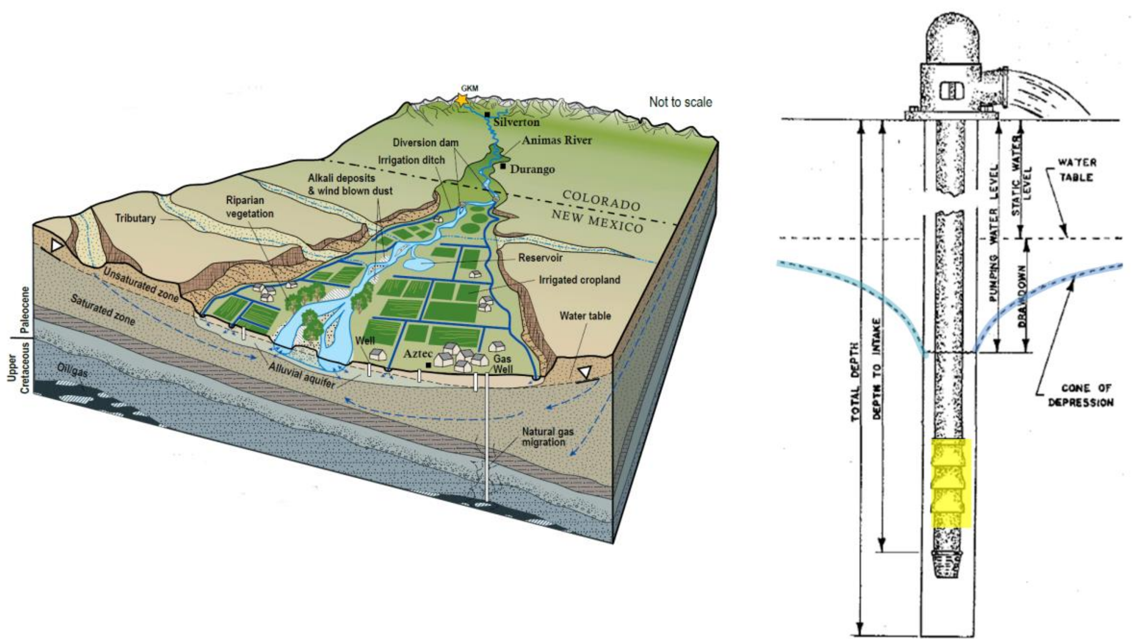


Figure D-1. A conceptual graphic of the floodplain aquifer of the Animas River and presence of water supply wells and irrigation ditches. A) The groundwater flow lines indicate that on a regional basis the river is gaining water from groundwater, but on a local basis, perhaps under the influence of pumping wells, the reach may switch to a losing condition. The New Mexico Bureau of Geology and Mineral Resources has a dedicated aquifer monitoring program. A synoptic survey of river and well water levels was conducted in August 2015, and January and March of 2016. After Timmons et al. (2016). B) A zoom-in engineering drawing of a typical community water supply well, showing influence of pumping from the screened interval on the water table resulting in a local cone of depression. After WestWater Associates (2010).

The definitive question the groundwater investigation addresses is: “Could drinking water or irrigation wells drawing from river alluvium become impacted from the chemicals associated with the GKM release?” (USEPA, 2016, pg. 70). This question may be broken up into three interrelated questions:

a) Which wells, if any, receive some of their water from the river?

   It is assumed that most of the time the Animas River is “gaining’’ water from the surrounding groundwater aquifer as it flows from Silverton, Colorado to Farmington, New Mexico, meaning that the floodplain is draining groundwater to the river. Under this scenario, dissolved contaminants present in the river flow would travel downstream and not enter subsurface groundwater and have an exposure pathway to the floodplain water supply wells.

   It would surprise few to find out that a high pumping well screened in the shallow permeable alluvium and located adjacent to the river receives some of its water directly from the river, even if that stretch of river is understood to be a gaining reach. But how far away would the well need to be to stop sourcing from river water? And at what pumping rate would the well not be able to locally reverse the regional groundwater gradient toward the river, and thus stop sourcing from river water? Are there scenarios in location and time where the Animas River loses water to the floodplain aquifer, and thus bring the exposure pathway into play? And what happens with well-to-groundwater interactions if the river reach is “losing” water to the aquifer? Does this bring low volume private pumping wells into play?

b) What are the travel times of water from the river to the sourcing wells?

c) What is the dilution in the sourcing well of possible contaminants received from the river?

In contrast to the highly visible and publically tracked surface water plume associated with the GKM release, the subsurface is hidden and, for this event, the empirical data are limited. The groundwater assessment is open to multiple lines of evidence, including insights gained from physics-based computer simulations that conform to field observations. Question [a] can be answered with capture zone analyses for the various wells. Question [b] can be answered by use of forward particle tracking starting at the river and ending in the well. Question [c] can be answered by tracing particles backward in time from the well, using a uniform distribution of particles around the well, and then comparing the number of path lines that reach the river to those that do not.

This Appendix details the data requirements and methodology for the capture zone analysis and particle tracking. First, the foundations of the geology for the study region are described, including the nature of the flood plain deposits that make up the alluvial aquifer of the Animas River. Second, a discussion is presented about the basis for computational model selection and the approach taken for this study. Third, the results of the capture zone and particle tracking investigations for the lower and mid Animas River water supply wells are presented.

The Appendix closes with an investigation of empirical evidence of river-to-well communication and possible GKM plume capture. Of the several community wells investigated, there was a single community pumping well located in the mid Animas River floodplain and only 35m from the river that had observed dissolved metals concentrations with the characteristics of a breakthrough of a river plume moving through the aquifer to the well within a plausible time window. The signal was not definitive since there were other dissolved metals that did not indicate a breakthrough. In other words, the hypothesis that this well experienced a river-to-well plume could not be rejected. Note the raw well water concentrations of the dissolved metals (i.e, pre-treatment and distribution) were significantly below human health advisory levels.

As a caveat, this study was limited to an investigation of the potential for impact. An investigation of the significance of impact would require a more detailed human exposure and drinking water risk assessment. For example, only assessment of raw well water was considered, and not the water quality post treatment and distribution (i.e., water at the tap). The analysis was limited to publically available data; no site-specific data were collected by the authors of this Report. And the groundwater assessment was limited to the dissolved constituents of the GKM plume and did not consider the deposited metals in the sediment, which could be a long-term source.

Background: Groundwater-surface water interactions in the Animas River floodplain deposits

The Animas River of Colorado and New Mexico is in dynamic communication with the permeable floodplain deposits, which contains a shallow aquifer that in some locations supports public community wells and private irrigation and household wells, among other water uses. See Figure D-2. The aquifers of interest are the “ribbon” floodplain deposits of the Animas River as it moves through the igneous/metamorphic rocks of the upper watershed, the sedimentary/sandstone-dominated middle area, and the shale-dominated lower area. The different geology has influence on the floodplain geomorphology and the shallow groundwater quality.

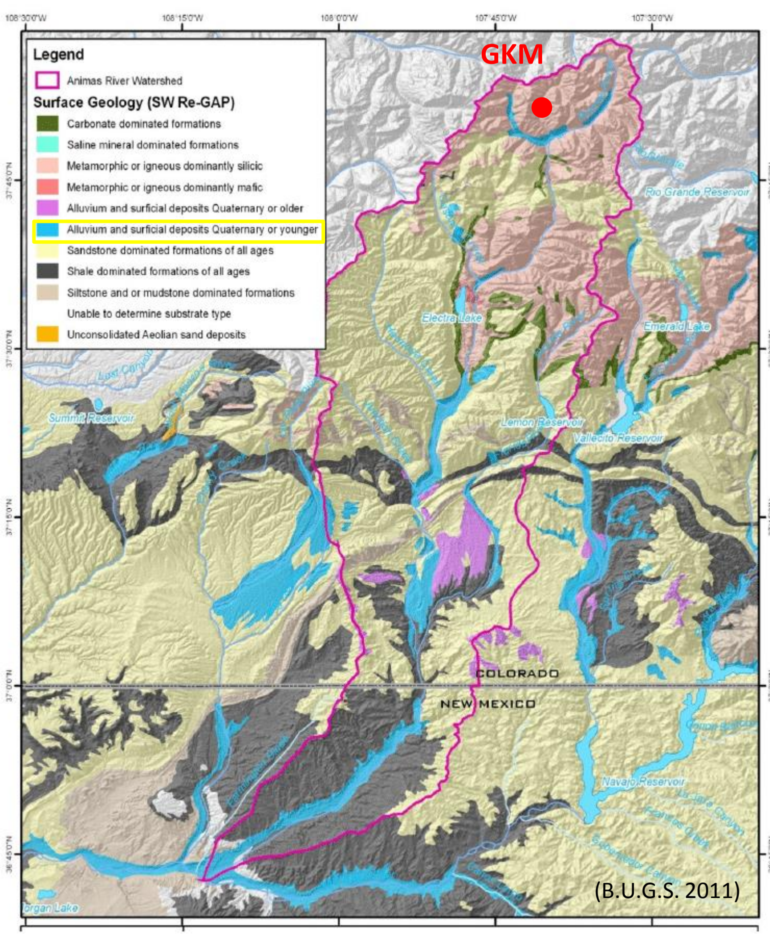


Figure D-2. Surficial geology of the Animas River watershed. The aqua blue designates the alluvial floodplain deposits. (B.U.G.S., 2011). Gold King Mine is in the far northern headwaters of the watershed. Broadly, the Animas River runs over three distinct geology zones: (1) the upper Animas and igneous/metamorphic rocks; (2) the mid Animas and the sandstones; and (3) the lower Animas and the shales. These distinct geology zones have influence on stream geomorphology and floodplain deposit water quality.

The Animas River floodplain of Colorado and New Mexico and the aquifer beneath is tapped by a large number of water supply wells and irrigation ditches. While the river is predominately a gaining stream on a regional basis, there are some times and locations where a river reach may be losing water to the shallow groundwater system (Timmons et al., 2016). This Appendix will examine multiple lines of evidence for groundwater-surface water interactions, including a water flow balance investigation, and a high resolution water elevation investigation.

A Water Flow Balance Investigation for the Upper Animas River

The Animas River discharge reflects the annual cycle of late spring to early summer snowmelt runoff, with subsequent decreases in discharge, interrupted by infrequent rain events. This is demonstrated for the upper Animas River near Silverton, Colorado (See Figures D-3 and D-4A). The cluster of U. S. Geological Survey (USGS) streamflow gages near Silverton allows a flow balance analysis to be conducted:

$$Q_{A@S} + Q_{C@S} + Q_{M@S} + Q_{GW} = Q_{AbS} \quad (1)$$

or

$$Q_{GW} = Q_{AbS} - Q_{A@S} - Q_{C@S} - Q_{M@S} \quad (2)$$

where USGS gages include the Animas River below Silverton (Q_{AbS}), Animas River at Silverton ($Q_{A@S}$), Cement Creek at Silverton ($Q_{C@S}$), Mineral Creek at Silverton ($Q_{M@S}$). The difference between the sum of the cumulative tributary stream flows upstream and the measured streamflow downstream is inferred to be made up of contributing diffuse groundwater inflow (Q_{GW}) along the Animas River between the upgradient and downgradient stations. The Animas River around Silverton is understood to be a gaining stream much of the time, with groundwater draining toward the river, with some episodic exceptions during high river stage, such as annually during late-spring early-summer snowmelt, or during high rain events, as shown in Figure D-4B.

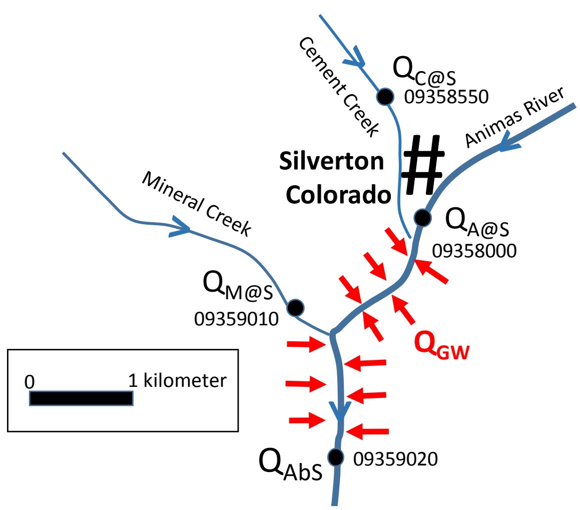


Figure D-3. Conceptual representation of the Upper Animas River discharges measured by the US Geological Survey and diffuse groundwater discharge near Silverton, Colorado. USGS gages include Animas River below Silverton (Q_{AbS}), Animas River at Silverton ($Q_{A@S}$), Cement Creek at Silverton ($Q_{C@S}$), Mineral Creek at Silverton ($Q_{M@S}$). The inferred averaged groundwater contribution to the outlet flow (Q_{GW}) includes diffuse subsurface flows and discrete spring flows as shown in red.

A)

B)

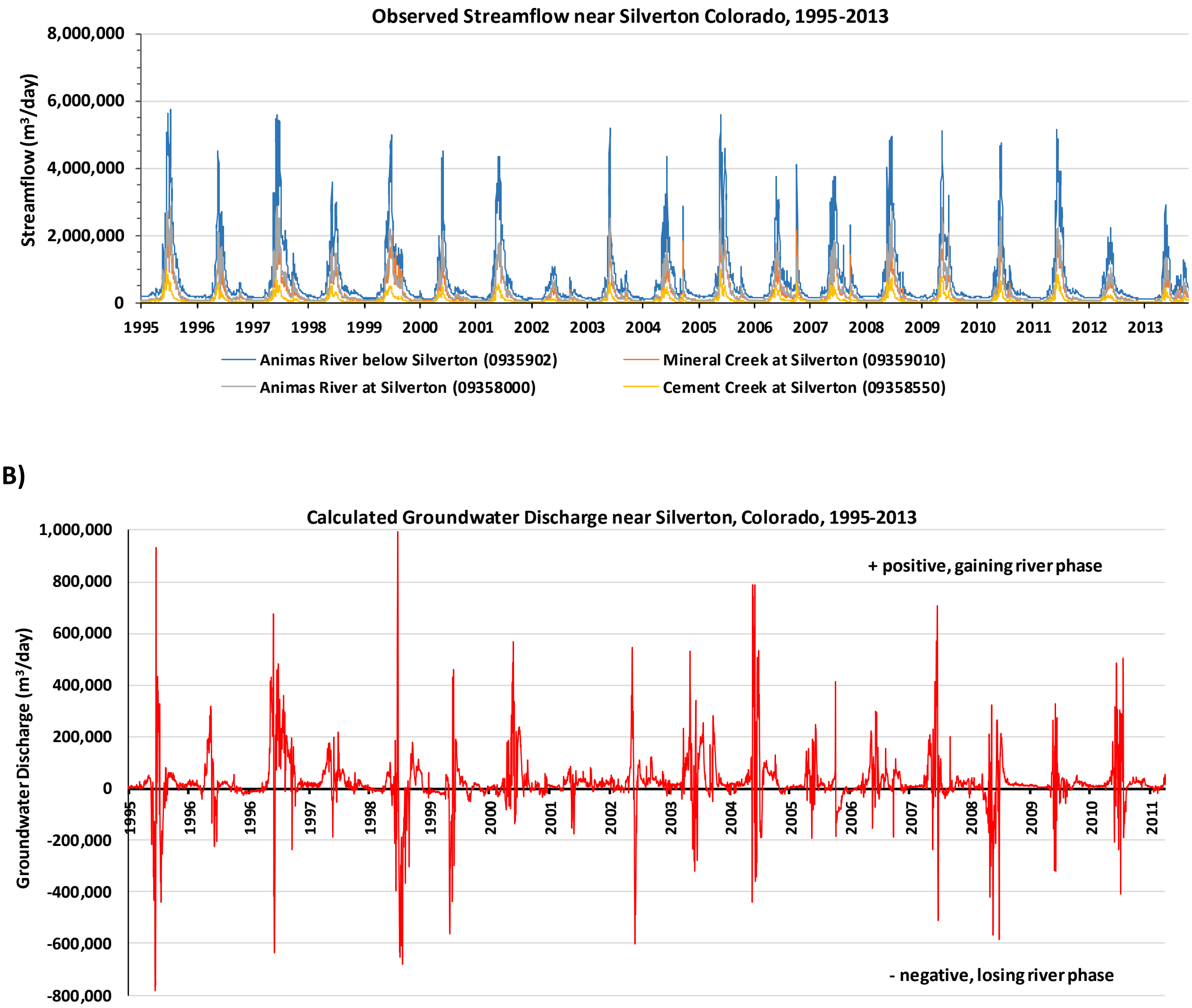
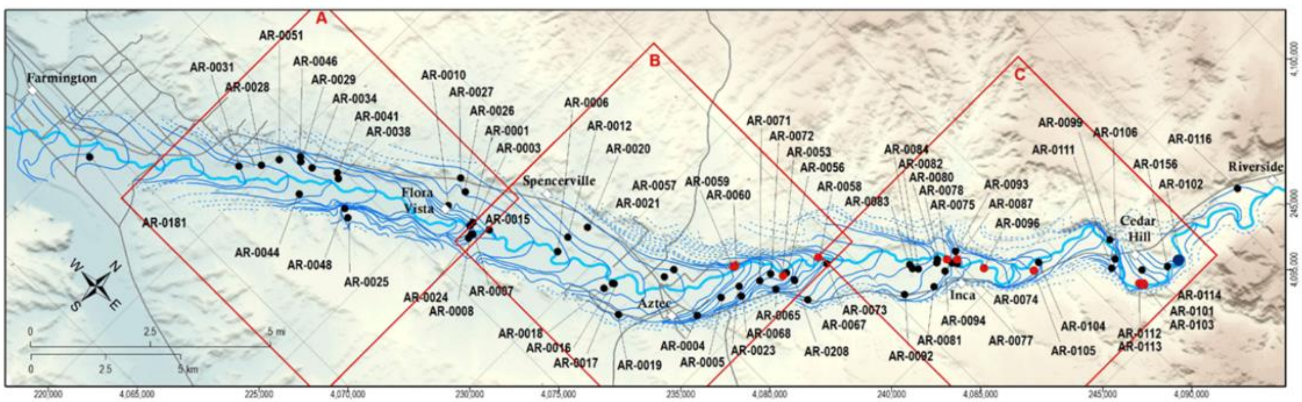


Figure D-4. Streamflow analysis of the upper Animas River near Silverton, Colorado, 1995-2013. A) Streamflow hydrographs of measured discharge in cubic meters per day of the Animas River and tributaries near Silverton, Colorado. B) Inferred groundwater inflows along the section of the Animas River around Silverton, Colorado. The positive inflow implies that the Animas River is gaining groundwater. The negative exceptions suggest the river losing flow to the alluvial groundwater system.

Church *et al.* (2007, Chapter E9, pg. 488) applied a tracer-dilution method in the Cement Creek watershed and suggest that up to 21% of streamflow can be related to diffuse subsurface flow discharging to the stream; the rest comes from discrete mine effluent, springs, and tributaries.

High Resolution Water Levels Investigation for the Lower Animas River

An investigation has begun of the potential for groundwater-surface water interactions in the lower Animas River between Riverside and Farmington, New Mexico. Timmons et al. (2016) of the New Mexico Bureau of Geology and Mining Resources (NMBGMR) are conducting a monitoring program supported by high-resolution land surface elevation mapping using LiDAR data, verified locations of the sampled wells using hand-held GPS, and surveying of well water levels. The January 2016 data represents the water table under "baseflow" conditions and not under the influence of mountain snowmelt runoff or irrigation ditches. There are a number of wells indicating the lower Animas River is losing water between Riverside and Farmington, New Mexico (See Figure D-5). The negative hydraulic head gradient would suggest that, in these sections, the Animas River is losing water to the aquifer during the January time period. Most of the potential losing reaches are in the northern half of the study region. The sporadic spatial distribution of the potential losing reaches underscores the site-specific nature of the phenomenon. The NMBGMR also monitored the August 2015 and March 2016 time periods.



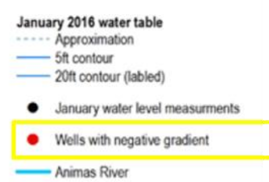


Figure D-5. High-resolution survey of river and well water elevations in the lower Animas River. Based on high-resolution synoptic mapping of well water levels and river water levels during "baseflow" conditions of January 2016. Hand-held GPS used for geo-referencing well locations. LiDAR DEM used for estimation of land surface elevation. The wells with negative gradient shown in red. Note their more likely presence in the northern half of the study area, and the sporadic distribution.

Under the conditions where the Animas River is a gaining stream, a nearby pumping well would need to overcome the hydraulic head gradient in order to directly source river water, and if the river was transporting a plume of dissolved metals, this establishes a potential exposure pathway. The wells at risk would tend to be the community wells located in proximity to the river and that pump larger volumes of water. Under the conditions where the Animas River is a losing river, the 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 the domestic or household wells. The groundwater modeling investigation was chosen to further the understanding of these potential exposure pathways for two areas: (1) mid Animas River; and (2) lower Animas River (Figure D-6) and this is described in the next section.

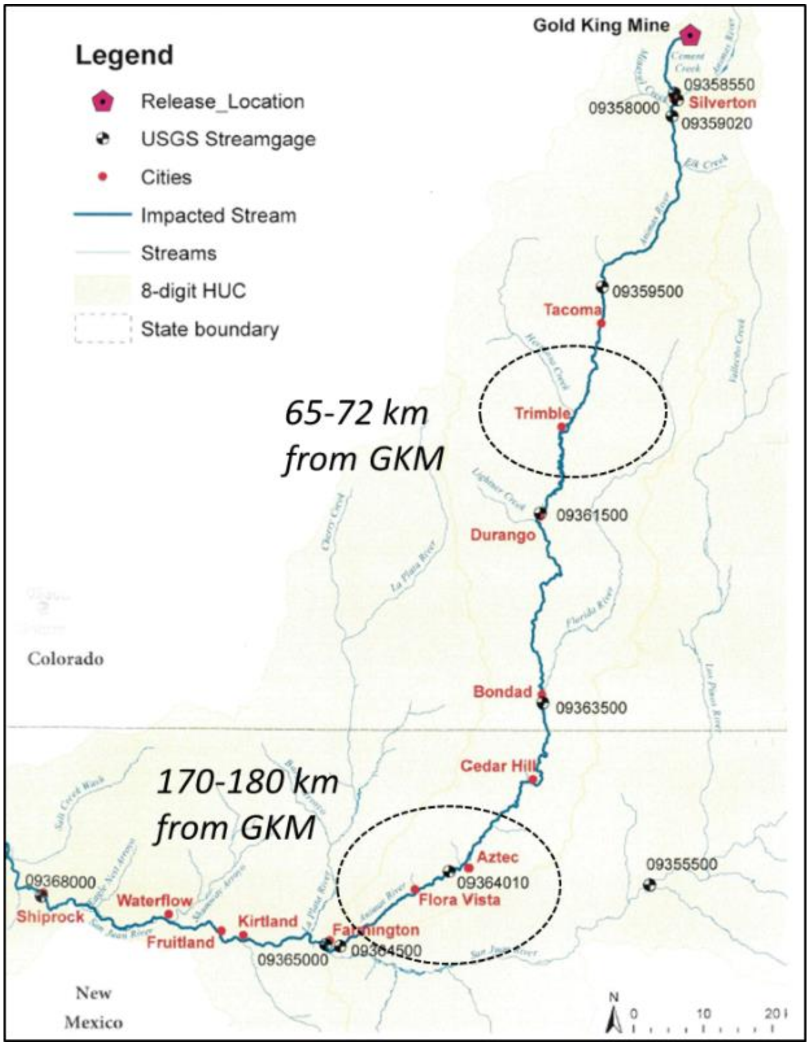


Figure D-6. The mid Animas and lower Animas River clusters of community and private wells selected for groundwater modeling analyses. (1) the mid Animas River area between Tacoma and Durango, Colorado, 65-72 km downstream of the GKM release site; and (2) the lower Animas River area between Aztec and Farmington, New Mexico, 170-180 km downstream of GKM.

Groundwater Modeling Approach

The groundwater impact investigation used a step-wise and progressive computational modeling approach incorporating hand calculation, empirical and spreadsheet analyses, and mechanistic groundwater simulations using analytic element and finite difference methods.

Analytic element modeling is especially well suited for the progression from simple to more complex representations of the geohydrologic system in order to test understanding. A suite of simple models with few measurable parameters is often preferred over a multi-parameter model that could better fit the data, at least for groundwater flow problems (Kelson et al. 2002). Simple models are used within a deterministic approach in this GKM investigation; a stochastic approach would require more field data than are available. The theoretical foundations of the analytic element method are documented in Strack and Haitjema (1981a, 1981b) and Strack (1989). The practical application of the analytic element method is covered in Haitjema

(1995). A community of practice web page includes a survey of analytic element models (www.analyticelements.org).

While especially suitable for groundwater flow modeling at different scales, analytic element modeling does have some limitations. For instance, both transient flow and three-dimensional flow are only partially available. While an analytic element model can represent macro-scale heterogeneities (e.g., the difference in hydraulic conductivity associated with alluvium and hard-rock aquifers) in a piece-wise manner, the models do not currently represent gradually varying aquifer properties. Numerical methods for computational groundwater simulation, including finite element and finite difference methods, are better positioned for more complex conceptual model representation (e.g., transient flow, fully 3D flow, spatially discretized aquifer properties). Fitts (2012) offers a review and comparison of analytic element and numerical modeling techniques in the context of groundwater geology applications, including subsurface solute and contaminant transport. What follows is a discussion of the specific computational models selected for this study.

GFLOW Groundwater Model

The analytic element computer program GFLOW (v.2.2.2) was used in this project to solve for regional and steady groundwater flow in single-layer aquifers (Haitjema 1995). GFLOW 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 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.

GFLOW solves the regional steady-state groundwater flow equations using the analytic element method (Haitjema 1995; Strack 1989) based on the principle of superposition of elements where line-sink elements represent streams, point-sink elements represent wells, line-doublet polygon elements represent discontinuities of aquifer properties (e.g., hydraulic conductivity, base elevation, and no-flow boundaries), and area elements represent aquifer recharge. The model domain is unbounded making solutions flexible in scale, from regional to local, and vice versa. Boundary conditions corresponding with physical features are superimposed, putting more detailed representations in the nearfield and coarser representations in the far field. The separated influences of these elements on the regional flow field are shown in Figure D-7.

The areas of interest for GFLOW models in this project ranged in scale from full “ground watershed” aligned with the surface watershed down to an individual pumping well. Theoretically, analytic element solutions are spatially infinite, and good modeling practice typically represents both a far field, with coarse representation of elements and geohydrologic features, and a near field at higher resolution.

In GFLOW, to create a bounded flow solution assigned to a topographically defined surface watershed, a closed string of no-flow line elements is placed on the perimeter of the surface watershed. Even though the static no-flow boundary is an artificial one (i.e., not actually occurring in the natural system), the setup is justified in geohydrologic systems where the shape of the shallow water table tends to follow the shape of the surface topography, permitting the assumption that groundwater fluxes in and out of this boundary are insignificant. Also, the base of the single-layer aquifers is assumed to be horizontal and to constitute a no-flow boundary and, indeed, it is assumed that deep leakage is minimal. GFLOW can represent flow in the aquifer as either unconfined or confined, or both. The bounded solution setup simplifies the calibration of a water balance associated with a surface watershed in the mountain terrain.

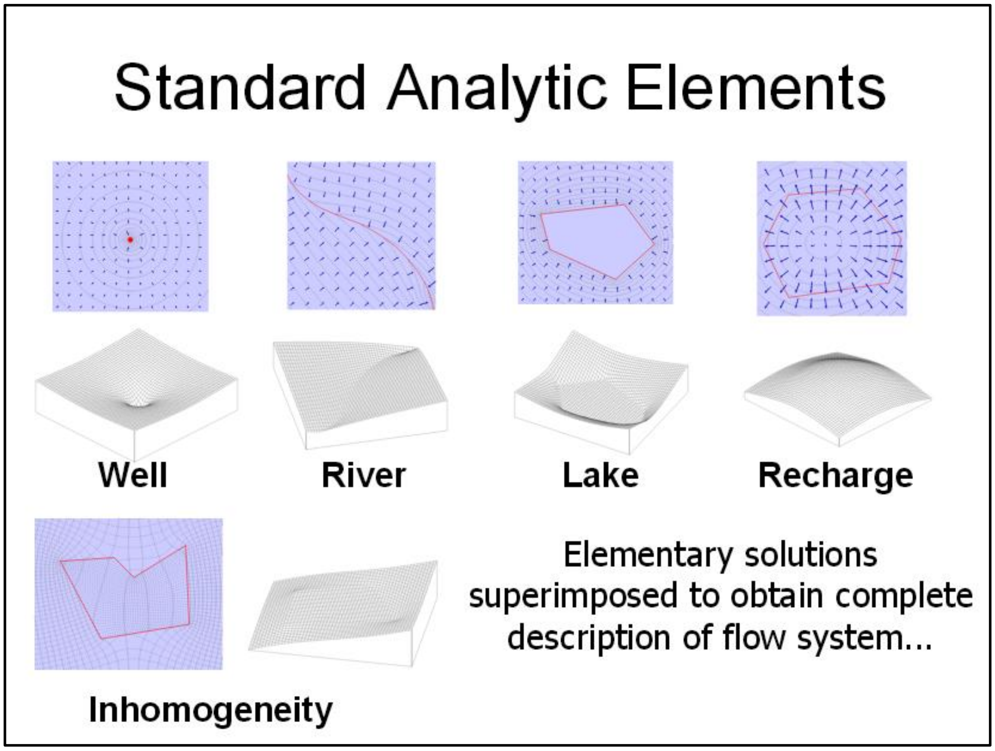


Figure D-7. Analytic elements: elementary mathematical points, lines, and polygons and associated landscape features. The suite of standard analytic elements available for superposition in the model domain to create a site specific model. The influence of the element on the hydraulic head contours and gridded water table surface and the velocity vectors is shown (Source: Craig 2014).

Shallow groundwater flow systems are often intimately linked with surface drainage. The perennial stream network is understood to be flowing year round. In contrast, the ephemeral stream network is dry most of the year, only flowing during intense rainfall events and contributing to rapid surface runoff. The intermittent stream network is understood to be supported by shallow drainage of the unsaturated soil horizon. For a stream to be flowing when it has not rained for many days, the source of the river water is subsurface groundwater drainage, also called baseflow. The distinction on the landscape of perennial, intermittent, and ephemeral flow is dynamic and dependent on antecedent soil moisture conditions.

An output of the GFLOW regional groundwater model is a continuous surface representing piezometric head, or groundwater flow potential. This surface of heads is the same as the water table surface for unconfined aquifers such as in the Animas River alluvium. The model-predicted elevation of the water table depends on the aquifer recharge rate and the aquifer transmissivity (i.e., hydraulic conductivity times aquifer thickness). Assuming a constant transmissivity, the higher the recharge rate, the higher the model-predicted elevation of the water table. Conversely, assuming a higher recharge rate, the higher the aquifer transmissivity, the lower the model-predicted water table will be. Once the recharge rate is known after conducting baseflow analysis, the model can be calibrated to "fit" the observed water table elevations at points by varying the aquifer transmissivity, and monitoring the model-predicted water table at monitoring wells where the water table elevation is measured.

In summary, the two calibration targets, baseflow at the watershed outlet and observed elevations of the water table in unconfined aquifers, allow for the parameterization of the average recharge and transmissivity of the regional steady state aquifer flow system equations in the GFLOW model.

GMS-MODFLOW

Sometimes, conceptual complexity, particularly at the local scale, suggests numerical modeling techniques. The USGS MODFLOW model is the most widely used groundwater flow model in the world. MODFLOW uses the finite difference numerical solution technique, with grid-based rows and columns, cells, multi-layer aquifer, non-horizontal base elevations, hydraulic conductivity, porosity and storativity can vary by cell (Harbaugh 2005; See Figure D-8). MODFLOW has undergone 30 years of development and quality testing by USGS.

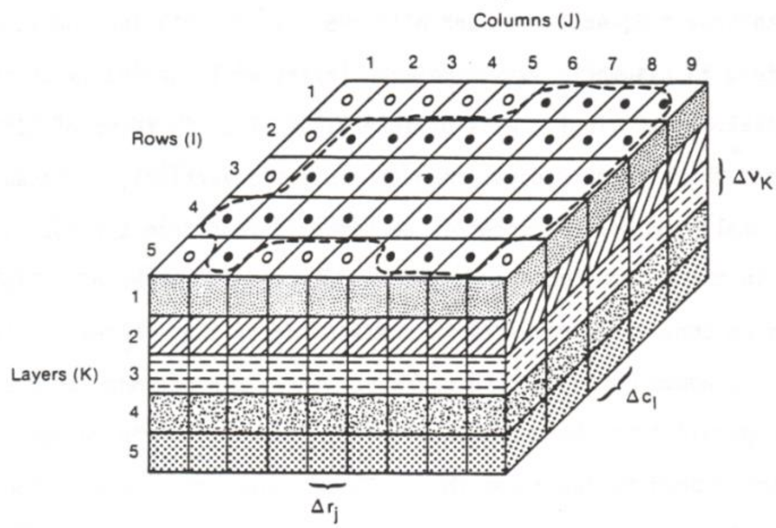


Figure D-8. The finite difference solution in MODFLOW solves for groundwater flow between cells as defined by rows, columns, and layers. The aquifer boundary (often a no-flow boundary) is shown as a dashed outline.

For this project, the EPA team used the MODFLOW-NWT and MODPATH (particle tracking) solvers within the Groundwater Modeling System (Aquaveo, GMS v 10.1). GMS includes standard MODFLOW example run files to confirm proper model installation. In addition to facilitating a standard cell-based interface to the MODFLOW finite difference grid, GMS includes a geohydrological conceptual design environment much like GFLOW.

AnAqSim Groundwater Model

The AnAqSim (release 3, 29 Sept 2016; www.fittsgeosolutions.com) groundwater modeling system invokes hybrid semi-analytic and numerical solution techniques. It uses subdomain analytic element models as described in Fitts (2010), which 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.

AnAqSim uses one separate two-dimensional model for each subdomain. In each subdomain model, the resistance to vertical flow is neglected and the head is independent of elevation within the subdomain (Dupuit assumption). Resistance to vertical flow and three-dimensional flow are modeled by using multiple levels with vertical leakage between levels. The simplest model would be one level (i.e., two-dimensional), and only one subdomain (i.e., homogeneous). A plan view of such a simple model is show in Figure D-9.

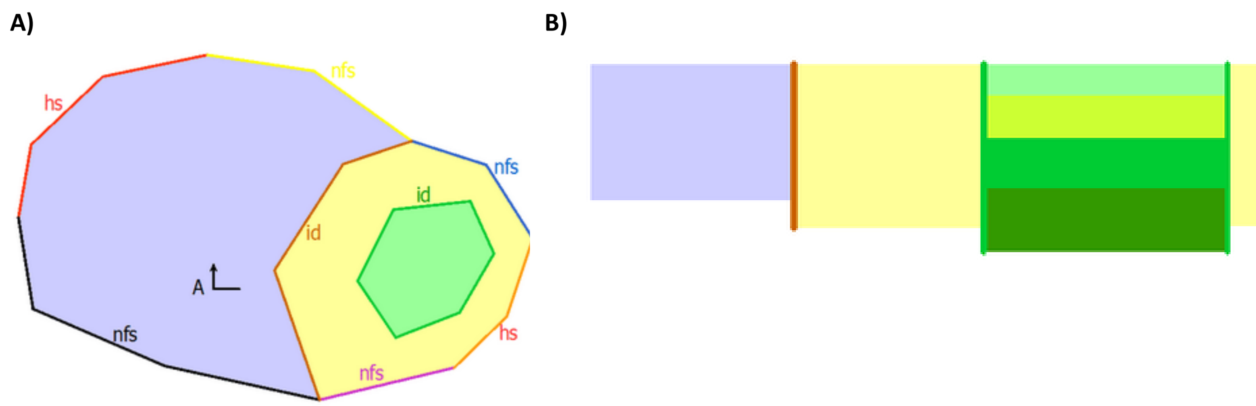


Figure D-9. Simple hypothetical AnAqSim model. A) Plan view showing domains and boundaries (head specified (hs), normal flux specified (nfs); internal domain (id). B) Cross-sectional view A-A' showing layers within domains.

Stepwise Progressive Approach

The stepwise and progressive groundwater modeling approach is not new (Sullivan et al., 2015, Appendix C; also http://www.haitjema.com). Ward et al. (1987) applied what they called a telescopic mesh refinement (TMR) computational groundwater modeling approach to the Chem-Dyne hazardous waste site in southwestern Ohio. They used three different finite differences numerical computer models for the three different scales at which they were modeling. Conditions on the grid boundary of the local scale were obtained from the regional-scale modeling results, while, similarly, the conditions on the grid boundary of the site scale were obtained from the local-scale modeling results. In contrast, the analytic element method for computational groundwater modeling allows these different scales to be treated within the same model by locally refining the input data, thus avoiding transfer of conditions along artificial boundaries from one model into the other. The step-wise progressive groundwater modeling approach taken for this study starts with regional scale analytic element modeling with GFLOW and progresses to local scale finite difference modeling with MODFLOW and local scale hybrid modeling with AnAqSim, as understanding and data justify.

The step-wise progressive groundwater modeling approach puts the emphasis on testing conceptual understanding, and less focus on site-specific prediction. The modeling steps for this study included: (1) building the regional scale model including the far-field hydrogeologic boundary conditions; (2) testing the model performance with field observations of streamflow and water levels in wells as part of the calibration/harmonization process; (3) zooming down within the regional model to include local refinement of the conceptual model around the pumping well, such as aquifer heterogeneities, three-dimensional flow, transient responses; (4) another round of testing the model performance with field observations, such as pumping test data; and (5) repeating the modeling process by returning insights to the regional scale, and so on. Ideally, the modeling stops when the degree of hydrogeological and numerical complexity is sufficient that adding more detail does not change the essence of the model simulation, and impact the answer to the study questions.

The GFLOW model was used for the initial regional-scale and local-scale modeling of steady state flow. The regional models provide initial boundary conditions for local scale transient and full 3D modeling using MODFLOW, and local scale aquifer heterogeneity, including anisotropy, using AnAqSim (See Table D-1). The implications of the various levels of complexity are discussed in the next sections.

Table D-1. Conceptual Complexity and Groundwater Model Selection

	Spatial Scale	Conceptual Complexity	GFLOW	MODFLOW	AnAqSim
	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			☑
	Both	Particle tracking (reverse – capture zones; forward – breakthrough response)	☑	☑	☑

Dupuit-Forchheimer Flow

The analytic element models used in this project fall in the class of codes that solve "two-dimensional flow in the horizontal plane," at least that is how these types of models are routinely referenced (USEPA, 2016, pg.71). This is misleading terminology. GFLOW is a *Dupuit-Forhheimer model* (DF model*)*, which is a model in which resistance to vertical flow is being ignored, thus not vertical flow itself (Strack, 1984). While the underlying partial differential equation in GFLOW involves only the horizontal coordinates (x and y), flow into the vertical direction can and is being approximated using conservation of mass considerations. Consequently, path lines in GFLOW are being traced in three dimensions.

The DF models offer a better approximation to actual three-dimensional flow systems in aquifers that are rather thin when compared to their lateral extent. In practice, this translates into groundwater flow systems in which the distances *L* between boundary conditions (e.g., distance of the well from the river) is larger than five times the aquifer thickness. This is for isotropic aquifers. In case the aquifer is anisotropic, with a lower vertical hydraulic conductivity than the horizontal conductivity, the following criterion may be used (Haitjema 2006):

$$L \geq 5H\sqrt{k_h / k_v} \qquad (3)$$

Where H is the aquifer thickness, k_v is the vertical hydraulic conductivity, and k_h is the horizontal conductivity. For example, consider a well which is 35 horizontal meters from the river with a well screen that is about 25 meters below river. If Kh/Kv = 10 (Note: ratios of 5 to 50 are common), the vertical distance in an equivalent isotropic medium would be about 80 meters vertical distance (i.e., scale the vertical axis by the square root of Kh/Kv to make an equivalent isotropic medium). In this case, the vertical resistance between river and well screen would likely be greater than the horizontal resistance. Neglecting the vertical resistance in the GFLOW model overestimates the communication between well and river, and underestimates the travel time for flow from river to well (USEPA, 2016, pg. 81). The condition in the displayed formula above is not meant for wells that are relatively close to the Animas River, and unfortunately these are the wells of most interest (most likely to receive river water).

What is the consequence of violating the Dupuit-Forchheimer (DF) criterion for wells near the river? In reality the well-river interaction is influenced by possible bottom resistance to flow between the river and the aquifer, as well as resistance to vertical flow inside the aquifer. Neither is included in the model presented, although bottom resistance could have been applied. By not including any of these resistances, the flow potential for drawing water from the river that flows into the well is *overestimated*. In other words, the model as constructed *is conservative* with respect to the objectives of this study (USEPA, 2016, pg 81). Computer simulations of capture zones including full 3D flow from MODFLOW are compared to DF capture zones using GFLOW later in this Appendix.

Single Homogeneous Aquifer with Horizontal Base

GFLOW represents the alluvium near the Animas River as a single homogenous aquifer, which means that it lumps the various depositional layers in the alluvium into a single homogenous layer. Furthermore, it assumes a horizontal aquifer base below which no flow is considered. The question is how these simplifications affect the modeling results. Specifically, what effect does this simplification have on the potential well-river interaction? (U.S. EPA, 2016, pg. 73)

There is not much known about the alluvial aquifer in terms of spatial heterogeneity and depth. The actual aquifer base at a specific location is unknown, but a geophysical survey gives some insight.

The Animas Water Company invested in a geophysical/gravimetric survey of the floodplain aquifer of the mid Animas River watershed near Hermosa, getting estimates of the base of the aquifer in five survey lines (or cross-sections). The permeable deposits are much deeper (i.e., 600 to 1000 feet) than the current depth of the community wells in this area (i.e., approximately 100 feet; See Figure D-10).

The geophysical survey offered depths based on a two-layer model and three-layer model. The selection of the depths associated with the two-layer model most likely lead to an underestimation of the aquifer thickness. This is does not affect the flow regime much since the range of transmissivity in the model does not depend on this assumption because it has been constrained by pump test data. Assuming for a moment that the transmissivity is accurate. or reasonable, an underestimation of the aquifer thickness will result in an overestimation of the hydraulic conductivity, since the product of the two is the known transmissivity. So while the discharge rates in the aquifer, including the flow component from the river if present, are not affected (See Question [a]), the specific discharges and associated average groundwater flow velocities are. An underestimation of the aquifer thickness will result in an underestimation of the groundwater travel times (question [b]). This is *conservative* in view of the model objective since actual arrival of contaminants may be later than predicted by the model.

The actual aquifer heterogeneity offers the potential for preferential pathways from the river to the 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 (See Figure D-11).

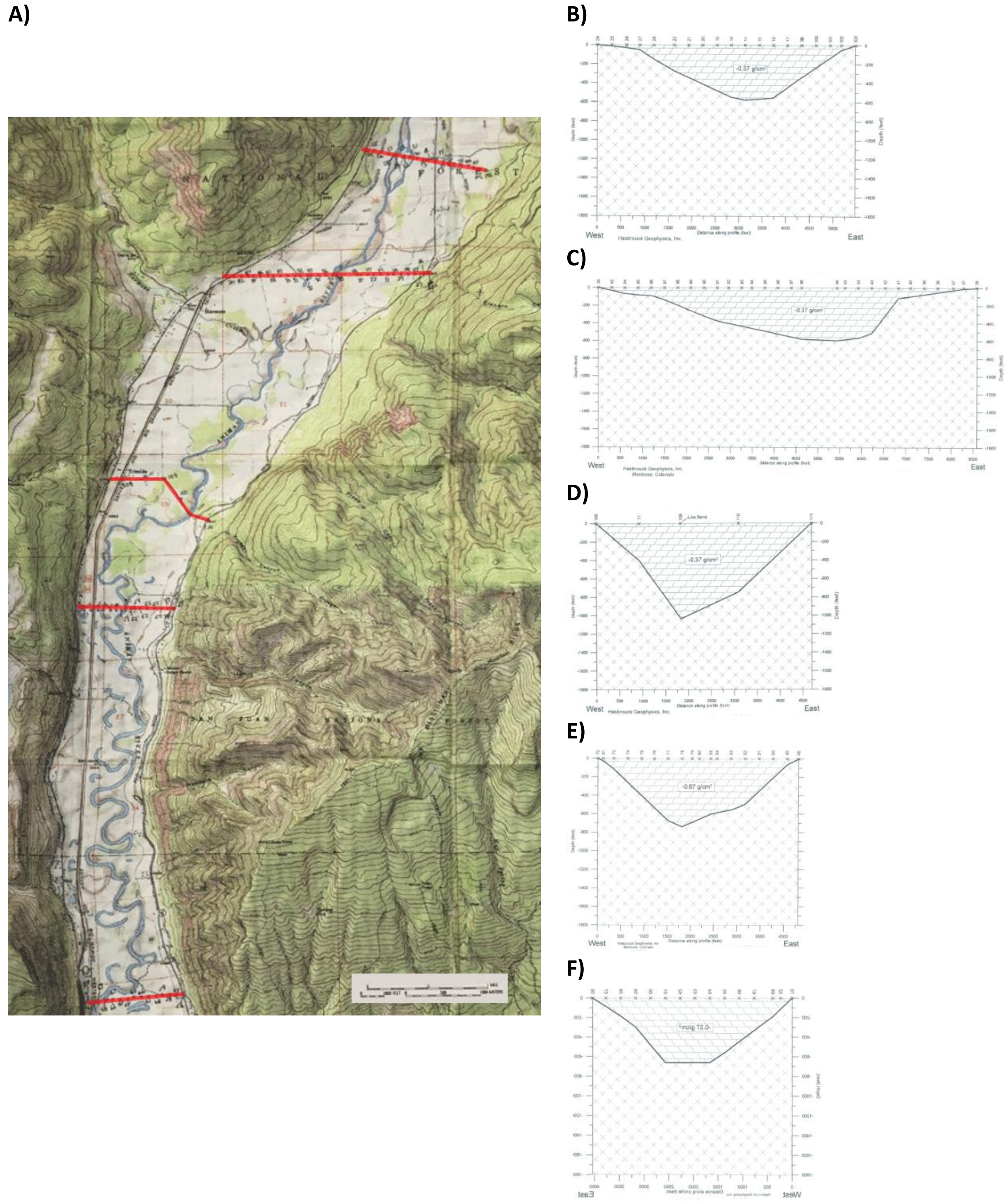


Figure D-10. Geophysics modeling of the shallow floodplain aquifer base elevation based on a gravity survey. (a) map of the five gravity survey lines; (b) line 1 gravity and depth profile – 2-layer model; (c) line 2; (d) line 5; (e) line 3; and (f) line 4. The model suggests the depth of the aquifer ranges from 600 ft to 1000 ft. Data source: Hasbrouk Geophysics, 2003.

A)

B)

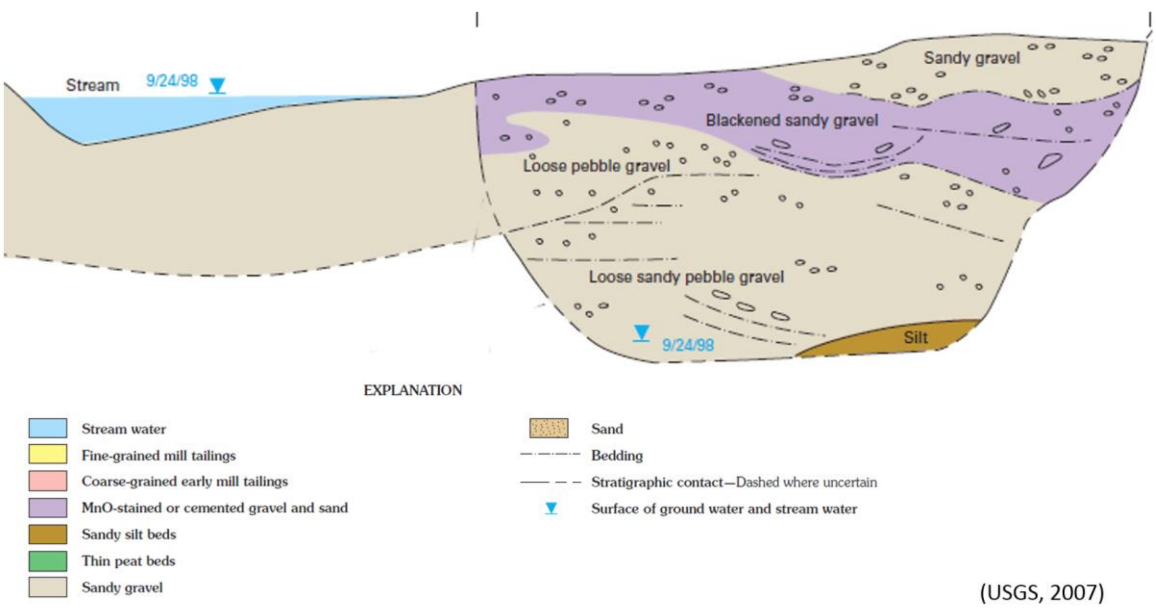


Figure D-11. Animas River in floodplain near Eureka above Silverton, Colorado. A) Google Earth image showing the braided dry channels and the location of the geologic cross section. B) Generalized geologic cross section of the shallow floodplain deposits of the Animas River above Silverton (Vincent, Elliott, 2007). The shallow stratifications include pebble and sandy gravels.

The GFLOW model assumes a homogeneous aquifer that lacks preferential flow. Consequently, the assumption of homogeneity is not conservative in view of the model objectives. Preferential pathways would shorten the travel times from the river to the well (See Question [b]). While a multi-layer model could be able to capture this effect to some degree, such as AnAqSim, data on aquifer stratification near the study wells or between the wells and the river are absent.

Preferential flow may well outweigh the effect of the aquifer thickness on the groundwater velocities. This will enter into the discussions regarding the empirical evidence of river-to-well communication at the end of this appendix.

Steady-state flow

The GFLOW simulates steady state flow, ignoring water that may go into storage or is released from storage due to temporal changes in the water table (i.e., unconfined flow) or head (i.e., confined flow). For the purpose of capture zone delineation in the context of wellhead protection, a steady state model is considered adequate (USEPA, 2016, pg 75). In fact, producing capture zones that change over time seems impractical for the purpose of managing wellhead protection areas. However, replacing the actual transient flow system by a steady state, one raises the question what the steady state model actually represents. Haitjema (1995, 2006), using a study by Townley (1995), presents a dimensionless response time, τ:

$$\boldsymbol{\tau = \frac{SL^2}{4TP}} \qquad (4)$$

where *S* [-] is the aquifer storage coefficient, *L* [m] the distance between head specified boundaries, *T* [m^2/day] the aquifer transmissivity (i.e., the product of aquifer thickness and hydraulic conductivity), and *P* [*days*] the period of a periodic forcing function. When considering seasonal variations in flow in the alluvial aquifer, the definition of *L* can be more conveniently defined as the distance between the river and the valley boundary (e.g., rock outcrop). Haitjema (2006) offers the following rules of thumb:

$\tau < 0.1$ treat transient flow in the aquifer as successive steady state.

$0.1 \leq \tau \leq 1$ transient flow cannot be meaningfully represented by a steady state model.

$\tau > 1$ represent transient flow by a steady state model using average boundary conditions.

These guidelines are approximate in that values just below 0.1 or just above 1 are to be considered transitional from the aquifer responding relatively quickly or slowly to transient forcing, respectively.

A periodicity of *P*=365 days is appropriate to assess the response of the flow system to seasonal variations in recharge (e.g., inflow into the aquifer near the rock outcrop) and seasonal variations in river stages; it is not suitable to assess the response of the flow system to short term variations in pumping and short-term variations in river stage (e.g., storm surges). For that purpose, a periodicity of *P*=1 day would be a better choice. This reduction in the value of *P* would further increase the value of τ indicating that the aquifer responds rather slowly to storm events and pumping variations. This will be explored in testing against mid Animas River data later in this appendix.

Groundwater Levels and Calibration

In this study, the groundwater flow model GFLOW is being calibrated using observed potentiometric heads (e.g., confined flow rock areas) or water table elevations (e.g., unconfined flow alluvium). In addition, base flows in the Animas River are also included as calibration targets. Calibration leads to the determination of most likely hydrogeological parameters such as hydraulic conductivities, aquifer recharge due to precipitation, and perhaps stream bottom resistances (USEPA, 2016, pg. 78). In the Animas River of New Mexico, high-resolution synoptic surveys of static water levels were available. In the Animas River of Colorado, the EPA team used the static water levels reported in well driller's logs.

Currently, hydraulic gradients toward the Animas River are generated in the model by defining head specified boundaries away from the river. The water released by these head-specified boundaries presumably comes from the surrounding mountains. A common approach in modeling flow in alluvial valleys is to apply so-called "mountain range recharge" along the valley boundaries at the bottom of the surrounding mountains. In GFLOW, this could be done using discharge-specified line-sinks along the base of the mountains or boundary of the alluvium. Since there were not data to support the mountain range recharge, the contribution was estimated using observed baseflow increases along the Animas River.

Lower Animas River Groundwater Models

A pumping well located in proximity to the river has the possibility of reversing the background hydraulic gradient and capturing water from the river, depending on proximity and pumping rates. Groundwater flow modeling was used to investigate pumping scenarios consistent with observed conditions. The lower Animas River regional groundwater modeling will be presented first because of the existence of a high-resolution topographic data set (i.e., digital elevation model, DEM) and a series of synoptic surveys of the well water levels and river water levels from August 2015 and into 2016.

Lower Animas River GFLOW Model Setup

The regional groundwater model solves the hydrological water balance between the USGS gages at Aztec and Farmington. The DEM is used to define the outer boundary of the catchment (See Figure D-12).

The surficial geology of the lower Animas River watershed for the study region is mapped in Figure D-13. A sampling of community wells was extracted from the New Mexico Water Rights Reporting System (NMWRRS) for the Animas River floodplain between Aztec and Farmington (RK 170-180), and the data reported in Table D-2.

The layout of analytic elements used in the GFLOW representation of the lower Animas River are shown in Figure D-14. The base of the single-layer aquifer is assumed to be horizontal and to constitute a no-flow boundary. The GFLOW model represents the outer boundary as a no-flow boundary, that is, no solution occurs outside of this boundary. GFLOW also uses a polygon to distribute area recharge over the catchment only. Another analytic element polygon encloses the floodplain alluvium and associates a higher hydraulic conductivity than the outer rock domain. The perennial stream network defines an internal boundary condition. The nominated stream locations from USGS topographic maps or digital elevation models (DEM) were translated into GFLOW line-sink representations of streams. Head at a location on the landscape is understood to be the elevation at which water saturates an open pipe piezometer driven into the aquifer. The strength (i.e., inflow/outflow per unit length) of the line-sink is determined in the analytic element solution by maintaining a specified head in the center of the line-sink element. A combination of methods was used to estimate the land surface elevation at select locations on the base map: (1) labeling elevations where elevation contour lines from the USGS map crossed the stream channel; and/or (2) linear interpolation along the line-sink. The line-sinks were then manually superimposed on the base map, ensuring that vertices at the end of line-sink strings corresponded with points of known head/elevation from the USGS sources. The head at the center of each of the line-sink strings is calculated through linear interpolation. Wells are represented with point elements. A piece-wise representation of the hydraulic conductivity (k) property is achieved with the polygonal representation of the higher-k unconsolidated floodplain deposits.

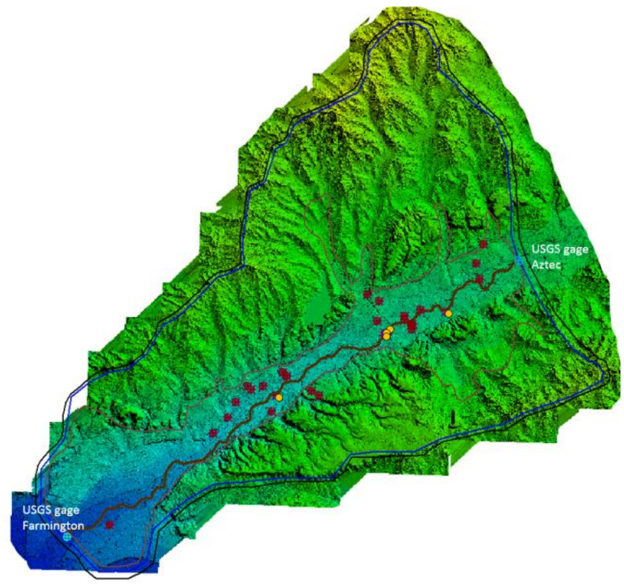


Figure D-12. Community wells (orange) and private wells (red) for the Lower Animas River floodplain study area. The catchment draining between the USGS gages at Aztec and Farmington was delineated as guided by the LiDAR DEM. Data source: New Mexico Resource Geographic Information System (http://rgis.unm.edu/)

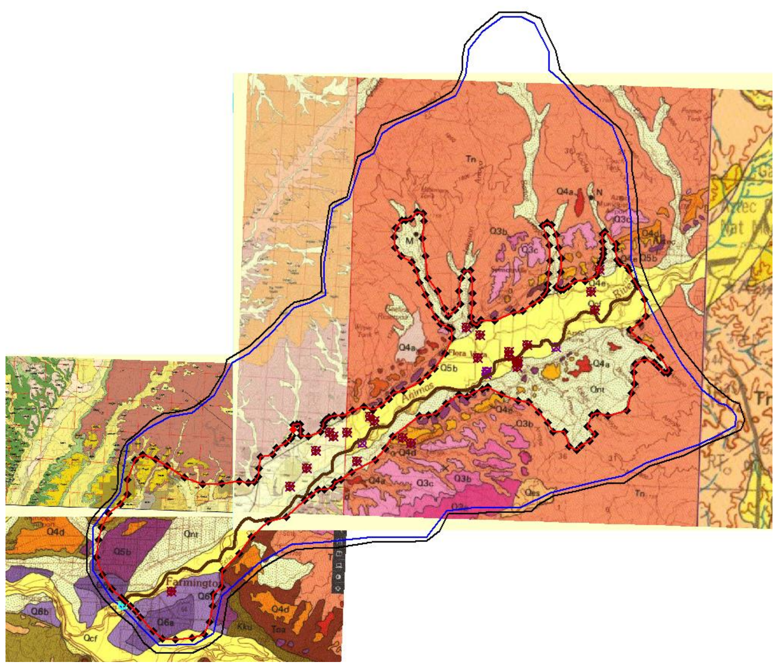


Figure D-13. Lower Animas River geology. The interpreted boundary of the alluvial aquifer is delineated. Data: USGS national geologic model database.

Table D-2. Lower Animas River floodplain, community well data, New Mexico

Identification*	Total Depth (Ft)	Static Water Level (Ft bgs[&])	Pumped Water Elevation (Ft bgs)	Well Yield (gpm) Observed, Estimated	Average Annual Well Diversion Right (Acre-ft)
76m174km	21	6	NA	150	62.9
21m174km	23	7	NA	150	62.9
101m174km	21	7	NA	150	62.9
90m179km	25	NA	NA	1,000	1,935
18m171km	NA	NA	NA	125	1.36

*An ID was assigned to the community wells incorporating distance from river (in meters) and downstream distance from GKM (in kilometers) in the name.
[&] Feet below ground surface

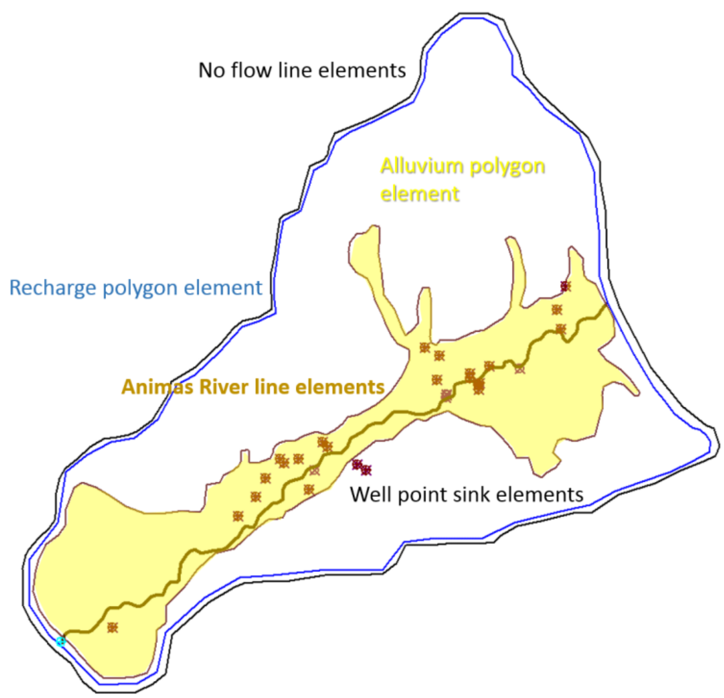


Figure D-14. Layout of GFLOW analytic elements for the Lower Animas model.

Lower Animas River GFLOW Model Calibration

The areal recharge was distributed over the catchment between the USGS gages in order to satisfy the water balance of August 2015. The observed stream flows are shown in Table D-3. USGS gage data for Farmington was provisional at the time of analysis, so estimated based on historical observations at two gages.

Table D-3. Observed stream flows and statistics in the lower Animas River of New Mexico.

USGS Gage Name	USGS Gage Number	Discharge average 8/12-8/15/2016 (cfs)	Discharge on 1/14/2016 (cfs)	Discharge average August-October, 2015 (cfs)	Discharge average August-October, 2003-2015 (cfs)
Animas River below Aztec NM	09364010	654.7	229	365	428
Animas River Farmington NM	09369500	684.3	240 estimated*	360	438

*Q_{farm}/Q_{aztec} = 1.049 based on 2003-2016 data for January.

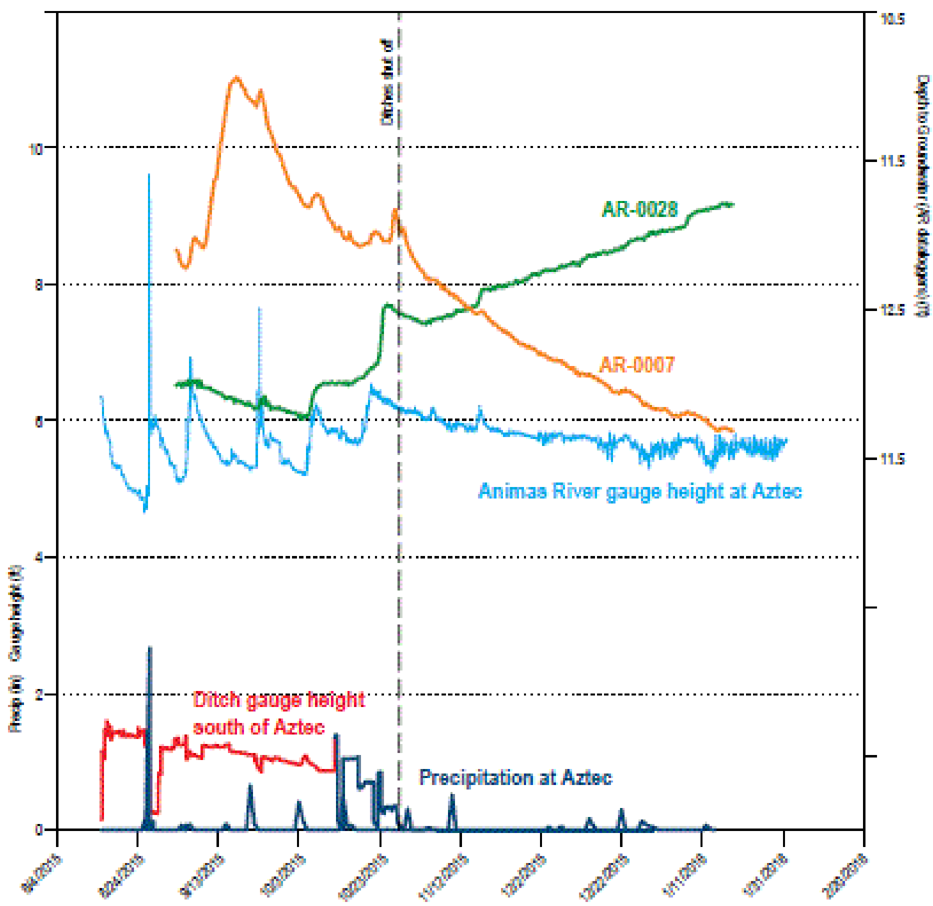


Figure D-15. Hydrographs from Aztec area including a well with continuous data recorder plotted with influences from precipitation and Animas River stage and ditch gage height. Well AR-0007 is located on the south side of Aztec, is 32 ft deep, and is located on the east side of the river. (modified from Timmons et al., 2016).

The NMBRMR conducted a synoptic survey of water levels in private wells during the period August 2015, January and March 2016 (Timmons et al., 2016). They also monitored continuous precipitation and Animas River and irrigation ditch stages at select locations (See Figure D-15). 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. An approximate five-day delay in the signal from river stage to well response is expected based on observations at an alluvial well. Also, the influence of the irrigation ditches is apparent. Once the irrigation ditch is drained for the winter, the water levels in the alluvial well drop to the baseflow levels. A significant observation is the sensitivity of aquifer water levels to the operation of the irrigation ditches which are important sources of water for the irrigated cropland in the growing season.

Scenario 1. GFLOW regional model for January 2016 hydrologic condition

The GFLOW model was calibrated first for areal recharge over the catchment area, and second for hydraulic conductivity of the rock and alluvium. The January 2016 period was used for calibration since during this baseflow period the irrigation ditches were not involved in the water balance (i.e., the start-simple-and-add-complexity strategy). The EPA team used the synoptic survey of water levels conducted by Timmons et al. (2016). The regional recharge over the study area was calibrated to satisfy the regional water balance at the Farmington USGS gage (See Figure D-16). The water balance means input – output = change storage = zero (i.e., or $Q_{farm} = Q_{aztec} + N_{study\ area}$ * study area – Q_{wells}). The river flows Q_{farm} and Q_{aztec} are known from USGS gage data. An average pumping rate for the private domestic water wells was assumed to be 400 gallons per day, recognizing that this is an overestimate of consumptive use given that there will be an expected return flow to the aquifer via septic discharge. The study area is calculated using GIS and the USGS DEM and an estimate of the catchment boundary. The water fluxes of rock⇔alluvium and alluvium⇔river are computed internally to the GFLOW model. The model is calibrated to match the Q_{farm} at the outlet by varying the net recharge, including lumped ET loss, over the study area ($N_{study\ area}$). The result was a recharge over the catchment area of N=1.556E*-4 m/d*.

The GFLOW map of hydraulic head contours are shown in Figure D-17 (a). The resulting manual calibration of the hydraulic conductivity that minimized the residual error was k_rock = 0.035 m/d and k_alluv=2.2 m/d. The calibration statistics for the wells located in the alluvial floodplain are shown in Figure D-17 (b). The GFLOW model parameters are summarized in Table D-4.

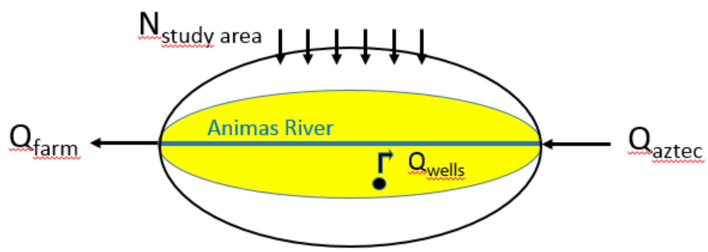
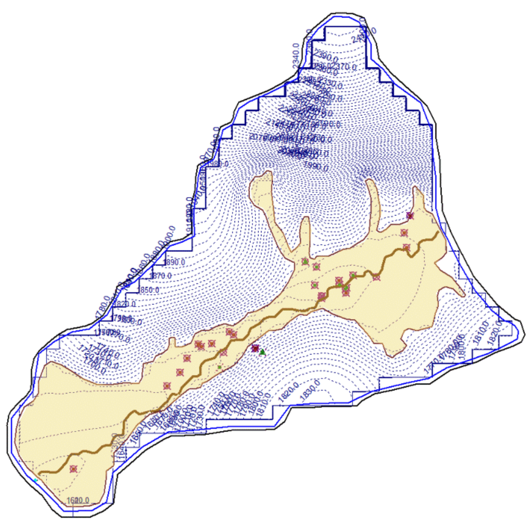


Figure D-16. Conceptual diagram of water balance used in the GFLOW model for the lower Animas River without ditch diversions.

Table D-4. Summary of Lower Animas GFLOW parameters for January 2016 model calibration.

Parameter	Model Value
Alluvium porosity (n) [-]	0.2
Alluvium base elevation [*m*]	1600
Alluvium thickness [*m*]	100
Alluvium hydraulic conductivity [*m/d*]	2.2
Rock porosity (n) [-]	0.2
Rock base elevation [*m*]	1600
Rock thickness [*m*]	100
Rock hydraulic conductivity [*m/d*]	0.35
Areal recharge (N) (*m/d*)	1.556E-4
Net flow Farmington (Q_{farm}) [m^3/d]	587,178.1

A)



B)

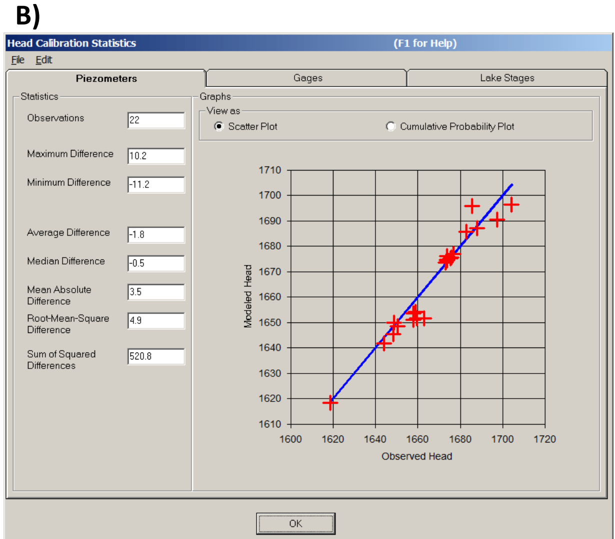


Figure D-17. GFLOW calibration for lower Animas River regional groundwater model for January 2016 flow conditions. The model areal recharge satisfying water balance was N =1.556E-4 m/d. Static water levels were measured at wells and entered into the GFLOW model as test points. Calibration minimizes the residual error or difference between the observed water levels and the model predicted water levels. A) resulting calibrated model and regional hydraulic head contours; B) calibration statistics for the test points located in the alluvium, alluvium hydraulic conductivity k_alluv=2.2 m/d. Thus, at any specific alluvium well the model is on average low by 1.8 m.

Scenario 2. GFLOW regional model of the August 2015 hydrologic period

During the August 2015 period, the time of the GKM release and plume transport, the irrigation ditches would be expected to be in full operation in the Lower Animas River area. A GFLOW model was constructed to include the irrigation ditches as constant head linesinks. The location of the ditches in Farmington are shown in Figure D-18. The elevation of the water levels in the ditches was estimated using the LiDAR DEM. The layout of linesink representation of the ditches in the GFLOW model is shown in Figure D-19.

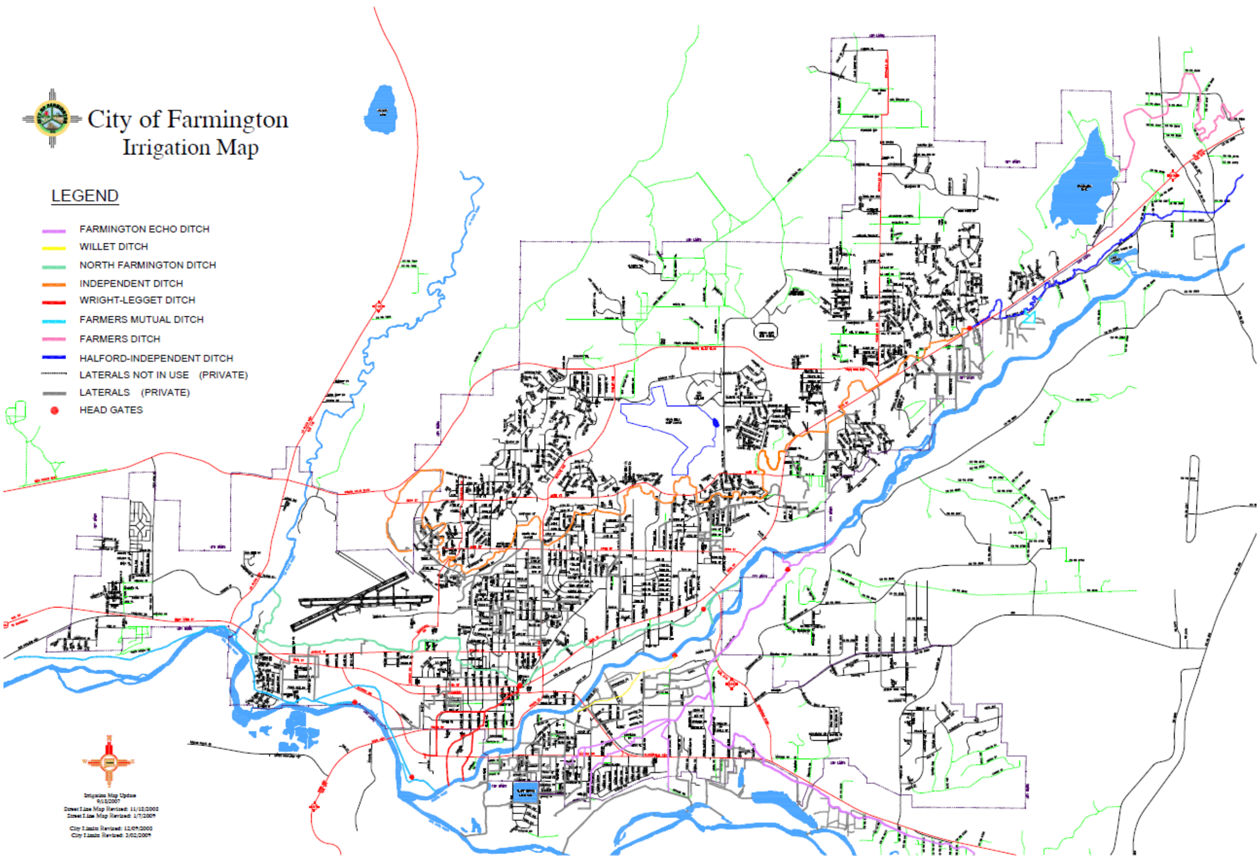


Figure D-18. City of Farmington, NM, irrigation ditch map. The streets are shown as black lines; the irrigation ditches are shown in colors (city map, updated 2009).

The NMBGMR provided a synoptic survey of private water well elevations for the dates, 8/17 – 8/20/2015. A five-day delay from Animas River stage to well response is expected. Therefore, Animas River discharge was averaged for dates 8/12-8/15/2016, see Table D-3 for the water flows.

The GFLOW solution that satisfies the steady water balance for the August 2015 time period, and which minimizes the residual error between model calculated hydraulic head and observed water levels in the water supply wells is shown in Figure D-20. The only parameter changed from the previous Scenario 1 was the net flow at Farmington 1,548,682.3 m^3/d as a calibration target. The areal recharge that minimized the model difference in predicted flow at the catchment outlet at Farmington was N=0.215e-4 *m/d***.**

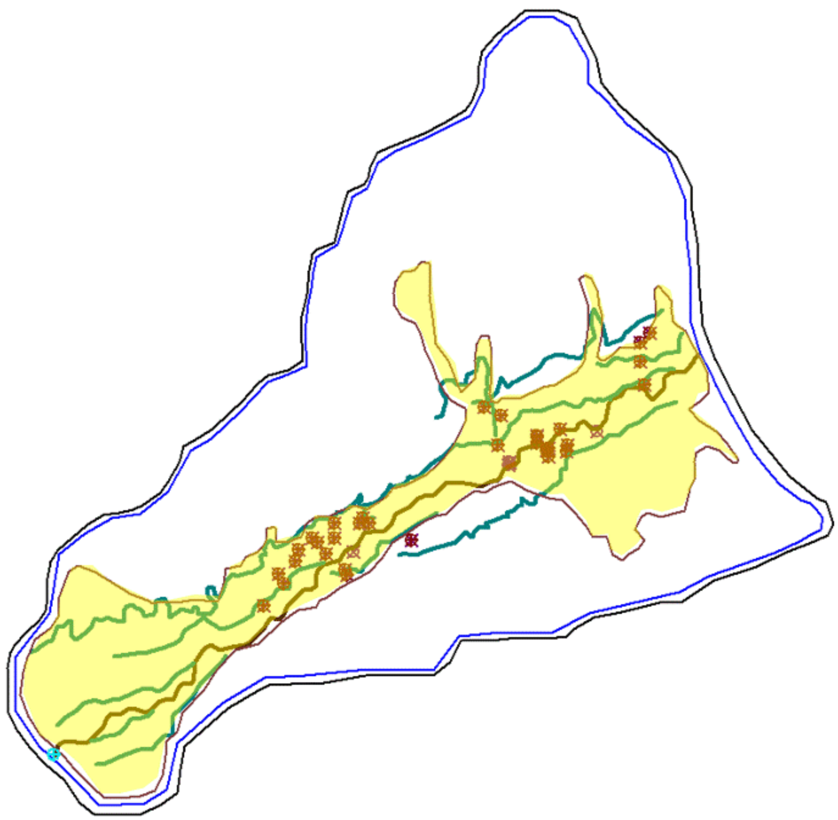
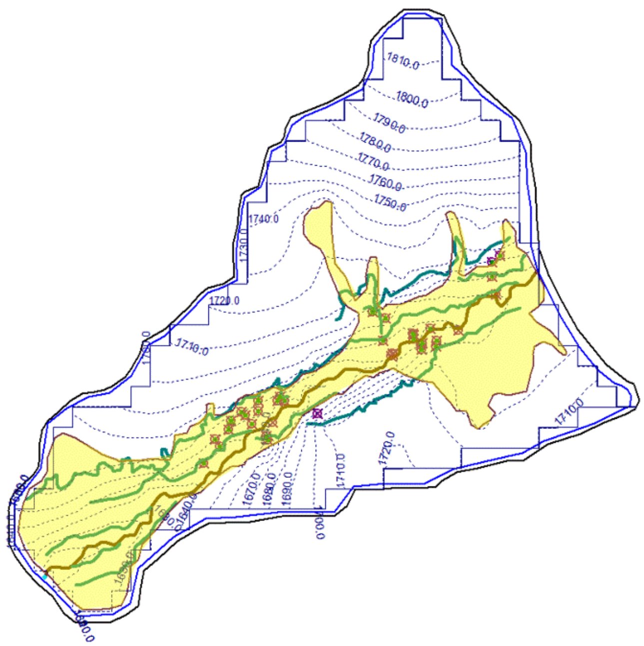


Figure D-19. GFLOW layout of elements including line-sink representation of irrigation ditches in the lower Animas River study area. The elevation of the water levels maintained by the ditches informed by the high-resolution LiDAR elevation data.

A)



B)

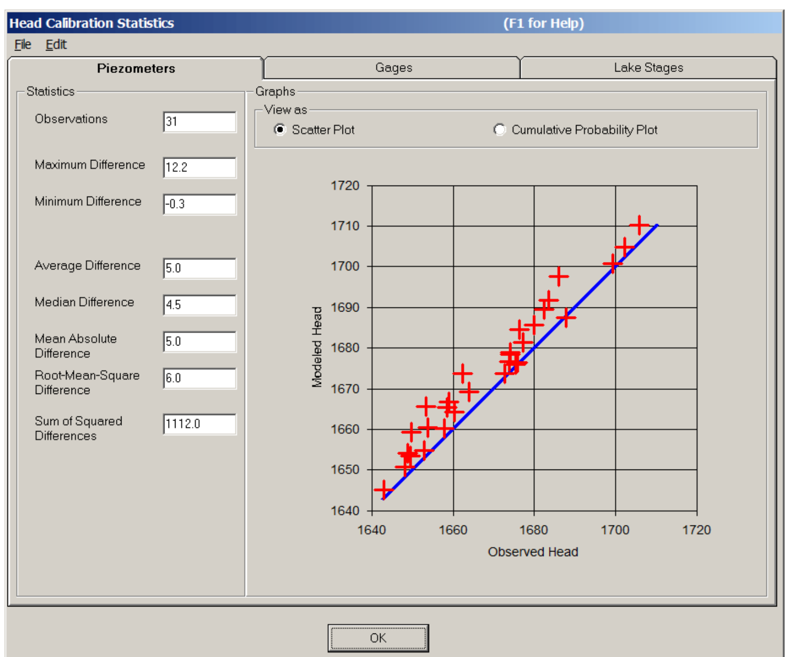


Figure D-20. GFLOW regional groundwater model lower Animas River for August 2015 time-period, including irrigation ditches. The effective recharge over the catchment area N=0.215e-4 m/d minimized model predicted error at the outlet at Farmington. The average head difference error went up to plus 5m.

Scenario 3. GFLOW Regional odel of the August-October 2015 Hydrologic Period

The water balance for the lower Animas River study area can be refined to include the observed major diversions from the Animas River to the irrigation ditches. These data are collected by the New Mexico Office of the State Engineer, Interstate Stream Commission, and publically available on the Real-Time Water Measurement Information System webpage (http://meas.ose.state.nm.us/). The sum of the diversions for the August to October 2015 time-period is summarized in Table D-5.

Table D-5. Irrigation ditch diversions (New Mexico Office of the State Engineer)

Ditch Name	Diversions Aug-Oct 2015 (m^3/d)
Kello-Blancett	21,166.3
Halford-Independent	40,105.1
Ranchmans-Terrell	7,358.2
Farmington Echo	69,476.7
North Farmington/Wright-Leggett	11,649.0
Sum total	149,755.3

The Scenario 2 GFLOW model was adjusted to represent the August-October 2015 water balance, including the influence of ditch diversion and pumping well extraction. With reference to the conceptual diagram of the water balance of Figure D-21, the study area Animas River inflows at Aztec, NM was estimated as the measured flow (from Table D-2, 428 cfs or 894,142.6 m3/d) minus the total diversions (149,755.3 m3/d) or Q_{aztec} = 744,387.3 m^3/d. The observed average flow at Farmington, NM is Q_{farm} = 880,128.6 m^3/d. The estimated pumping rates included those of the community wells (i.e., reported average diversions) and estimated for the private wells (i.e., 400 gallons per day; Note this is a high estimate since it does not include return flow via septic fields). The water fluxes of rock⇔alluvium and alluvium⇔river/ditches are computed internal to the GFLOW model. The GFLOW manual calibration varied the net recharge (i.e., lumps the ET losses and return flows) over the floodplain alluvium deposits until the residual error (i.e., model observed minus model simulated flow at the Farmington outlet, Q_{farm}) was minimized, resulting in model recharge over the alluvium N_{alluv} = 0.0053 m/d. The results of the calibration are presented in Figure D-22. The 90-day capture zones of the wells are too small to be seen at this scale. The model suggests only the 21m-174km community well pumping at a maximum rate of 817.6 m3/d sources from the river.

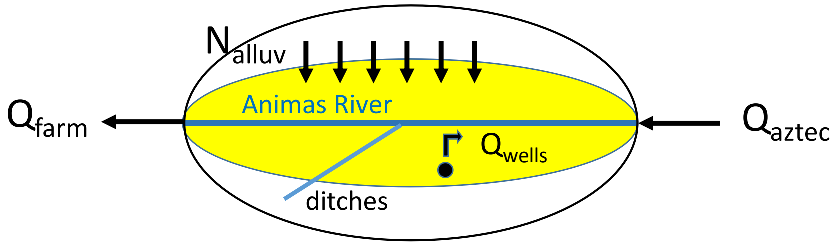


Figure D- 21. Conceptual diagram of water balance used in the GFLOW model for the lower Animas River including the influence of irrigation ditch diversions.

Local Scale GFLOW Model for a Lower Animas River Floodplain Community Well

The calibrated regional GFLOW model for the averaged hydro period August-October 2015 provides the basis for the evaluation of floodplain water supply well sourcing from the lower Animas River, where an example community well (i.e., 21m174km) is used to explore local scale capture zone delineation and solute breakthrough.

While the GFLOW model predicted the 21m174km community well could source from the Animas River, the first arrival of the plume was predicted to take over 90 days, with significant dilution predicted. The aquifer would take almost two years to flush under these conditions (See Figure D-23).

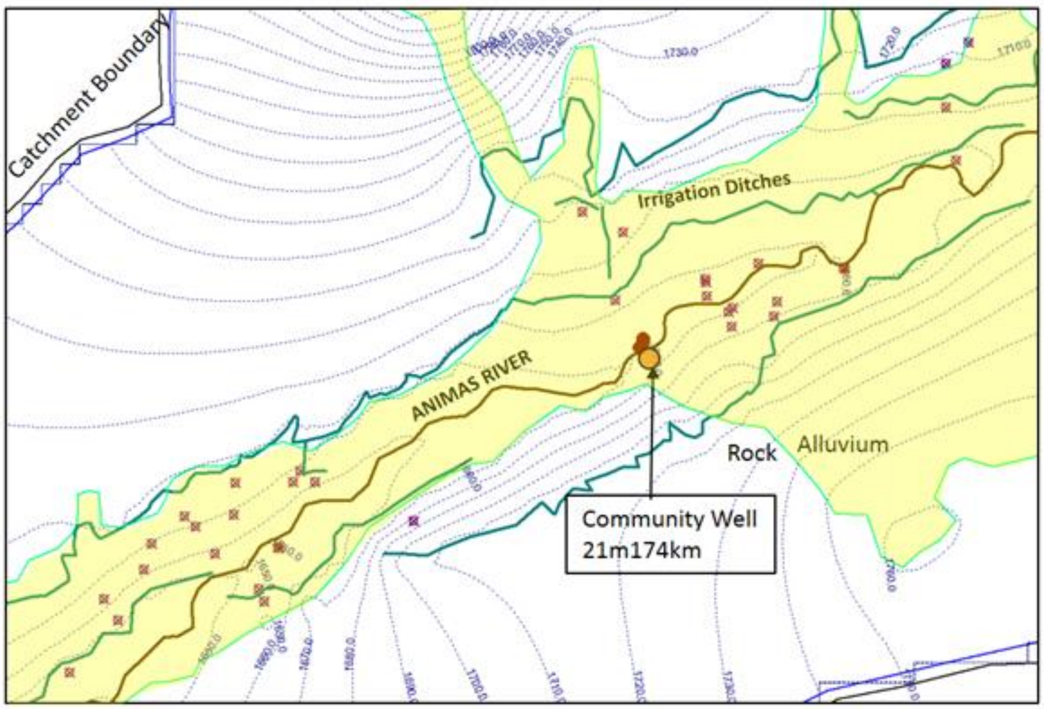
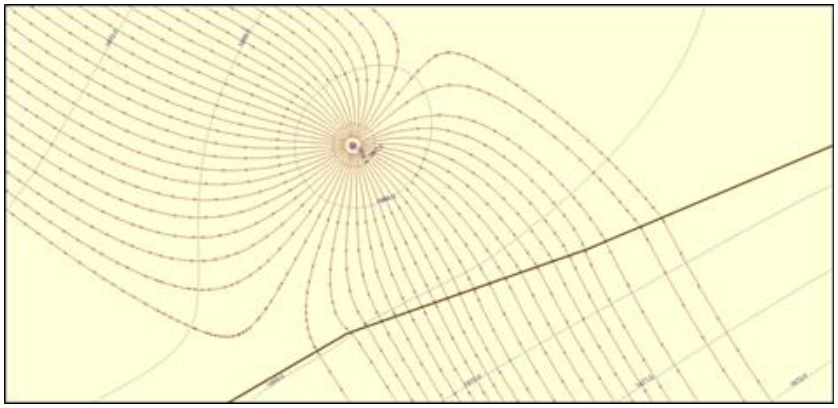


Figure D-22. GFLOW model of groundwater-surface water interactions in the lower Animas River floodplain between Aztec and Farmington, New Mexico (RK 170-180) for the averaging period August – October 2015.

A)



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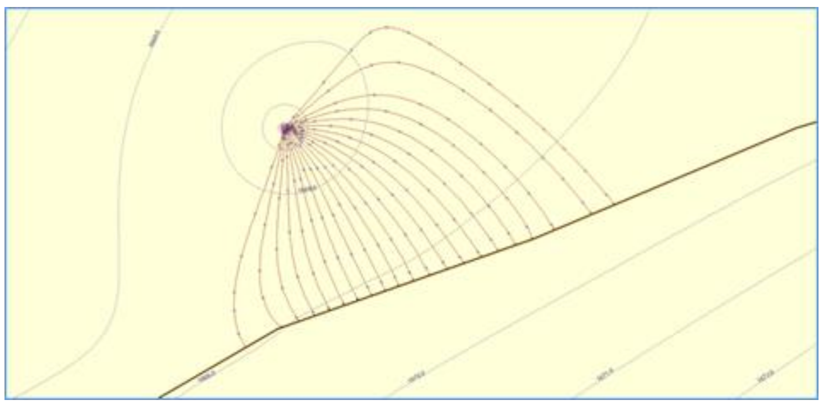


C)

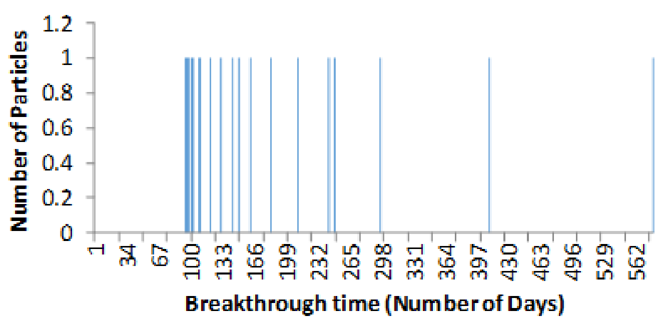


Figure D-23. GFLOW capture zone and solute breakthrough histogram for lower Animas community well. Community well (21m-174km), high pumping (Qw=817.6 m3/d) and low porosity (n=0.25). A) capture zone delineation with 48 reverse streamlines; B) particle tracking with 21 forward pathlines; C) predicted time of arrival breakthrough (days) are reported in a histogram, with a particle arriving in 94 days. Breakthrough time with same pumping but higher porosity (n=0.35) has a particle arriving in 131 days. Suggested peak river concentration is diluted to about 2% (1/48). Flushing of the aquifer in about 565 days. Note that advective transport is steady (time invariant pumping and hydrology) and does not account for dispersion, sorption, or decay of solute.

Mid Animas River Groundwater Models

A second cluster of community wells was the focus of the mid Animas River floodplain groundwater modeling (RK 65-72). The floodplain also supports a large number of private/domestic wells (See Figure D-24).

Five community wells located in the mid Animas River floodplain of Colorado were identified by EPA Region 8. The initial modeling focused on the northern cluster of wells around Hermosa, CO. The sanitation department wells were not selected for modeling. The straight-line distance of each community well from the river ranges from 35 m to 1,000 m. The location of the nearest river shoreline was defined using the latest Google Earth imagery. The wells are approximately 66-71 km downstream of the GKM release point. The name of each community well combines the distance from the river, in meters, and the distance downstream from the GKM release, in kilometers (See Figure D-25).

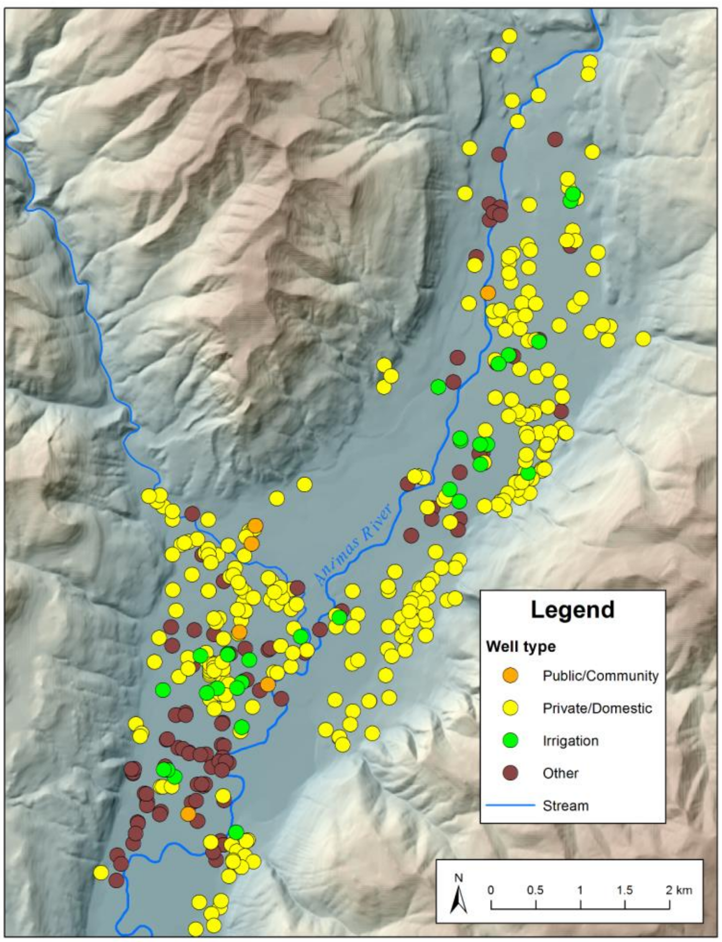


Figure D-24. Water supply wells of the floodplain of the mid Animas River. The background is the topographic DEM and the hydrography of the USGS Hermosa Quad. Well data are available from the Colorado DWR well permit search database. The community wells are represented by the orange circles.

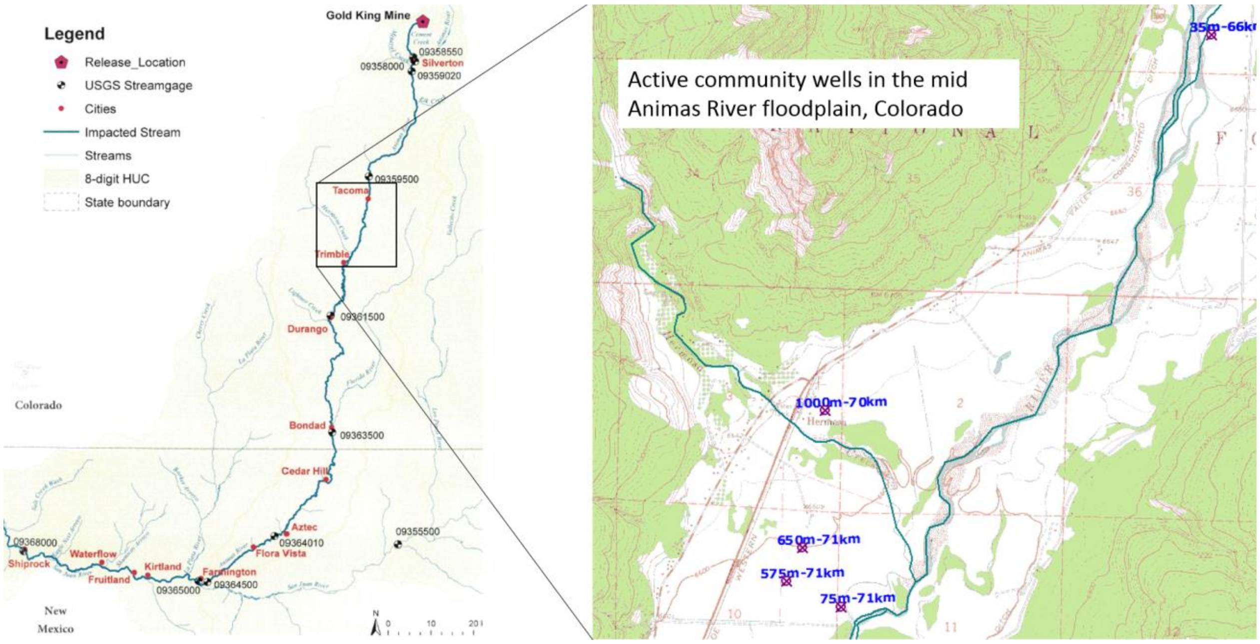


Figure D-25. Selected community wells for investigation located in the mid Animas River floodplain near Hermosa between Tacoma and Trimble, Colorado. Basemap: USGS 7.5 minute topographic DRG (digital raster graphic).

Basic information regarding the wells is reported in the Colorado Department of Water Resources Well Permit online database (www.dwr.state.co.us/WellPermitSearch). The (x, y) location of the wells are geo-referenced to electronic base maps in the UTM Zone 13 NAD83 projection and attempted confirmation with Google Earth imagery. The sustained yield and water level drawdown are reported in the driller's log. An ID was assigned to the community wells incorporating distance from river, in meters, and downstream distance from GKM in kilometers, in the name (See Table D-6).

Table D-6. Community well data (source: Colorado Div Water Resources, Well Permit Search, CDNR CDSS)

Identification*	Total Depth (Ft)	Screened Intervals (Ft bgs[&])	Static Water Level (Ft bgs)	Pumped Water Elevation (Ft bgs)	Well Yield (gpm) Observed, Estimated	Average Annual Well Diversions (Acre-ft, Years)
35m66km	100	70-95	22.5	25.0	480 (580)	56.4 (1996-2014)
75m71km	87	45-85	10.5	13.5	445 (600)	145.74 (1997-2014)
575m71km	210	NA	18.2	19.3	100 (450)	139.38 (2009-2014)
650m71km	120	50-60,70-95,105-115	24	28.75	400 (600)	162.65 (1998-2014)
1000m70km	100	72.75-100	31.2	35.2	425 (425)	NA

*An ID was assigned to the community wells incorporating distance from river (in meters) and downstream distance from GKM (in kilometers) in the name.
[&]Ft bgs is Feet Below Ground Surface

Table D-7. USGS streamflow data at gaging stations in mid Animas River area.

USGS Gage Name	USGS Gage Number	Discharge on 8/1/2015 (m^3/d)	Discharge Averaged 2015, Aug-Oct (m^3/d)	Discharge Historical, 1947-1955, Aug-Dec (m^3/d)
Animas River Tall Timbers Resort, CO	09359500	1,350,510	739,318	521,194
Animas River Durango, CO	09361500	1,313,811	898,984	776,519

The regional GFLOW model solves the Animas River water balance for the area draining between USGS Tall Timbers Resort, CO and USGS Durango, CO for different time periods, as shown in Table D-7. The catchment between the two USGS gages of the study area and the boundary of the Animas River floodplain is defined using the USGS digital topographic map and the USGS Hermosa, CO quad geology map (Figure D-26**)**.

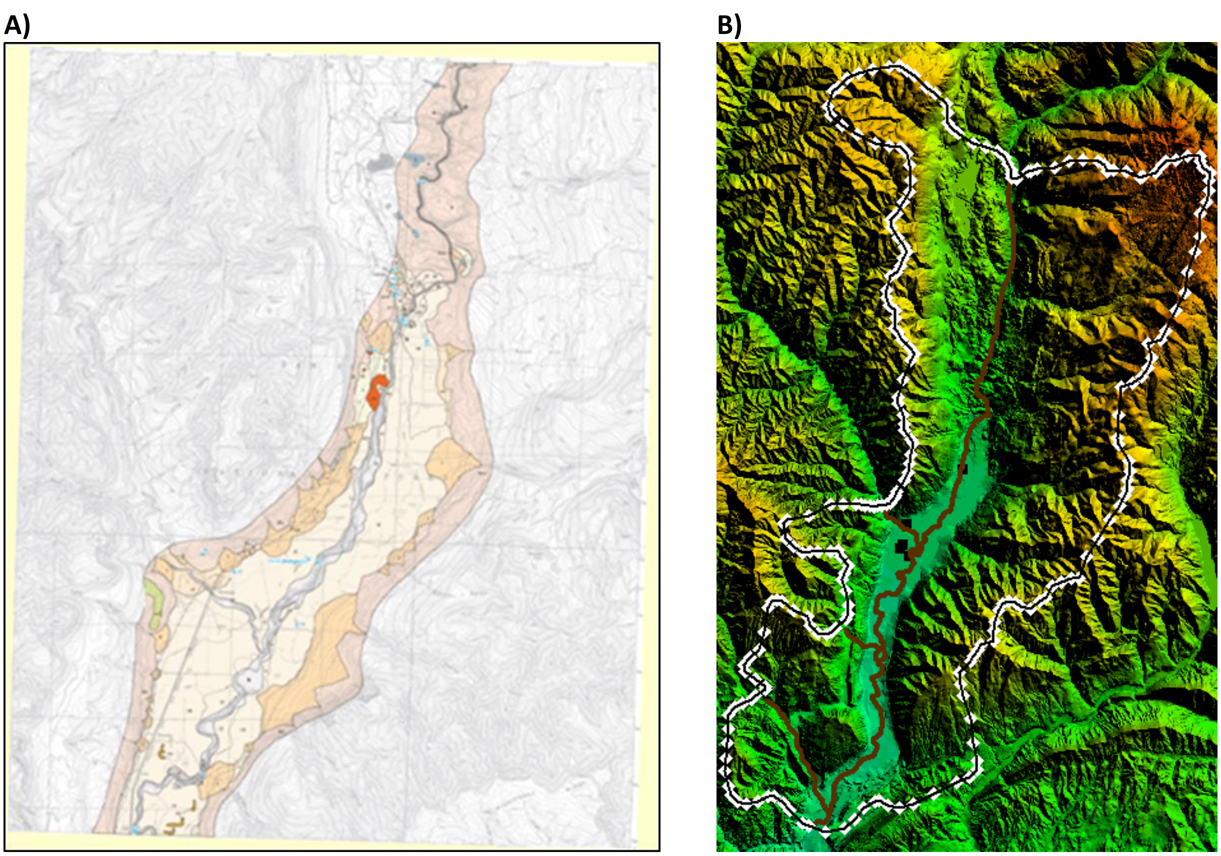


Figure D-26. Mid Animas River geology and digital elevation. A) USGS surface geology map Hermosa, Colorado quad, showing the alluvial floodplain deposits surrounded by rock (Blair, Yager, 2002). B) USGS NED 10-m resolution and the topographically defined catchment between USGS gage stations at Tall Timbers Resort and Durango, Colorado. The alluvial floodplain shows up in light blue-green.

Mid Animas River GFLOW Model Setup

The layout of GFLOW analytic elements for the mid Animas River floodplain groundwater model is shown in Figure D-27. 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 Anims River near Duragno. The aquifer base elevation is considered no-flow in the GFLOW model. The gravimetric estimate of aquifer thickness occurred at each of the scan lines (Hasbouk Geophyiscs, Inc., 2003; Figure D-10). These were used to parameterize a stepping base representation in the GFLOW model.

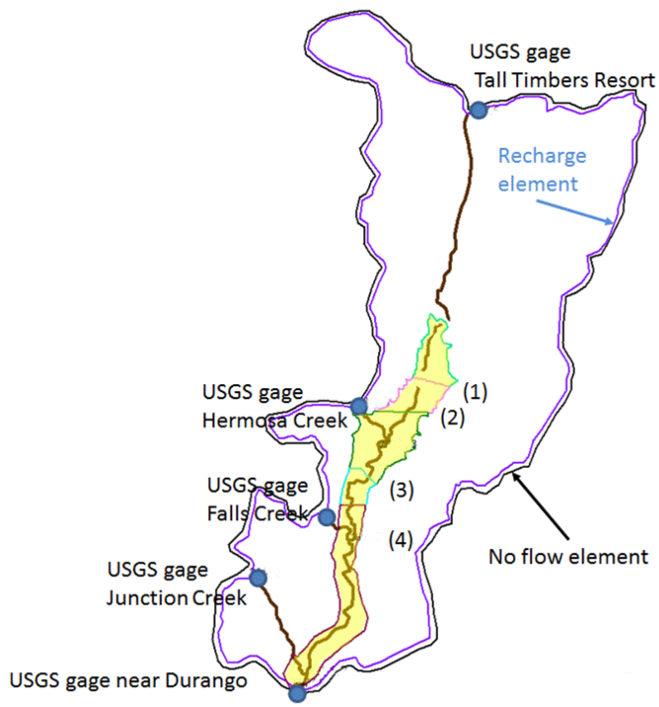


Figure D-27. GFLOW layout of analytic elements for the mid Animas River floodplain groundwater model. A no-flow boundary is maintained at the catchment boundary or drainage area between the USGS gage on the Animas River at Tall Timbers resort, and the USGS gage on the Anims River near Duragno. The aquifer base elevation is considered no-flow in the GFLOW model. The gravimetric estimate of aquifer thickness occurred at each of the scan lines. These were used to parameterize a stepping base representation in the GFLOW model.

Mid Animas River GFLOW Model Calibration

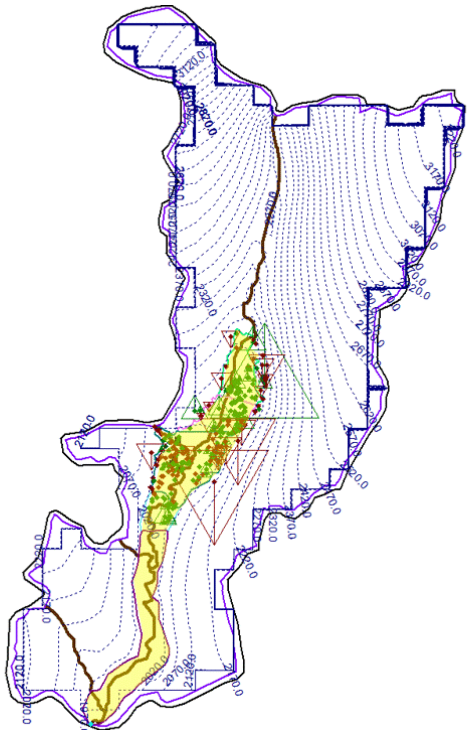
Scenario 1. GFLOW Regional Model for the Aug-Dec, 1947-1955 Historical Time Period

The August-December historical record from 1947-1955 of daily stream flows at the USGS gages at Tall Timber Resort and Durango where used to estimate the average area recharge on the catchment draining between these two stations. Model calibration for exiting average stream flows provides the estimate for average areal recharge (N = 0.000463 m/d = 6.6 in/yr). Model calibration minimizing the difference between model calculated hydraulic heads and observed water levels in wells was used to estimate hydraulic conductivity of the rocks and floodplain deposits. Unlike in the lower Animas River floodplain, the team did not have the synoptic survey of water levels in wells. We used the static water levels reported in the well driller's logs. This had impact on the model error (See Figure D-28 (a), (b), (c)).

Table D-8. Summary of Mid Animas GFLOW parameters for Aug-Dec, 1947-1955 model calibration.

Parameter	Model Value
Alluvium porosity (n) [-]	0.2
Alluvium 1 base elevation [*m*]	1915.1
Alluvium 1 thickness [*m*]	92
Alluvium 1 hydraulic conductivity [*m/d*]	60
Alluvium 2 base elevation [*m*]	1897.1
Alluvium 2 thickness [*m*]	92
Alluvium 2 hydraulic conductivity [*m/d*]	60
Alluvium 3 base elevation [*m*]	1755.2
Alluvium 3 thickness [*m*]	92
Alluvium 3 hydraulic conductivity [*m/d*]	60
Alluvium 4 base elevation [*m*]	1875.1
Alluvium 4 thickness [*m*]	92
Alluvium 4 hydraulic conductivity [*m/d*]	60
Alluvium 5 base elevation [*m*]	1808.1
Alluvium 5 thickness [*m*]	92
Alluvium 5 hydraulic conductivity [*m/d*]	60
Rock porosity (n) [-]	0.2
Rock base elevation [*m*]	1977
Rock thickness [*m*]	92
Rock hydraulic conductivity [*m/d*]	0.2
Areal recharge (N) (*m/d*)	4.63E-4
Net flow Durango ($Q_{durango}$) [m^3/d]	776,518.6

A)



B)

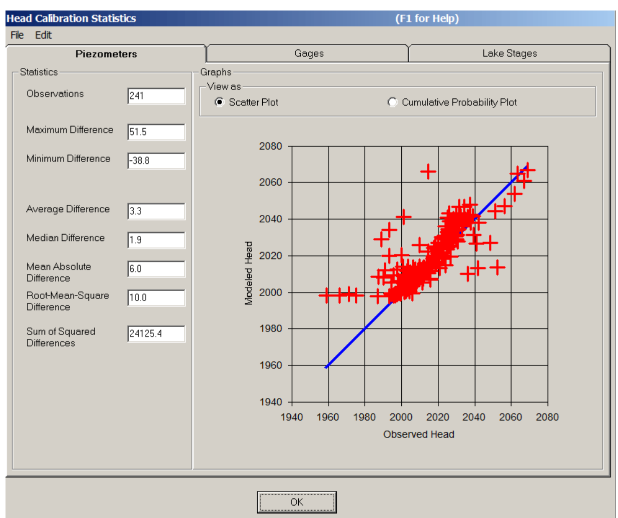


Figure D-28. GFLOW mid Animas River floodplain regional groundwater model calibration results. The model used the water balance areal recharge of N = 0.000463 m/d = 6.6 in/yr. The result of the calibration suggested the hydraulic conductivity of the rock, k_rock=0.2 m/d, and of the floodplain alluvium k_alluv = 60 m/d.
(a) plot of head contours in the mid Animas River and showing test points of observed static water levels (historical). The triangles indicate the magnitude of the residual error (model – observed) and direction of triangle signifies sign of residual, positive tip of triangle up, negative tip of triangle down. (b) plot of model predicted heads vs the observed heads for the floodplain test points (avg error +3.3 m).

Scenario 2. GFLOW regional model for the August – October 2015 hydrologic period

Building on the previous result, the GFLOW model was adapted for the August –October 2015 mid Animas River water balance. The flow of the mid Animas River groundwater model was input at the USGS gage location at Tall Timbers resort, and the areal recharge over the study area was solved for such that the model predicted outflow in the Animas River outlet at Durango matched the observed, using data from **Table D-7**. The resulting areal recharge was N=4.377E-4 m/d.

Local scale GFLOW model for a mid-Animas River floodplain community well

The GFLOW model was used to zoom into the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015 (See Figure D-29). The GFLOW model suggests that only three private wells in the mid Animas River area directly source river water, with distances of the wells from the river ranging from 10-123 m. There were many other wells within 123 m of the river that the model suggested do not source river water. Therefore, distance from the river alone is not predictive of well sourcing from the river. Geomorphology and the location of losing sections of the river are factors. The model suggests that the Baker's Bridge area where the Animas River leaves the mountain pass and enters the floodplain valley has groundwater seeping into the aquifer and a potential "hyporheic" zone.

A) **B)**

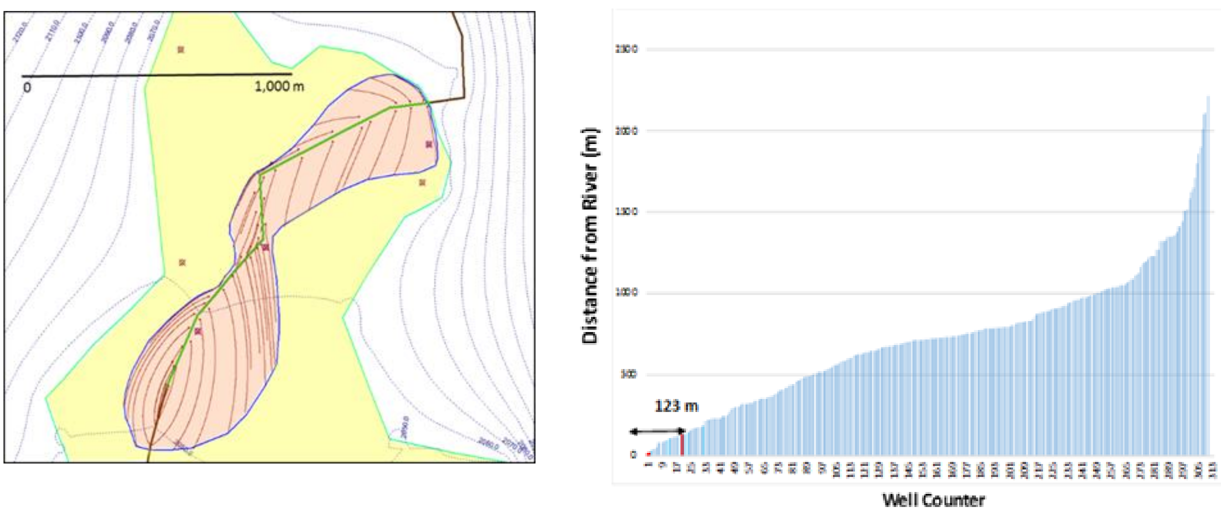


Figure D-29. GFLOW model of the mid Animas River floodplain near Baker's Bridge (RK 65-72) showing groundwater-surface water interactions for the averaging period August-October 2015. A) Hydraulic head contours (m) are shown as dotted lines and the river flow is north to south. The gaining sections of the river are colored black; the losing sections 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. B) The bar graph shows the distances of wells from the river of over 300 wells. Distances ranged from 10m to over 2,000 m.

The calibrated regional mid Animas River GFLOW model for the August–October 2015 hydro period was used to evaluate the local scale capture zones and particle tracking solute transport for the mid Animas River floodplain community well 35m66km (Figure D-30). The combination of parameters (i.e., low recharge, high alluvium hydraulic conductivity, high well pumping rate, low alluvium porosity) creates the earliest breakthrough of 25 days. Full sensitivity analysis on area recharge, hydraulic conductivity of aquifer material, and pumping rate of well is described in a later section. Note that advective transport is steady (time invariant pumping and hydrology) and does not account for dispersion, sorption, or decay of solute.

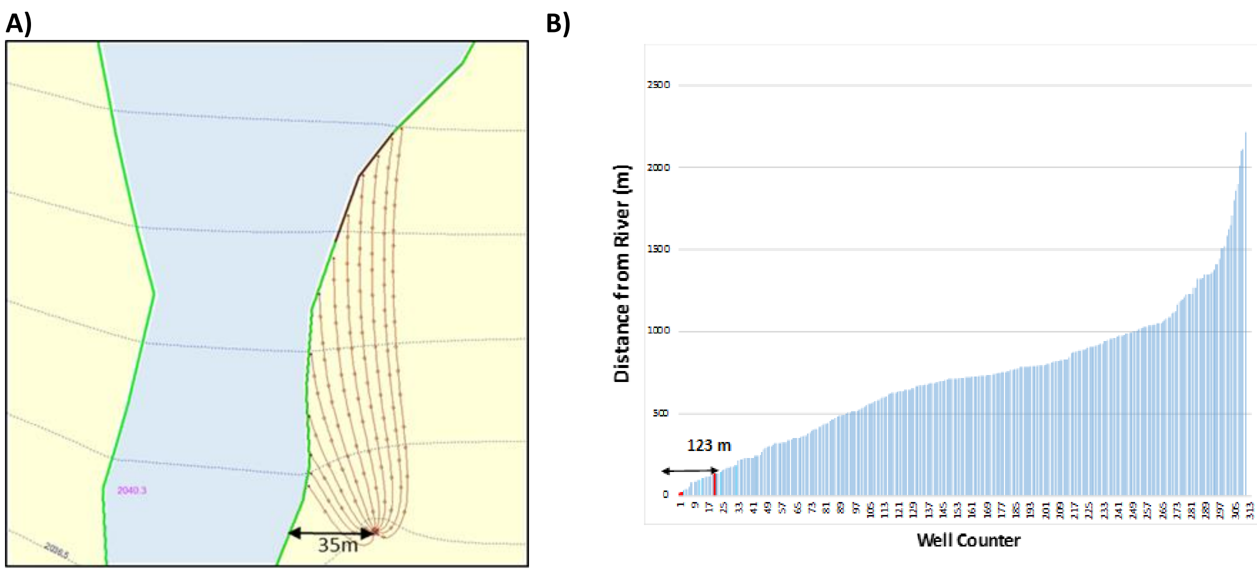


Figure D-30. GFLOW capture zone and solute breakthrough histogram for a mid-Animas River community well. GFLOW analysis of mid Animas River community well (35m-66km), high pumping (Qw= 2,616.5 m3/d) and low porosity (n=0.2) A) particle tracking with 12 forward pathlines; B) time of arrival breakthrough, in days, are reported in a histogram, with a particle arriving in 25 days. Breakthrough time with same pumping but higher porosity (n=0.35) has a particle arriving in 44 days. Suggested peak river concentration is diluted to about 17% (2/12). Flushing of the aquifer in about 160 days.

Consideration of Uncertainty in the Groundwater Modeling

Mid Animas: Exploration of the steady-state modeling assumption

Analytical solution

Revisiting the issue of steady state modeling, recall Equation (4) for a dimensionless groundwater system response time τ:

$$\tau = \frac{SL^2}{4TP}$$

where S [-] is the aquifer storage coefficient, L [m] the distance between head specified boundaries, T [m^2/day] the aquifer transmissivity (product of aquifer thickness and hydraulic conductivity), and P [days] the period of a periodic forcing function. When considering seasonal variations in flow in an alluvial aquifer, the definition of *L* is more conveniently defined as the distance between the river and the valley boundary (rock outcrop). Haitjema (2006) offers the following rules-of-thumb:

$\tau < 0.1$ treat transient flow in the aquifer as successive steady state.

$0.1 \leq \tau \leq 1$ transient flow cannot be meaningfully represented by a steady state model.

$\tau > 1$ represent transient flow by a steady state model using average boundary conditions.

For select community wells in the mid Animas River floodplain, the calculations for τ are shown in Table D-9.

If the daily forcing of the community water supply wells is assumed (i.e., 1 day), then $\tau > 1$, independent of other properties, and steady state modeling can be applied using averaged river elevations and pumping rates. If the annual spring snow melt forcing is assumed (i.e., 365 days), then there are cases where $\tau < 0.1$, and successive steady state modeling can be applied, but also cases when $0.1 \leq \tau \leq 1$, and transient modeling would be required. In order to capture the full spectrum of capture zones with use of a steady state model, both actual and averaged pumping rates and river stages should encompass the full range of cases. This is explored in the sensitivity analysis presented in a later section.

Table D-9. Dimensionless time factor for mid Animas River floodplain wells.

Realization	Storativity, S, (-)	Distance, L, ft	Transmissivity, T, gpd/ft	Periodicity, P, days	τ
1	0.29	2,285	314,628	365	0.02
2	0.29	2,285	129,621	365	0.06
3	0.36	2,285	129,628	365	0.07
4	0.36	2,285	129,621	365	0.07
5	0.29	4,805	314,628	365	0.11
6	0.29	5,830	314,628	365	0.16
7	0.36	5,830	314,628	365	0.20
8	0.29	4,805	129,621	365	0.26
9	0.36	4,805	129,628	365	0.33
10	0.36	4,805	129,621	365	0.33
11	0.29	5,830	129,621	365	0.39
12	0.36	5,830	129,621	365	0.48
13	0.29	2,285	314,628	1	9.00
14	0.36	2,285	314,628	1	11.17
15	0.29	2,285	129,621	1	21.84
16	0.36	2,285	129,621	1	27.12
17	0.29	4,805	314,628	1	39.80
18	0.36	4,805	314,628	1	49.40
19	0.29	5,830	314,628	1	58.58
20	0.36	5,830	314,628	1	72.73
21	0.29	4,805	129,621	1	96.59
22	0.36	4,805	129,621	1	119.91
23	0.29	5,830	129,621	1	142.20
24	0.36	5,830	129,621	1	176.52

Note: The realizations indicated in green signify a situation where a steady state averaged condition groundwater model would suffice; the yellow realizations signify the situations for successive steady state modeling; the orange realizations signify where transient groundwater modeling would be suggested.

Modeling of Transient Flow

The numerical model MODFLOW is capable of simulating transient flow. The community well 1000m70km (Figure D-31) has pumping test data to support the parameterization of the transient simulation (WestWater Associates Inc, 2010). The regional steady-state GFLOW model has a MODFLOW grid extract feature to setup the initial conditions for the transient simulation (See Figure D-32). The GFLOW model was used to select the size of grid in that the outer boundary condition does not influence the local scale drawdowns of the pumping well. The reported data from the pumping test included 1) transmissivity equals 129,621-314,628 gpd/ft; 2) storage coefficient equals 0.006-003; and 3) specific yield equals 0.3616-0.2881. There were some complications experienced in conducting the pumping test; the ranges were reported reasonable for this type of geology.

The MOFLOW model representation of the initial condition is shown in Figure D-33. The transient pumping well is added to this solution and placed at the center of the refined grid. The transient "pulsed pumping" (i.e., 12 hours on daytime; 12 hours off night-time) 10-day capture zone, in comparison to the steady state solution, is somewhat bigger (See Figure D-34). The MODFLOW/MODPATH simulations may introduce some numerical dispersion.

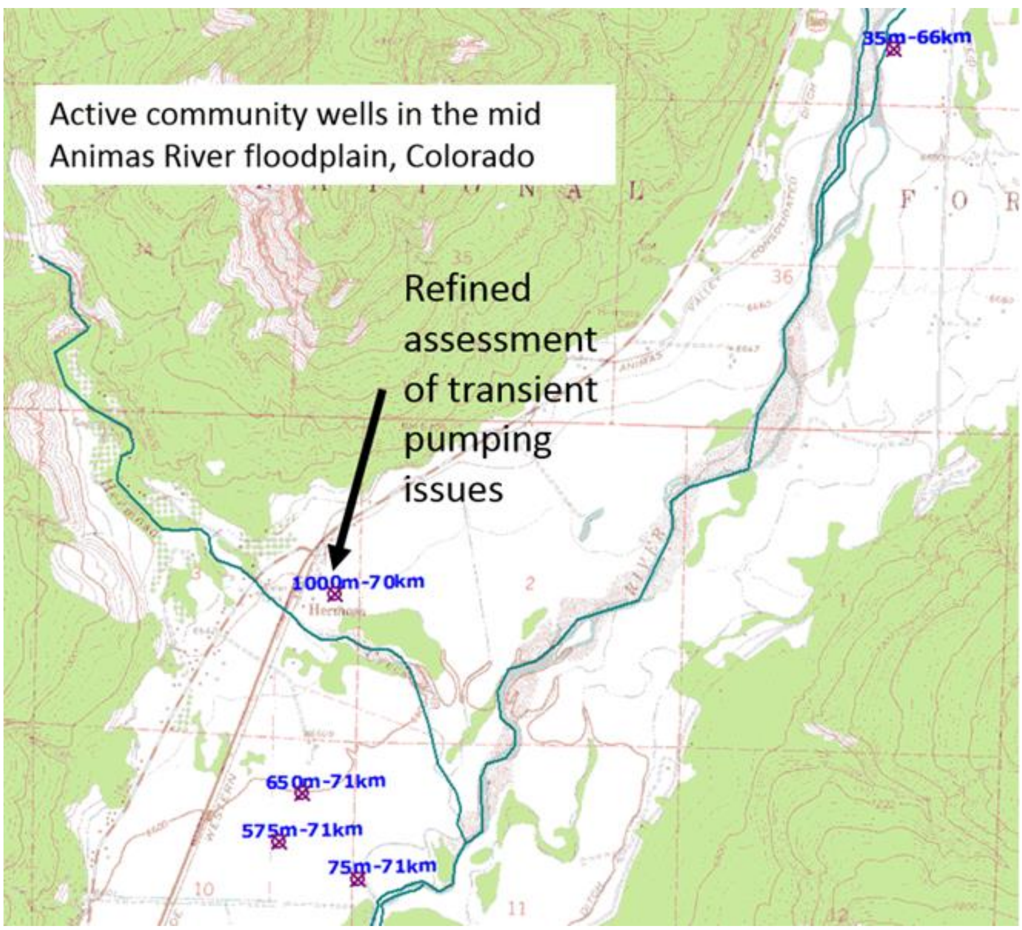


Figure D-31. The mid Animas River floodplain community well selected for exploration of transient flow. The well record included a pumping test.

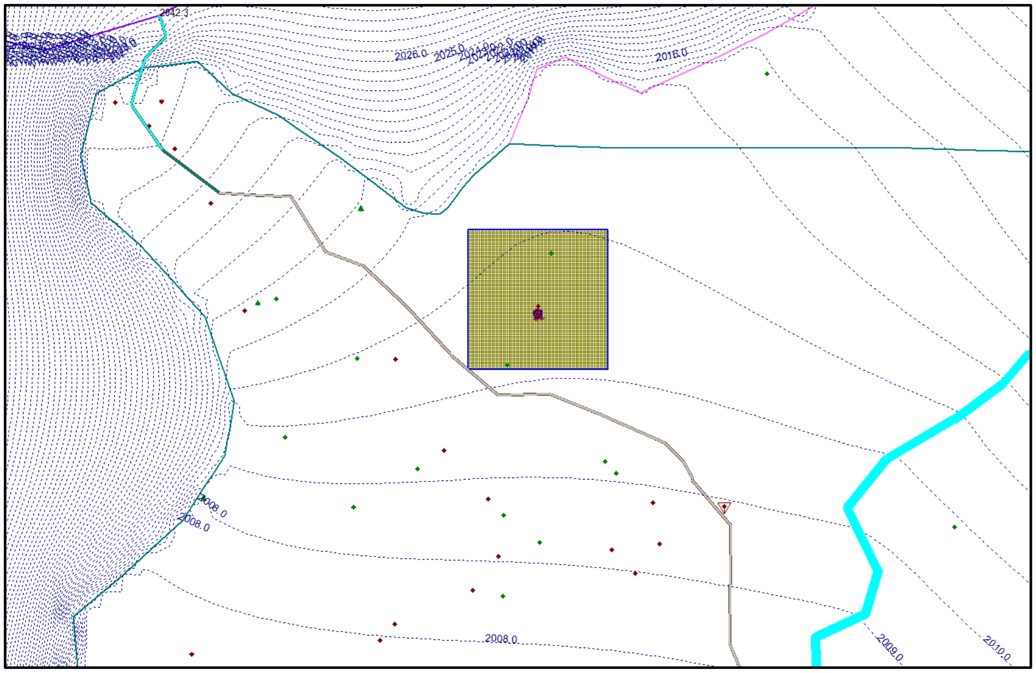


Figure D-32. The regional GFLOW model provides the initial heads to the outer cells of the MODFLOW model.

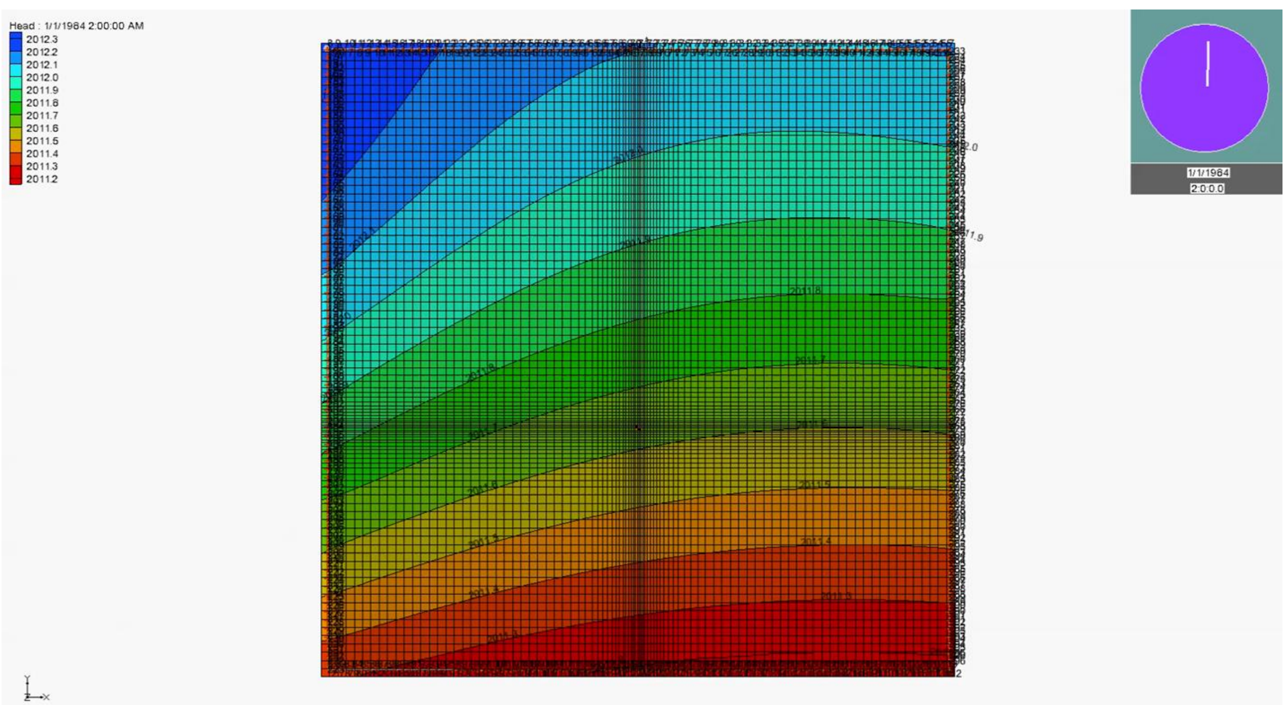


Figure D-33. The representation of initial (i.e., pre-pumping) hydraulic head conditions in the MODFLOW model.

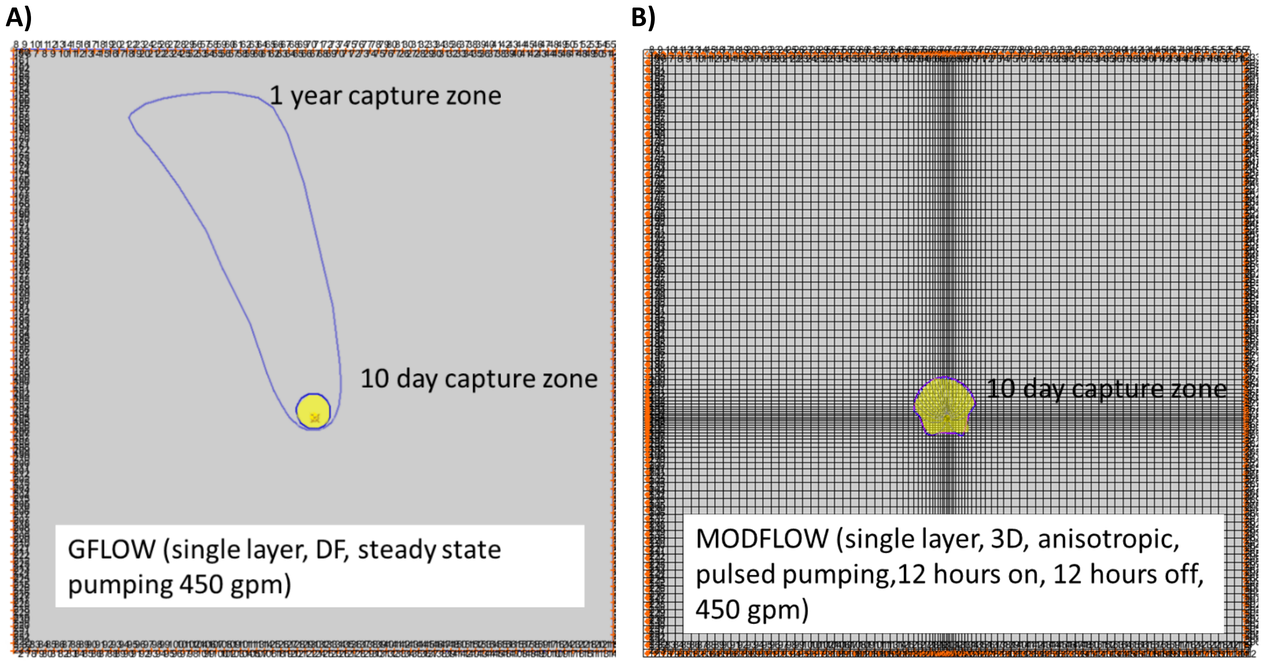


Figure D-34. GFLOW and MODFLOW models of capture zones for well 1000m70km. The pulsed and calibrated 10-day MODFLOW/MODPATH capture zone is assumed more realistic and is larger than the GFLOW steady state 10-day capture zone. This suggests there is some uncertainty in the simplified regional analysis.

Mid Animas: Exploration of Fully Three-Dimensional Flow vs. Dupuit-Forchheimer Flow

The numerical model MODFLOW is capable of simulating fully 3D flow, whereas the GFLOW model simulates 3D streamlines under the Dupuit-Forchheimer simplification that neglects resistance to vertical flow. The community well 35m66km (Figure D-35) has well driller's log data to support the parameterization of the 3D simulation (Beeman Bros. Drilling, 1984). The regional steady state GFLOW model has a MODFLOW grid extract feature to setup the initial conditions for the numerical simulation (See Figure D-36). The GFLOW model was used to select the size of grid in that the outer boundary condition does not influence the local scale drawdowns of the pumping well. The MOFLOW grid in plan and cross-sectional view is shown in Figure D-37; the location of the well is in the center of the grid refinement.

The total depth of the well is 100 feet. The 35m66km well is screened from 67 feet below ground surface to the bottom. The initial static water level was 31 feet, 10 inches below ground surface. The well sustained yield was 480 gallons per minute (i.e., 2,616.5 m^3/day) with a drawdown to 38 feet below ground surface.

The resulting capture zone and breakthrough times for the 3D MODFLOW simulation for mid Animas River floodplain community well 35m66km are shown in Figure D-38. The well is pumping at averaged rates.

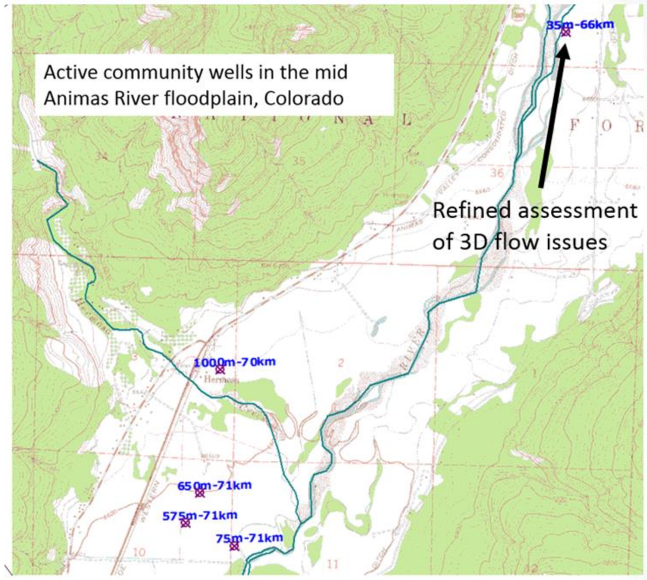


Figure D-35. The mid Animas floodplain community well selected for three-dimensional flow assessment.

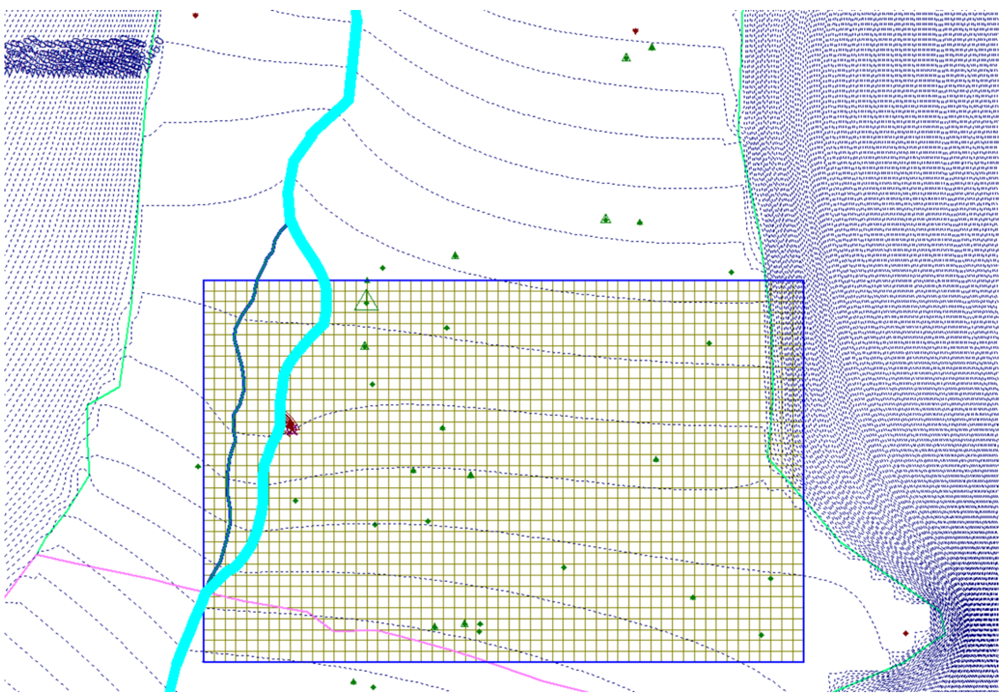


Figure D-36. The regional GFLOW model provides the hydraulic heads for the outer cells of the MODFLOW model. The boundary of the grid extract is 1,640 m by 1,020 m.

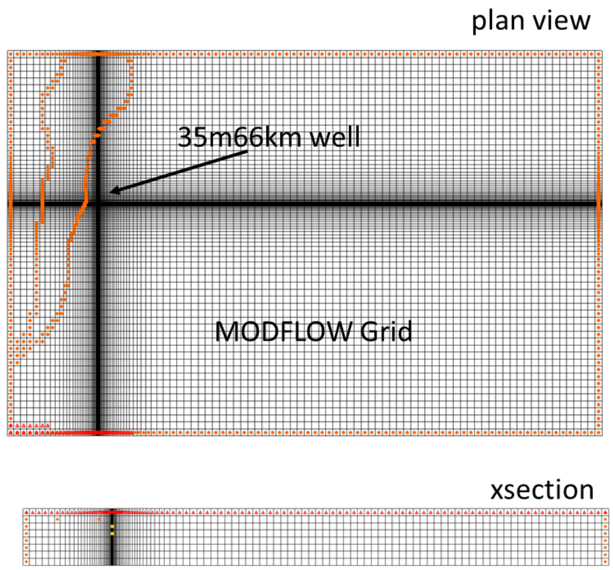


Figure D-37. The MODFLOW grid in plan view and cross-section view. The plan view cells are 1m x 1m in finest spatial resolution. Layers are 20-m thick. The well is represented in two stacked cells; the well discharge in each cell is proportional to the length of well screen in the associated layer.

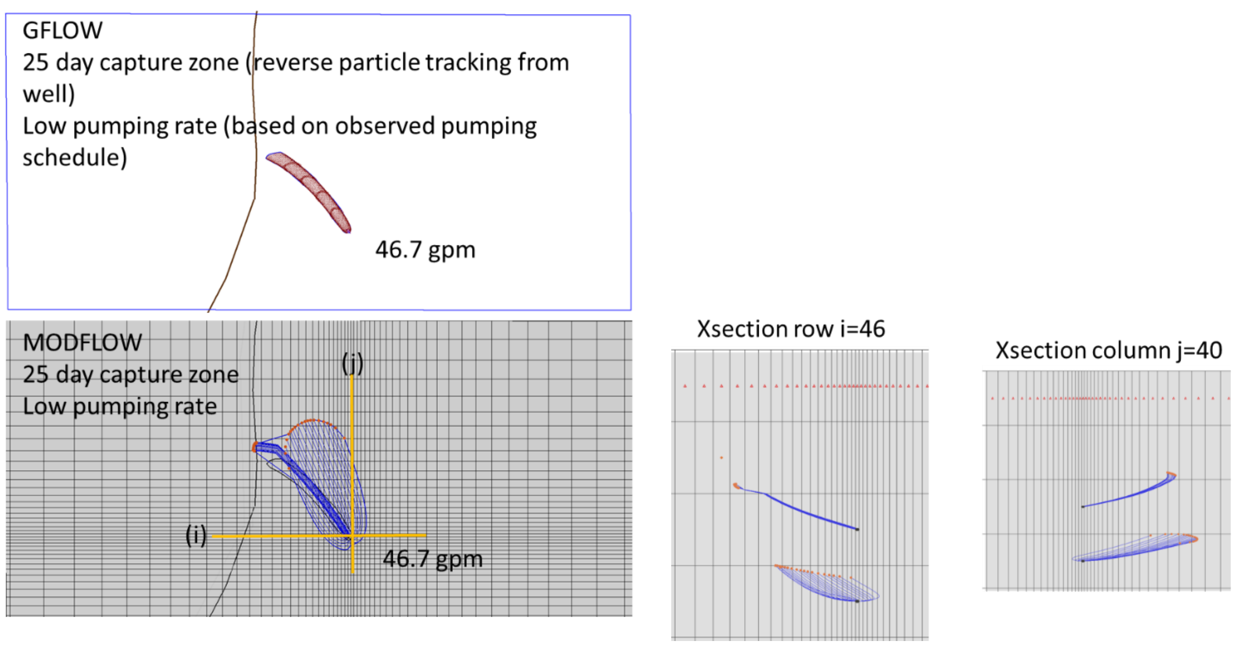
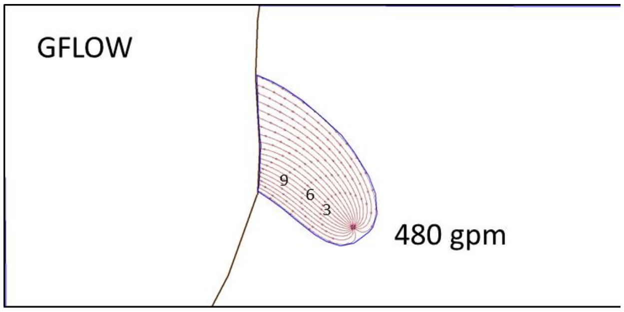
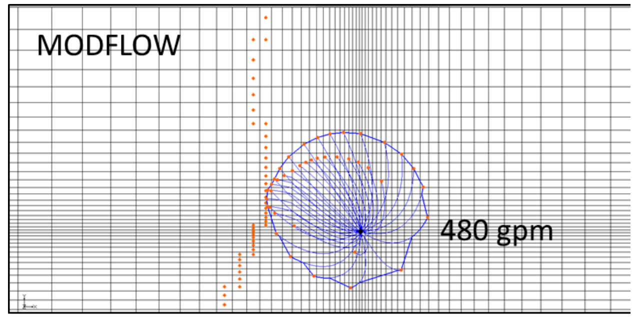


Figure D-38. The three-dimensional MODFLOW solution for the mid Animas community well. The simplified GFLOW model for well 35m66km is representative of the shallow transport pathways to the top of the well screen; the MODFLOW model shows a more complex story including different pathways to the top of the well screen and the bottom of the well screen. In both models the well communicates with the river, solute breakthrough using forward particle tracking in GFLOW is about 30 days and in MODFLOW is about 20 days.



GFLOW particle breakthrough 12 days



MODPATH particle breakthrough 9 days

Figure D-39. The influence of pumping rate on shallow breakthrough time, GFLOW in comparison to MODFLOW. Maximum pumping rates based on rated yield from driller's log. At the higher pumping rates, the 3D solution (MODFLOW) is closer in shape and breakthrough times to the DF solution (GFLOW). The 3D solution has earlier breakthrough times.

The simplified GFLOW model had comparable results for the shallow capture zone associated with the top of the well screen, although MODFLOW conservative solute breakthrough was about 30 days and GFLOW breakthrough around 20 days. The MODFLOW model suggested a broader and slower forming deeper capture zone associated with water entering the lower half of the well screen. If the well is pumped at maximum (unrealistic) rates, the simulated shallow capture zones for GFLOW and MODFLOW are closer in comparison, as shown in Figure D-39.

As expected, the simplified GFLOW model does not capture the local complexity of the MODFLOW model. The previous discussion suggested that the Dupuit-Forchheimer (DF) GFLOW model would overestimate the extent of capture. For the 35m66km well, the GFLOW model and MODFLOW/MODPATH model gave similar results for the shallow capture zone; MODFLOW suggested a broader and more slowly developing capture zone for the bottom of the well screen. The MODFLOW model would be expected to have lower head at the well than the DF model for the same discharge. The steeper hydraulic head gradients between the river and the well and thus an increase in velocities. The result would be earlier MODFLOW breakthrough times.

Mid Animas: Exploration of local scale aquifer heterogeneities and anisotropy

The presence of local scale aquifer heterogeneities, such as buried stream channels, or anisotropy introduced by layers of low permeable clays, might impact the interactions of nearby pumping wells with river waters. This section will focus on the 75m71km community well in the mid Animas River floodplain in order to evaluate the impact of heterogeneities on well capture zones and conservative solute breakthrough times (See Figure D-40).

A Google Earth image associated with the region around the 75m71km community well shows the Animas River and its immediate floodplain (See Figure D-41). A visual inspection suggests a potential buried alluvial channel associated with Hermosa Creek joining from the north. The photo interpretation suggests the boundaries to be represented in the local scale groundwater model.

The mid Animas regional GFLOW model provided the hydraulic heads on the outer domain boundary of the local scale AnAqSim model.

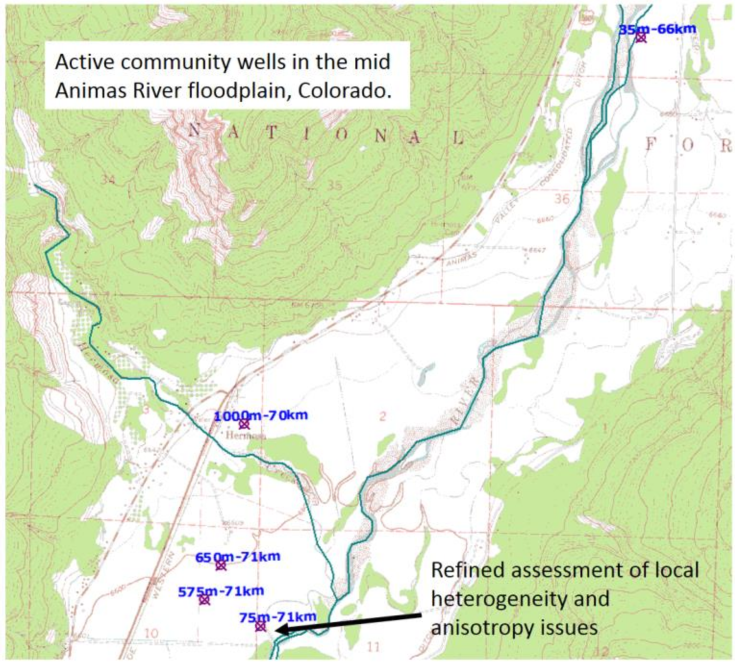


Figure D-40. The mid Animas River floodplain community well 75m71km selected for refined modeling of influence of local geologic heterogeneity.

Figure D-41. The domain of local scale heterogeneities to be detailed in the groundwater modeling of the 75m71km community well.

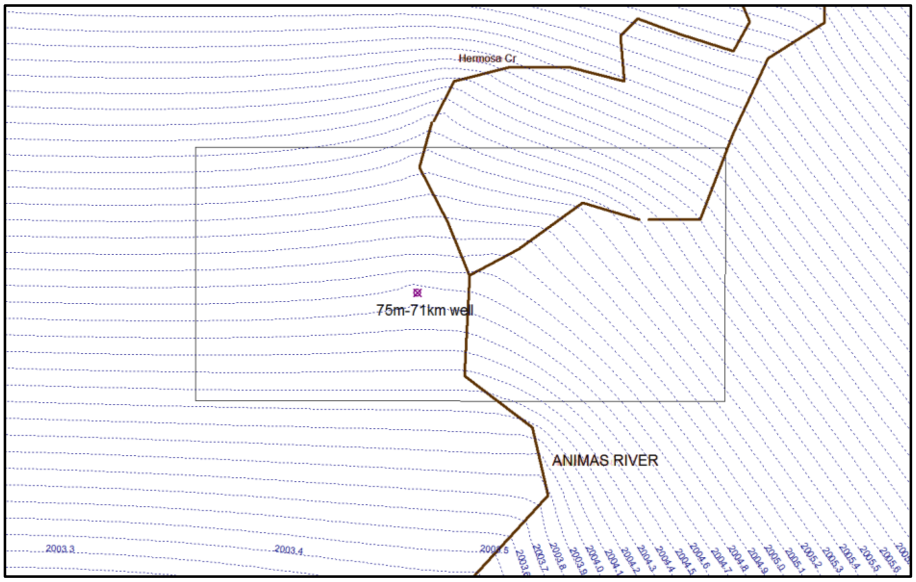
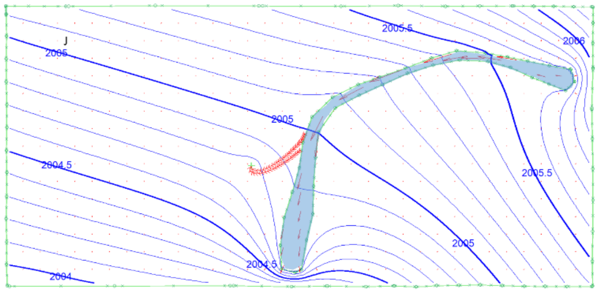


Figure D-42. The regional GFLOW model provides the heads on the boundary of the local scale AnAqSim model.

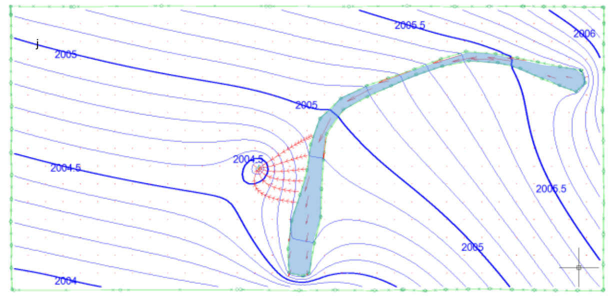
The AnAqSim model represents the local domain as a series of three potential subdomains. The Animas River channel is represented as a very high permeability (i.e., 1,000 m/day) subdomain. The Animas River floodplain subdomain is given a permeability of 100 m/day. The surrounding alluvium subdomain is given the permeability of 10 m/day. A series of scenarios are constructed based on average pumping rates (i.e., 145.74 acre-ft/yr=492.5 m^3/day) and high pumping rates (445 gpm = 2425.7 m^3/day) of the 75m71km community well. Porosity is assumed 0.25 in all domains. Also, all domains have anisotropic hydraulic conductivity (i.e., k_h/k_v = 10; See Figure D-43).

Under average pumping rates, the 75m71km community well would not be expected to source water from the Animas River. The scenario with no local scale heterogeneity is unlikely and presented for completeness. At the higher pumping rates, the community well is expected to receive Animas River water. The nature of the heterogeneity can cause a broad range of expected breakthroughs of a conservative solute from the river to reach the well, calculated by particle tracking, from 138 days to 289 days. Dilution is estimated to range from 25% to 33%.

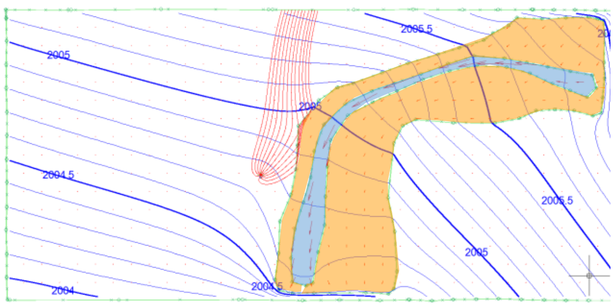
A) Avg Pumping, 1st arrival = 810 days, 17% dilution



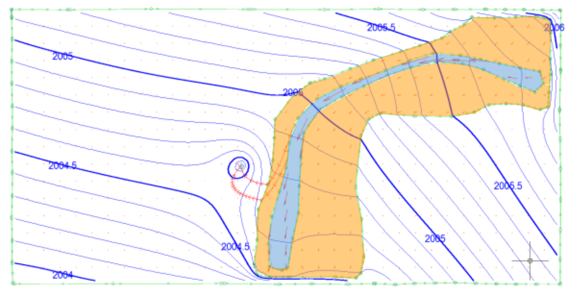
B) High Pumping, 1st arrival = 206 days, 50% dilution



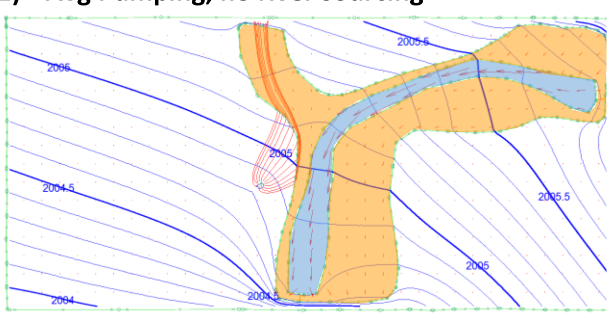
C) Avg Pumping, no river sourcing



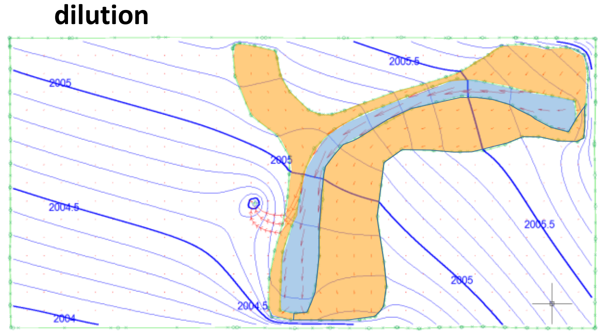
D) High Pumping, 1st arrival = 289 days, 25% dilution



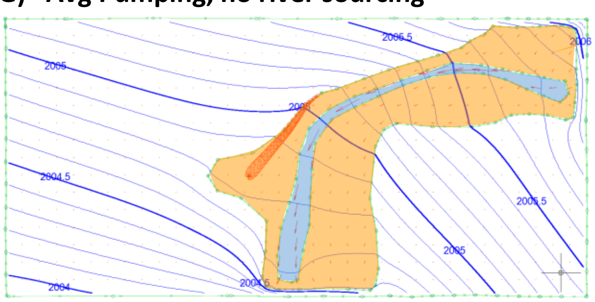
E) Avg Pumping, no river sourcing



F) High Pumping, 1st arrival = 176 days, 25% dilution



G) Avg Pumping, no river sourcing



H) High Pumping, 1st arrival = 138 days, 33% dilution

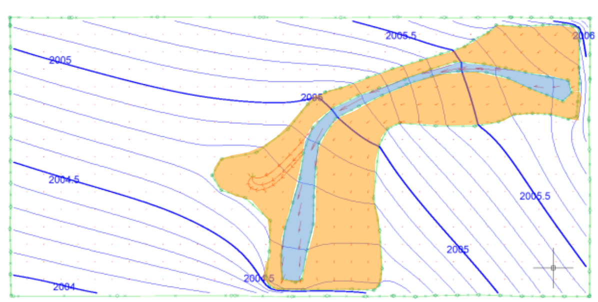


Figure D- 43. AnAqSim model runs exploring the influence of local scale heterogeneity on well capture, breakthrough times, and dilution of river-to-well source water.

Mid Animas: Sensitivity Analysis of Breakthrough Times of a Conservative Solute to a Pumping Well

Given the uncertainties in model conceptualization and parameterization, a sensitivity analysis was conducted to better understand the influence of major factors on capture zones and breakthrough times, including areal recharge, aquifer hydraulic conductivity, and well pumping rates. The mid Animas River floodplain community well 35m66km and the GFLOW model were used for the simulations. The summary of the runs is shown in Table D-10.

For this well and setting, a combination of high pumping rate, high aquifer hydraulic conductivity, and low seasonal recharge (i.e., August 2015 averaging) resulted in direct sourcing from the Animas River and the earliest dissolved solute breakthrough.

Table D- 10. The summary of GFLOW model simulations used for sensitivity analysis.

Run	Recharge Low N_{low}	Recharge High N_{high}	Hydraulic Conductivity Low k_{low}	Hydraulic Conductivity High k_{high}	Well Pumping Low Q_{low}	Well Pumping High Q_{high}	Source From River?	Model Predicted Breakthrough (days)
1	■		■		■		no	NA
2		■	■		■		no	NA
3	■			■	■		yes	154
4		■		■	■		yes	186
5	■		■			■	yes	66
6		■	■			■	yes	109
7	■			■		■	yes	25
8		■		■		■	yes	100

N_{low}= -1.165E-4 m/d; recharge low based on 8/1/2015 water balance, negative due to evapotranspiration possibly
N_{high}=+3.915E-4 m/d; recharge high based on August-October 2015 water balance
k_{low}=8.8 m/d; hydraulic conductivity alluvium low based on transmissivity from Smith well pumping test
k_{high}=36.63 m/d; hydraulic conductivity alluvium high based on transmissivity from Smith well pumping test
Q_{low}=190.2 m^3/d; well pumping rate low based on reported diversions
Q_{high}=2616.5 m^3/d; well pumping rate high based on well driller reported yield

Empirical Evidence

Dissolved metals that are 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 may have impacted floodplain wells through examination of empirical data (i.e., well water quality sampling).

Mid Animas River Floodplain Community Wells

There are interesting chemical signals of dissolved metals at the mid Animas River floodplain community well 35m66km (Figure D-43). Dissolved background dissolved 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 plume in Cement Creek was around 30 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 during August 12-18 show 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 (RK 65) was about 1.7 mg/l.

Based on empirical observation and analysis the GKM plume would be expected to arrive in the 35m66km community well area early in the day of June 6 and take less than 24 hours to pass. 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. Other metals showing an elevated response on August 14 included dissolved copper, lead, and nickel. Metals not indicating an elevated response on August 14 were aluminum, manganese, arsenic, beryllium, cobalt, selenium. The pH and iron values were not reported. See Figure D-44.

The CDPHE water quality measurements available in the other mid Animas community wells 75m71km, 650m71km, and 575m71km did not have noteworthy changes suggesting impact by the acid mine drainage release.

Might the elevated dissolved zinc and other metals be indicative of GKM plume water entering the 35m66km well? 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.

The groundwater modeling analysis did not include complications such as transient pumping and transient river flows, aquifer heterogeneities that might influence dissolve solute dispersion, or 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. The groundwater modeling at the 35m66km well did not include potential pumping interference from nearby private wells, or the influence of irrigation ditches. 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.

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

The significance of the potential impact is not commented on here. The secondary drinking water standard for zinc, based on taste, is 5 mg/l, and the observed peak well concentration is an order of magnitude below this standard.

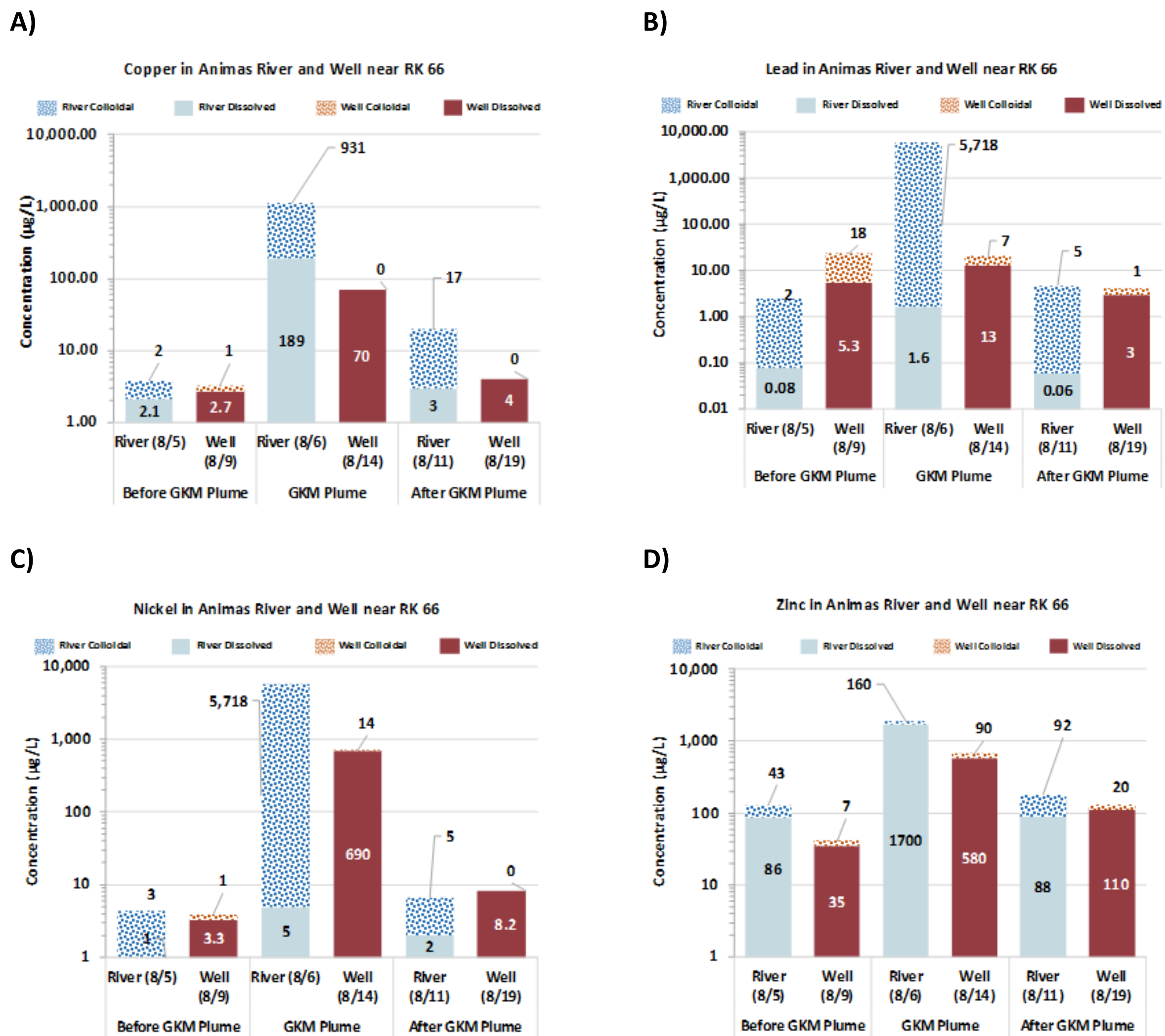


Figure D-44. River and well dissolved and colloidal metals concentrations around RK 66 of the mid Animas River in Colorado. The data are organized into before, during, and after plume time windows assuming the peak river plume passed the location on 8/6 and a potential 8-day lag in transport in the groundwater system before arrival at the well.

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 (i.e., near RK 163; See Figure D-45). The dissolved metals concentrations in the lower Animas River associated with the GKM release are 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 forms occurs. The community wells seem to indicate a fairly consistent groundwater quality concentration for copper, lead, nickel, and zinc, perhaps indicating the aquifer waters are in a state of equilibrium or long term mixing. The active spreading of river water via irrigation ditches may be a factor.

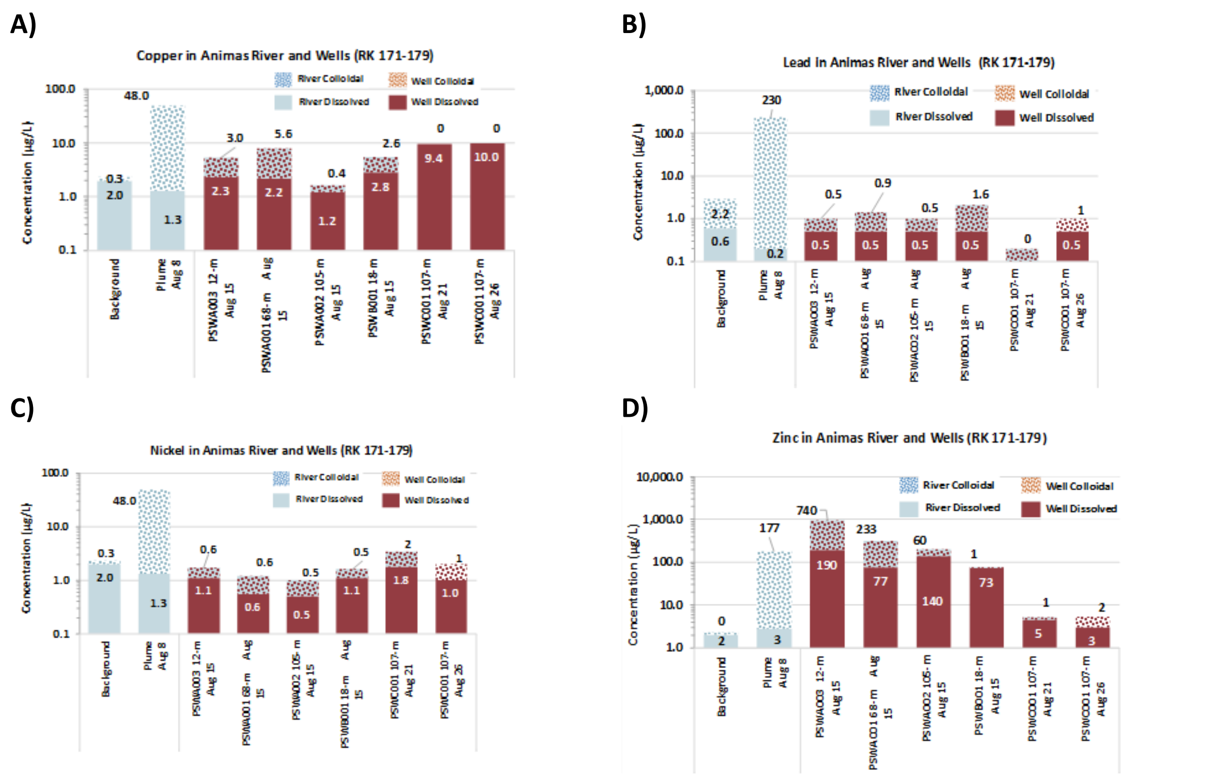


Figure D-45. River and well dissolved and colloidal metals concentrations around RK 163 of the lower Animas River in New Mexico.

Summary

The assessment of exposure of the floodplain wells to the GKM river plume evaluated the potential for the well to source its water directly from the Animas River, and if so, the expected breakthrough time of conservative river solutes to reach the well. In addition, dilution of direct river water compared to other sources of water in the well, such as rainfall recharge or deep aquifer contributions, were estimated. The empirical and computational methods used to evaluate the potential exposure were described in this Appendix. The results of the groundwater assessment are discussed in Chapter 8 of the main report and placed into context with the overall study.

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