Demonstrating BMP Effectiveness with Microbial Source Tracking and Host Fecal Score

Mauricio Larenas
Source Molecular Corporation, FL
mlarenas@sourcemolecular.com

ABSTRACT

Stakeholders in the Animas and San Juan watersheds routinely measure, among others, E. coli concentrations in the rivers. Microbial source tracking (MST) has been used to identify sources of contamination. MST markers, being specific to their targeted fecal sources, can specifically demonstrate if a particular source has been mitigated by the BMP even if FIB levels show little change. Additionally, a site human fecal score (HFS) has been developed by a team of researchers, from the U.S. Environmental Protection Agency, Southern California Coastal Water Research Project (SCCWRP), and Stanford University, to objectively assess the extent of human fecal contamination at a site using a standardized mathematically defined approach. The HFS gives a simple and intuitive way to assess and communicate BMP effectiveness by providing a score before and after BMP implementation.

INTRODUCTION

The most common pollutants and water quality problems reported in New Mexico include bacteria, nutrients, sediment, toxic metals and PCBs. The state is tasked under the Clean Water Act (CWA) to monitor all of its waterways, present that information to the public and restore polluted waters. The San Juan Soil & Water Conservation District (SWCD) noted that in recent years, the Animas and San Juan rivers have exceeded recommended limits of bacteria and nutrients in numerous locations.

Stakeholders in the Animas and San Juan watersheds routinely measure, among others, E. coli concentrations in the rivers. E. coli is one of the three most common causes of river and stream water quality impairments based on stream mileage in New Mexico.

Water quality issues often make headlines, increasing pressure on watershed managers to fix the problem. In addressing fecal contamination, watershed managers have traditionally turned to fecal indicator bacteria (FIB) in monitoring the presence of fecal matter in environmental waters. The chain of inference in water quality monitoring generally assumes that FIB in the water means there is waste. Waste is assumed to be human waste, which is understood to have pathogens. Pathogens are the organisms that can cause diseases. But the chain is broken when the assumptions aren't correct.

FIB are generally not pathogens themselves. FIB can come from a lot of sources - humans, animals, plants, soil, and biofilm. The public health risk changes from the different sources. This makes FIB an unreliable surrogate for pathogens and an ineffective tool to assess fecal contamination in areas where multiple sources exist.

MICROBIAL SOURCE TRACKING

The San Juan SWCD and its partners, including the San Juan Watershed Group, have been working to identify the sources of pollution in local rivers. Watershed managers recognize that it is difficult to implement mitigation measures without knowing exactly where the bacteria came from. One of the technologies used to identify bacteria sources is microbial source tracking (MST).

MST is a set of methods used to identify the bacteria source. The technology analyzes gut bacteria and looks for genetic markers that are unique to specific hosts. The unique microbial DNA sequences are used as markers in PCR assays for the detection of fecal contamination in water for that particular source.

Genetic testing has been used in other industries such as forensics and food. It's been dubbed as the new gold standard in forensic science and used by the Centers for Disease Control and Prevention in finding the source of E. coli outbreaks.

Genetic technology provides answers to questions such as where is the pollution coming from, who is responsible, and how to evaluate effectiveness of best management practices (BMPs). BMPs are used to target the identified sources of contamination for mitigation. By using MST markers, watershed managers can specifically demonstrate if their BMPs have been effective in mitigating a particular source regardless of the FIB levels.

MST DEVELOPMENT & APPLICATIONS

There is a tremendous amount of precedent in the utilization of MST technology. MST projects are being conducted all over the United States. It has achieved national validation and recognized in projects such as the State of California Source Identification Pilot Project (SIPP) Method Evaluation Study, where they developed a source identification manual that includes MST. An MST laboratory in Florida has also been accredited by the International Organization for Standardization (ISO), in further recognition of the testing methods. Moreover, an objective interpretation of MST results have also been developed by a team of researchers to remove biases found in best professional judgment (BPJ).

MST is also being applied at each stage in the Clean Water Act. The primary objective of the Clean Water Act is to restore and maintain the integrity of the nation's waters. The water quality-based approach of the CWA includes assessing the waters, listing impaired and threatened waters, and developing the Total Maximum Daily Load (TMDL). DNA analysis of water samples is also being accepted in stormwater permitting.

The Georgia Department of Natural Resources, for example, indicated in its Authorization to Discharge Under the National Pollutant Discharge Elimination System (NPDES) Storm Water Discharges Associated with Industrial Activity that scientific testing, such as DNA analysis, may be used to document that bacteriological constituents found in stormwater discharges from the facility are not present as a result of industrial activity at the site or are below the impaired waters benchmark for fecal coliform.

Planning an MST project involves careful selection of sampling sites, sampling events and tests. Sampling sites must be selected based on fecal bacteria hotspots and must represent the watershed's spatial variability. Samples must be collected near physical sources. Sampling events should occur during wet and dry weather and should take into account seasonal changes. There must be a significant number of sampling events to represent temporal variability. In choosing the tests, focus should be given on anthropogenic sources such as human, dog, and agriculture. If wildlife is the most likely source, then test for birds and deer.

MST CASE STUDIES

Martin County, FL

MST is useful in site prioritization as demonstrated by a project conducted by Martin County in Florida. The County identified high levels of fecal contamination at an estuary that had a septic system. They had an assessment and determined that they need to switch the septic system into a sewer system. They hired a consultant who calculated that the system change was going to cost the County at least $138 million. The County did not have the money on hand do this so they developed a 100-year plan to implement the change. Their problem was how to begin in a way that would have a positive impact on the water quality. The County determined that they needed to rank the sites in order to know which sites to prioritize. They used MST markers to do the site ranking. Out of 25 geographic sites, the County was able to identify two principal areas where they would have the biggest impact on the human waste in the estuary. This could only be achieved with MST and not legacy technologies.

Boston, MA

The first ever effectiveness assessment of an MS4 Illicit Discharge Detection and Elimination (IDDE) program used DNA markers. It was for a study that won an award from the National Association of Clean Water Agencies (NACWA). The MST study is entitled "Utilizing DNA Markers for Identification of Human and Non-Human Fecal Sources in Urban Stormwater." GeoSyntec Consultants designed and led the MST study for the Boston Water and Sewer Commission (BWSC). BWSC maintains the City of Boston's water and sewer services and continues to implement one of New England's most rigorous IDDE programs throughout their Municipal Separate Storm Sewer System (MS4). As an additional proactive measure, BWSC retained GeoSyntec to determine whether and where bacteria in their MS4 outfalls and interconnections are due to human versus non-human sources and to evaluate ongoing IDDE program efficiency. GeoSyntec developed a hypothesis-driven study that assesses bacteria and nutrient sources to and within BWSC's MS4. GeoSyntec also assessed the spatial/temporal patterns of these pollutants, and the reliability of conventional and EPA-recommended IDDE indicators. The study incorporated the latest and most proven analytical tools. This includes droplet digital quantitative PCR for human and non-human DNA markers.

Santa Barbara, CA

In California, MST technology helped Santa Barbara not only to identify pollution sources at their beaches but also to measure the impact of their best management practices (BMP). Under a Clean Beaches Initiative grant, Santa Barbara used MST to identify what was causing the high levels of fecal pollution in their beaches. They found out that one of the major contributors were dogs. One of the BMPs they carried out was an outreach program where they went door to door and encouraged dog owners to pick up after their dogs. After implementing this BMP, Santa Barbara conducted further MST analysis to determine if their outreach program was effective in reducing the dog fecal bacteria in the water.

HUMAN FECAL SCORE

BMP effectiveness can also be demonstrated using a site human fecal score (HFS). The HFS has been developed by a team of researchers, from the U.S. Environmental Protection Agency, Southern California Coastal Water Research Project (SCCWRP), and Stanford University, to objectively assess the extent of human fecal contamination at a site using a standardized mathematically defined approach.

MST data is usually interpreted using best professional judgment (BPJ) but a study showed that there is a high level of inconsistency among experts. For that reason, researchers sought to remove bias in MST data interpretation and reduce it into a single number that statistically integrates all human fecal marker data from all samples at a given site. All data means those that are quantifiable, detected but not quantifiable, and non-detect because even non-detects contain valuable information.

The HFS gives a simple and intuitive way to assess and communicate BMP effectiveness by providing a score before and after BMP implementation. This approach can also be applied to other fecal host sources, for example, a cow fecal score if a cow fecal MST marker is used in place of the human fecal MST marker. The use of these advanced technologies therefore can provide effective evaluation of BMP performance, and inform selection and implementation of BMP to obtain highest benefit of protecting public health with lowest cost of BMP implementation.

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NMBGMR AML Project: Characterization of Inactive/Abandoned Mine (AML) Features in New Mexico and Southern Colorado

Virginia T. McLemore[1]

[1]New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801

Marcus Silva[2], Navid Mojtabai[2]

[2]Department of Mineral Engineering, New Mexico Institute of Mining and Technology, Socorro, NM 87801

John Asafo-Akowuah[3]

[3]Aurifer Consulting, Accra Digital Center, Ring Road West, Accra, Ghana

ABSTRACT

Abandoned mine lands (AML) are lands that were mined and left un-reclaimed where no individual or company has reclamation responsibility and there is no closure plan in effect. These may consist of excavations, either caved in or sealed, that have been deserted and where further mining is not intended in the near future. The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and the Mineral Engineering Department at New Mexico Tech is conducting research to develop a better procedure to inventory and characterize legacy, inactive, or abandoned mine features in New Mexico. Many of these mine features do not pose any physical or environmental hazard. However, other inactive or abandoned mine features can pose serious health, safety and/or environmental hazards, such as open shafts and adits (some concealed by deterioration or vegetative growth), tunnels and drifts that contain deadly gases, radon, highwalls, encounters with wild animals, and metal-laden waters, locally acidic. Other sites have the potential to contaminate surface water, groundwater and air quality. Heavy metals in mine waste piles, tailings and acid mine drainage can potentially impact water quality and human health. The results of our study will prioritize the mine features in selected mining districts in New Mexico for safe guarding and remediation and determine if mine wastes are suitable for backfill and cover material. Many of the mine features in the districts examined so far are shallow prospect pits and short adits, but approximately 20-30% have physical hazards (open shafts, adits) and require safeguarding. Most of the waste rock piles surrounding the mine features are suitable for backfill material. Samples from the Silverton area, Colorado and the Jicarilla district, New Mexico have potential for generating acid and these materials need to be handled as such. Most mine features examined so far in these districts are stable, but a few have collapsed near the entrances. There is future mineral-resource potential for minerals in some of these districts.

INTRODUCTION

Legacy issues of past mining activities forms negative public perceptions of mining, and inhibits future minerals production in the state. Some legacy mines have the potential to contaminate the environment; the Gold King uncontrolled release into the Animas River is a recent example. At the time the General Mining Law of 1872 was written, there was no recognition of the environmental consequences of discharge of mine and mill wastes or the impact on drinking water and riparian and aquatic habitats. Miners operating on federal lands had little or no requirement for environmental protection until the 1960s-1970s, although the dumping of mine wastes and mill tailings directly into rivers was halted by an Executive Order in 1935. It is important to recognize that these early miners were not breaking any laws, because there were no laws to break, but legacy issues still exist and should be remediated.

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has been examining environmental effects of mine waste rock piles and tailings throughout New Mexico since the early 1990s (http://geoinfo.nmt.edu/staff/mclemore/projects/environment/home.html). There are tens of thousands of inactive or abandoned mine features in 274 mining districts in New Mexico (McLemore, 2017; including coal, uranium, metals, and industrial minerals districts), and many more in Colorado. However many of these inactive or abandoned mines have not been inventoried or identified as needing reclamation. The New Mexico Abandoned Mine Lands (AML) Bureau of the New Mexico Mining and Minerals Division (NMMMD) estimates that there are more than 15,000 abandoned mine features in the state (http://www.emnrd.state.nm.us/MMD/AML/amlmain.html). The New Mexico AML Program has safe guarded over 2,300 mine openings since inception in 1981 in about 250 separate construction projects (some of which were focused on coal gob reclamation and not safe guarding). The U.S. Bureau of Land Management (BLM) recently estimated that more than 10,000 mine features are on BLM lands in New Mexico and only 705 sites have been reclaimed (http://www.blm.gov/wo/st/en/prog/more/ Abandoned_Mine_Lands/abandoned_mine_site.html). The U.S. Park Service has identified 71 mine features in seven parks in New Mexico, of which 12 have been mitigated and 34 require mitigation (https://www.nps.gov/subjects/abandonedminerallands/upload/NPS_AMLinv-2013-1231-2.pdf). Additional sites have been reclaimed by the responsible mining companies or the Superfund program (CERCLA). Data in the NMBGMR mining archives suggest that these numbers are minimal conservative estimates of the actual number of un-reclaimed mine features in the state.

The NMBGMR has collected published and unpublished data on the districts, mines, deposits, occurrences, and mills since it was created in 1927 and is slowly converting this historical data into a relational database, the New Mexico Mines Database (McLemore et al., 2005a, b). More than 8,000 mines are recorded in the New Mexico Mines Database and more than 7,700 are inactive or abandoned. These mines often include two or more actual mine features. Most of these mine features do not pose any physical or environmental hazard. Some of these inactive or abandoned mine features can pose serious health, safety and/or environmental hazards, such as open shafts and adits (some concealed by deterioration or vegetative growth), tunnels and drifts that contain deadly gases, radon, highwalls, encounters with wild animals, and metal-laden waters, locally acidic. Other sites have the potential to contaminate surface water, groundwater and air quality. Heavy metals in mine waste piles, tailings and acid mine drainage can potentially impact water quality and human health.

Many state and federal agencies and mining companies have mitigated many of the physical safety hazards by closing some of these mine features, but very few of these reclamation efforts have examined the long-term environmental effects. There is still potential for environmental effects long after remediation of the physical hazards, as found in several areas in New Mexico (for example Terrero, Jackpile, and Questa mines). Understanding these effects involves petrographic studies and some of these observations only come from detailed geochemical and electron microprobe studies that are not part of a remediation effort.

The NMBGMR in cooperation with the Mineral Engineering Department at New Mexico Tech and the AML program is conducting research on legacy mine features in New Mexico. The objective of our research is to develop a better procedure to inventory and characterize legacy, inactive or abandoned mine features in New Mexico. This project will inventory, characterize, and prioritize for remediation the mine features in several mining districts in New Mexico. The project involves field examination of the mines features and collecting data on the mine features (Bureau of Land Management, 2014). Samples are collected to determine total whole rock geochemistry, mineralogical, physical, and engineering properties, acid-base accounting, hydrologic conditions, particle size analyses, soil classification, shear strength testing for stability analysis, and prioritization for remediation, including hazard ranking. Not only are samples collected for geochemical and geotechnical characterization, but the mine features are mapped, evaluated for future mineral-resource potential, and evaluated for slope stability. The results of this study will prioritize the mine features in selected mining districts in New Mexico for remediation.

DEFINITION OF ABANDONED MINE LANDS

A mine (or mine feature) is any opening or excavation in the ground for extracting minerals, even if no actual mineral production occurred. Abandoned mine lands (AML) are lands that were excavated, left un-reclaimed, where no individual or company has reclamation responsibility, and there is no closure plan in effect. These may consist of excavations, either caved in or sealed, that have been deserted and where further mining is not intended in the near future. AML includes mines and mine features left un-reclaimed on land administered by Federal, State, private, and Native Americans because the current owner was not legally responsible for reclamation at the time the mine was created. These mine features also are called inactive, legacy, and orphaned mines. In the NMBGMR AML project we are examining mines that are not technically AMLs and may have responsible owners that are in the process or have remediated the mine.

Note that other agencies have slightly different definitions of AML. The Surface Mining and Reclamation Act (SMARA) defines abandoned surface mined areas as mined lands that meet all of the following requirements (Section 2796 (b)(2)(A)(ii)):

- Mining operations have ceased for a period of one year or more.
- There are no approved financial assurances that are adequate to perform reclamation in accordance with this chapter.
- The mined lands are adversely affected by past mineral mining, other than mining for coal, oil, and gas, and mineral material mining.

California defines *abandoned mine* as the location of any mineral extraction, exploration or borrow operation that may include, but is not limited to, shafts and adits, buildings and workings, open pits, stockpiles, roads, processing areas, waste disposal areas, or tailing piles and ponds, and which meet all of the following conditions:

- Mining operations have ceased for a period of one year or more.
- There is no interim management plan in effect.

The National Orphaned and Abandoned Mines Initiative (NOAMI) in Canada defines *orphaned or abandoned mines* as those mines for which the owner cannot be found or for which the current owner is financially unable to carry out cleanup (http://www.abandoned-mines.org/en/).

METHODS

Field Inventory

Published and unpublished data on existing mines and mills within five districts in New Mexico (Figure 1) were inventoried and compiled in the New Mexico Mines Database (McLemore et al., 2005a, b; McLemore, 2017). Mines in the Silverton area were inventoried by Church et al. (2007). Names of types of mineral deposits (i.e., volcanic-epithermal veins, sandstone uranium deposits, etc.) are from Cox and Singer (1986), North and McLemore (1986, 1988), McLemore (1996, 2001, 2017), McLemore and Chenoweth (1989, 2017), and McLemore and Lueth (2017). Locations of mines were obtained from published reports, files at the NMBGMR, and patented mining claims files.

Known mines and mineralized areas were examined and mapped. Mining was by surface and/or underground methods (pits, shafts and/or adits) and waste rock piles are located around or near the openings of most of these features. Waste rock piles were mapped using a handheld GPS and/or measuring tape. Some mines were located and described in the literature or mines records, but could not be found during the field investigation; these features were included in the database and identified as not found.

A field inventory form was designed to collect data on all mine features during the field examination, which were later entered into the New Mexico Mines Database. Inventory procedures employed are described in Bureau of Land Management (2014). Photographs and sketch maps are included. Depths of shafts were rarely determined by a tape measure; generally depths of shafts were estimated by visual, if safe, or by pitching a rock into the opening and estimating the depth.

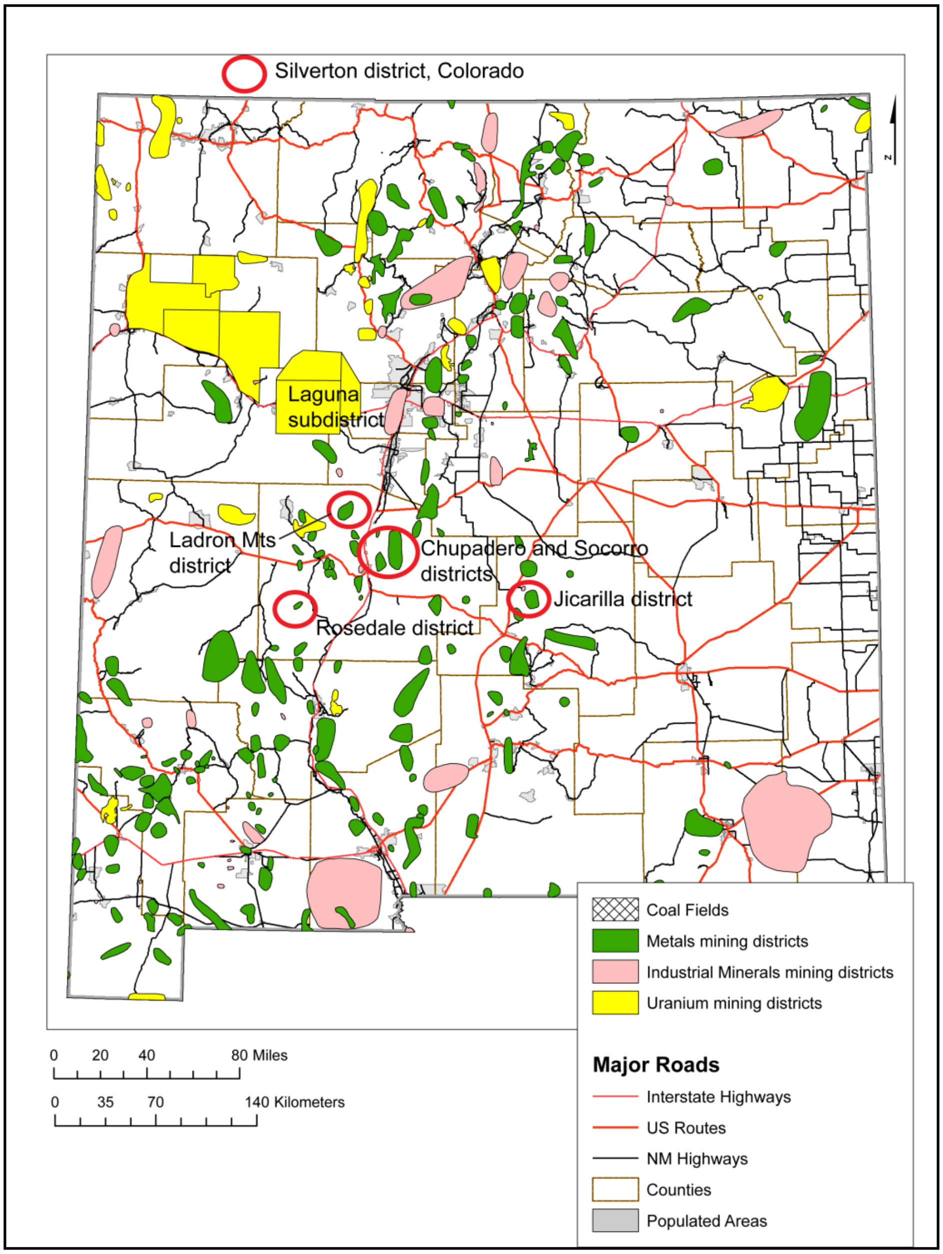

Figure 1. Location of mining districts examined during this study (McLemore, 2017).

Buildings, trash dumps, water wells, springs, and other archaeological and water features also were inventoried.

Sample Collection

In order to evaluate AML sites, a variety of field sampling methods of solid, water, and biological media are required, if present. Sampling and laboratory analyses are important to:

- Determine the mineralogy/chemistry of the mineral deposit and waste rock, especially sulfide minerals, in order to determine if the rock is potentially acid generating.
- Understand weathering processes, both at the surface and within the waste rock and tailings piles, in order to understand the effect of weathering on the acid drainage potential and the long-term physical stability of the rock piles, tailings, and other mine features.
- Identify water quality problems caused by drainage and related activities from legacy mines.
- Determine how reactive pyrite and carbonate minerals are in order to evaluate acid drainage potential and other water quality issues.
- Determine the suitability of existing waste rock piles for backfill material.

A *sample* is a representative portion, subset, or fraction of a body of material representing a defined population (Koch and Link, 1971; Wellmer, 1989; Davis, 1998; Neuendorf et al., 2005; Downing, 2008; McLemore et al., 2014). A sample is that portion of the population that is actually studied and used to characterize the population. Collecting a representative sample of waste rock-pile material can be difficult because of the compositional, spatial, and size heterogeneity of the material. It is necessary to define the particle-size fraction of the sample required and analyzed, because of the immense size heterogeneity in many waste rock piles (Smith et al., 2000).

Composite samples of waste rock piles were collected, using procedures developed by Munroe (1999) and the U.S. Geological Survey (Smith et al., 2000; Smith, 2007; McLemore et al., 2014). Evenly spaced metal flagging pegs were positioned across an entire rock pile at each site marking a subsample location. Subsamples are collected with a small stainless steel hand trowel or shovel and sieved using 0.5 mm mesh into a 5-gallon bucket. Approximately two shovels of material were collected from each marked location on the waste pile. Subsamples are then mixed thoroughly and stored in buckets or large plastic bags. Sampling equipment is cleaned after sampling each waste pile. A subsample of the homogenized, composite sample was split for petrographic, mineralogical, geochemical and geotechnical analyses. Figure 2 is a flow chart describing the steps in collecting samples and the laboratory analyses performed on selected samples.

Laboratory Analyses

Sample preparation

Laboratory analyses were performed on selected samples based upon a combination of criteria including the size of the mine waste rock pile (i.e., larger piles in the district) and mineral composition (i.e., presence of pyrite and/or jarosite and other sulfide/sulfate minerals). Selected rock chips and fragments from the waste rock piles or from outcrops were collected in order to determine the mineralogical and chemical composition. Sample preparation for different laboratory analyses is summarized in Table 1.

Petrographic descriptions and mineralogy

Petrographic analyses were performed using standard petrographic techniques (hand lens and binocular microscope); these analyses were supplemented by thin section petrography, electron microprobe analyses, X-ray diffraction (XRD) analyses, and whole-rock chemical analyses. Modal mineralogy was estimated using standard comparison abundance charts. Mineral concentrations and phase percentages, grain size, roundness, and sorting were estimated using standard charts (Carpenter and Keane, 2016). Data will be presented in future reports.

Bulk mineral identification can be used to identify minerals present in quantities greater than approximately 3%. Estimates of both primary and secondary minerals were determined, cementation and alteration described, and mineralogy and lithology identified (Folk, 1974; Carpenter and Keane, 2016). Any special features were noted. Altered, unaltered, and mineralized samples, including select samples of cement, are powdered and analyzed by X-ray diffraction (XRD).

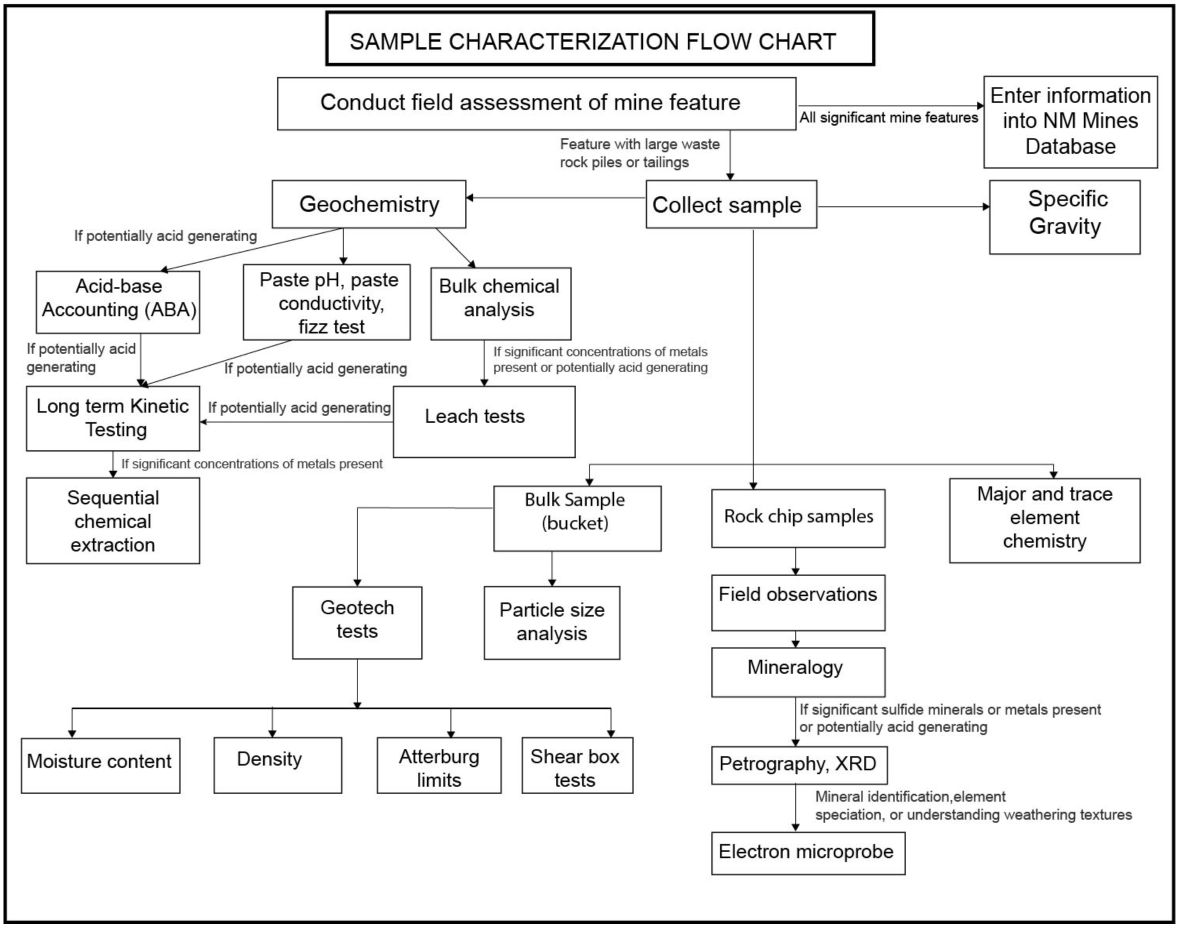

Figure 2. Sample characterization flow chart.

Table 1. Summary of sample preparation for different laboratory analyses. XRF–X-ray fluorescence analyses. XRD–X-ray diffraction analysis. ICP–Induced-coupled plasma spectrographic analysis.

Laboratory analysis	Type of sample	Sample Preparation	Method of obtaining accuracy and precision
Petrographic analyses	Collected in the field, used split from chemistry sample	Uncrushed, typically smaller than gravel size material used, thin sections made of selected rock fragments	Not applicable
Paste pH and paste conductivity	Collected in the field, used split from chemistry sample	Uncrushed, typically smaller than gravel size material used	Use duplicates, compare to mineralogical analysis
Whole-rock chemical analysis (XRF, ICP, S/SO_4)	Collected in the field in separate bag, analysis performed on powdered sample	Crushed and pulverized	Use reference standards and duplicates
Chemical analyses of water samples	Collected in the field in bottles	Refrigerated until analyzed	Use reference standards and duplicates
Particle size analysis	Bulk sample collected in the field	Sample sieved for each size fraction weighed	Not applicable
X-ray diffraction (XRD) analyses	Used select split from chemistry sample	Crushed	Compared to detailed analysis by electron microprobe
Electron microprobe analyses	Collected in the field or split from chemistry sample	Uncrushed, generally rock fragments or soil matrix	Use reference standards

Weathered mine waste rock piles typically contain some amount of amorphous material that cannot be identified by XRD (Smith et al., 2000), but by integrating electron microprobe and geochemical data this material are characterized. This amorphous material typically contains metals that can be released into the water and also may form clay minerals. This amorphous material in some cases acts as a cement.

Paste pH and conductivity

Paste pH and paste conductivity were determined to predict geochemical behavior of mine waste rock materials subjected to weathering under field conditions and to estimate or predict the pH and conductivity of the pore water resulting from dissolution of secondary mineral phases on the surface of oxidized rock particles. The paste conductivity values were converted to total dissolve solids (TDS) using standard procedures (http://www.chemiasoft.com/chemd/TDS). Data for selected samples will be presented in future reports.

Geochemistry of solid samples

Samples underwent multiple analyses such as X-Ray Fluorescence (XRF), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectrometry (ICP-MS) at the ALS Laboratory Group in Reno, Nevada for evaluation of major and trace elements (CCP-PKG03 and Au-ICP21; https://www.alsglobal.com/myals/downloads?keywords=Geochemistry+Fee+Schedule&category=b5b5208b58bc4609bd2fa20f32d820f8. Samples were dried, crushed, split and pulverized according to standard ALS Laboratory Group preparation methods PREP-31; https://www.alsglobal.com/myals/downloads?keywords=Geochemistry+Fee+Schedule&category=b5b5208b58bc4609bd2fa20f32d820f8). This package combines the whole rock package ME-ICP06 plus carbon and sulfur by combustion furnace (ME-IR08) to quantify the major elements in a sample. Trace elements, including the full rare earth elements (REE) suites, are performed after three acid digestions with either ICP-AES or ICP-MS finish: 1) a lithium borate fusion for the resistive elements (ME-MS81), 2) a four acid digestion for the base metals (ME-4ACD81) and 3) an aqua regia digestion (ME-MS42). Gold was analyzed separately (Au-ICP21). Chemical analyses will be reported in future reports.

Ongoing control and duplicate samples were submitted with each batch of samples submitted. Certified standards are commercial standards with certified values as determined by round robin analyses at numerous certified laboratories. Certified standards are expensive, so ongoing control samples were analyzed instead. The ongoing control samples are standards collected by NMBGMR personnel and analyzed by different methods over several years of analyses by different laboratories. A summary of the quality assurance and quality control (QA/QC) is in McLemore and Frey (2009).

X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis was conducted on selected portions of composite mine waste rock samples to determine the mineralogy. Samples were ground into a well-homogenized material with a mortar and pestle, forming a fine powder (~75µ/0029 mesh). This was poured into an aluminum sample holder and mounted with the silicon standard in the XRD instrument. A five-minute absolute scan analysis was run. Sample analyses were performed using an appropriate software program. More details are found at NMBGMR website (https://geoinfo.nmt.edu/labs/x-ray/home.html).

Electron microprobe mineralogical analyses

Samples were examined using a Cameca SX100 electron microprobe with three wavelength-dispersive spectrometers at New Mexico Institute of Mining and Technology (NMIMT) to characterize compositional, chemical and textural characteristics. Samples chosen for microprobe analysis were selected based on presence of pyrite or other sulfide minerals. Samples cut to an appropriate size were placed in 1-inch round sample mounting cups, set in epoxy, and cured overnight at around 80°C. Once cured, samples were first polished using coarse diamond grinding wheels and finely polished with diamond powder suspended in distilled water. Polished sample surfaces were then cleaned using petroleum ether and carbon coated to a 200 angstrom thickness.

Different types of analyses are performed. The initial observations of the samples are made using backscattered electron imaging (BSE), which allowed observation of sample textures, and location of high mean atomic number (Z) phases. BSE observations are coupled with acquisition of rapid X-ray maps and/or qualitative geochemical scans, which allow for qualitative assessment of the elements present in a given mineral phase. Peaks that appeared on the scans were identified using Cameca software. The elements shown by the peaks and their relative abundance, based on peak height, were used to identify the mineral phases. Qualitative scans were carried out using an accelerating voltage of 15 kV and a probe current of 20 nA. For more information on the electron microprobe laboratory see http://geoinfo.nmt.edu/labs/microprobe/home.html (accessed 6/1/16).

Stability analysis

Indicators of unstable waste rock piles include: lack of vegetation, sloughing, creep, signs of failure, tension cracks, and bent fence lines. Most waste rock piles are deposited at their angle of repose and over the years there has been some cementation and compaction. Disturbed samples for lab testing will show lower strength than what the in-situ materials have. If there is a sign of potential for instability in waste rock piles, standard strength analyses will be performed.

Quality control procedures and sample security

Samples were collected, prepared, and analyzed according to standard methods for each specific laboratory analysis. Samples were collected in the field and kept under direct control of the authors to avoid contamination. Samples are archived at the NMBGMR. Samples collected are complete, comparable, and representative of the defined population at the defined scale. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and are explained in McLemore and Frey (2009). Most geochemical laboratory analyses depend upon certified or on-going reference standards and duplicate analyses. The sampling and analysis plans for each segment of the field and drilling program as well as the control of accuracy and precision as defined here, provides a large high-quality set of observations and measurements that are adequate to support the interpretations and conclusions of this report. Field and laboratory audits by the senior author were performed to ensure that standard operating procedures were followed.

PRELIMINARY RESULTS

Petrography and Mineralogy

Most rock samples from mine waste rock piles exhibit iron-oxide alteration, mostly as pyrite replacements by hematite. Pyrite has weathered to jarosite in the Silverton and Jicarilla districts. Gangue minerals associated with many samples include quartz, potassium feldspar, biotite and kaolinite. Quartz and potassium feldspar are major constituents of the groundmass, whereas quartz forms the matrix of the sample. Calcite is abundant in only a few districts studied. The destruction and replacement of biotite by hematite and quartz in some portions of the samples were observed along fractures.

Geochemistry of Solid Samples

Average pH values of the mine features ranges between 4.9 and 6.6. The pH results indicate moderately alkaline to acidic waste rock piles. Total dissolved solids (TDS) values calculated were between 5.9 and 40 mg/L and these results provide an indication of the level of dissolved solids in the stream or lakes closer to the waste rock piles. TDS values of 1 to 500 mg/L are typical of lakes and streams.

Potential for Acid Rock Drainage

Acid rock drainage is formed when sulfide minerals are exposed to oxidizing conditions such as weathering. Field characteristics of potential ARD in mine waste rock piles include identification of pyrite and/or jarosite and low pH. The rate of sulfide oxidation depends on reactive surface area of sulfide, oxygen concentration and solution pH. ARD can be determined by Acid Base Accounting (ABA) and Net Acid Generation (NAG) Tests. The ABA procedure consists of two separate tests; the acid potential (AP) test and the neutralization potential (NP) test. ABA was calculated and plotted on the ARD classification plot for waste rock pile samples from the various mines (Sobeck et al., 1978). Results of ABA tests are presented in Figure 3. The assumption is that all C in the samples are as $CaCO_3$ (no organic carbon) and also the NAG pH is equals the measured paste pH of the sample. Below are the formula used:

AP (kg $CaCO_3$/tonnes) = 31.25 x S (%)

NP (total C) = 83.3 x C (%),

NNP = NP – AP,

NPR = NP/AP

PRELIMINARY CONCLUSIONS

- Samples that have higher concentrations of pyrite are more likely to have a higher acid generation capacity. Generally, Acid Potential (AP) depends on the amount of pyrite and other sulfide minerals and Neutralizing Potential (NP) depends upon the amount of calcite and other acid-neutralizing minerals. But, no single component controls the ABA and NAG tests.
- A few mine sites examined have potential to generate acid drainage and additional mine sites are physically dangerous and require proper safe guarding.
- Most of the waste rock piles surrounding the mine features are suitable for backfill material.
- Sulfide oxidation can be slow in some areas and metal release can be low, but other areas are the opposite—characterization of mine wastes is important.

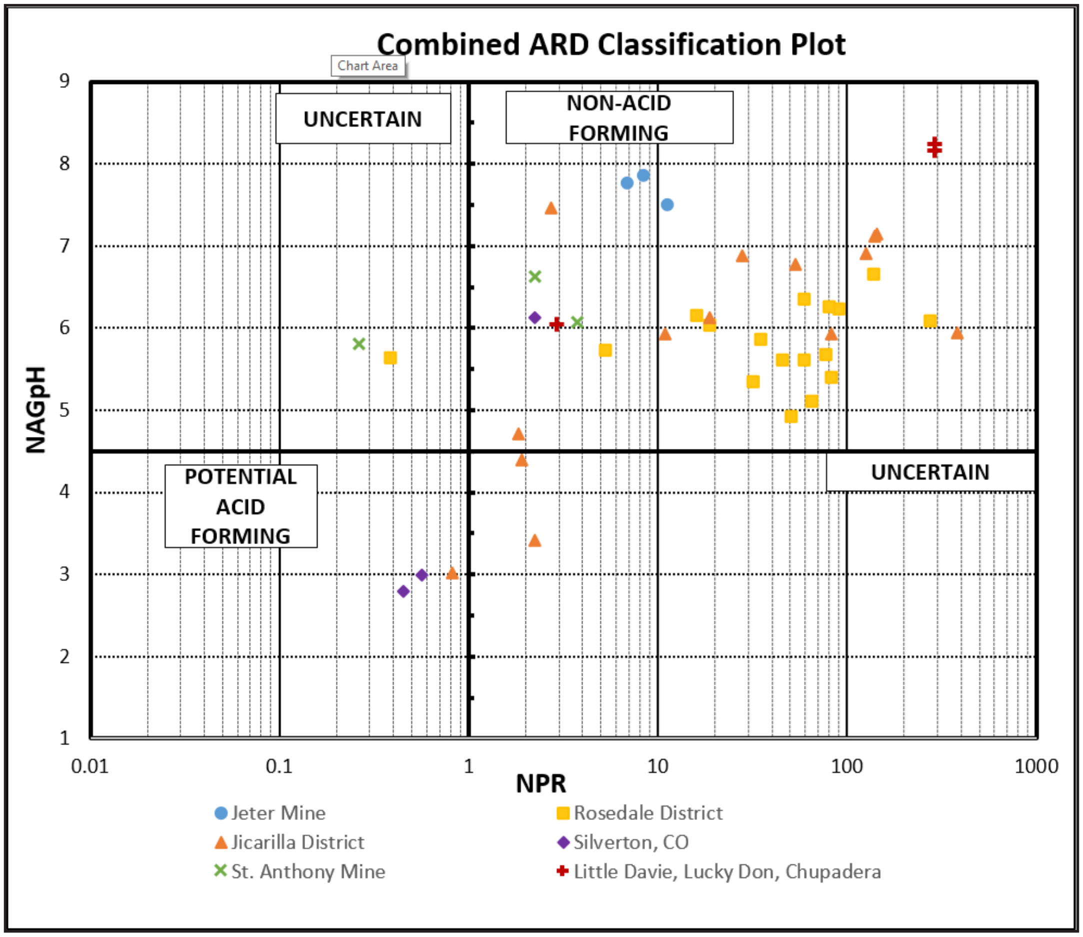

Figure 3. Acid Rock Drainage (ARD) plot of waste rock pile at mines examined during the NMBGMR AML project. The results for the waste rock piles from the Little Davie, Lucky Don, Chupadera, and Jeter uranium mines (Socorro County), St. Anthony uranium mine (Cibola County), Rosedale and Jicarilla gold mines (Socorro and Lincoln Counties) and Silverton gold-silver mines (Colorado) are shown for comparison (unpublished work in progress). Results of these mines will be published in future reports. Samples that plot in the uncertain and potential acid forming fields are not suitable for backfill material and need to be handled with care during reclamation. Locations of mining districts is in Figure 1.

ACKNOWLEDGEMENTS

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This project was partially funded by Energy Minerals and Natural Resources Department (Abandoned Mine Lands Bureau) and the U.S. Department of the Interior, Office of Surface Mining and Reclamation (OSMRE). Additional funding of student research was by the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), Mineral Engineering Department of NMIMT, Society for Mining, Metallurgy and Exploration (SME), New Mexico Geological Society (NMGS), and New Mexico EPSCoR (funded by the National Science Foundation, NSF, award #IIA-1301346). The Cameca SX-100 electron microprobe at NMIMT was partially funded by NSF Grant STI-9413900.

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

B. Talon Newton
Ethan Mamer
Stacy Timmons
NM Bureau of Geology and Mineral Resources, NM Tech, NM

ABSTRACT

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

INTRODUCTION

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

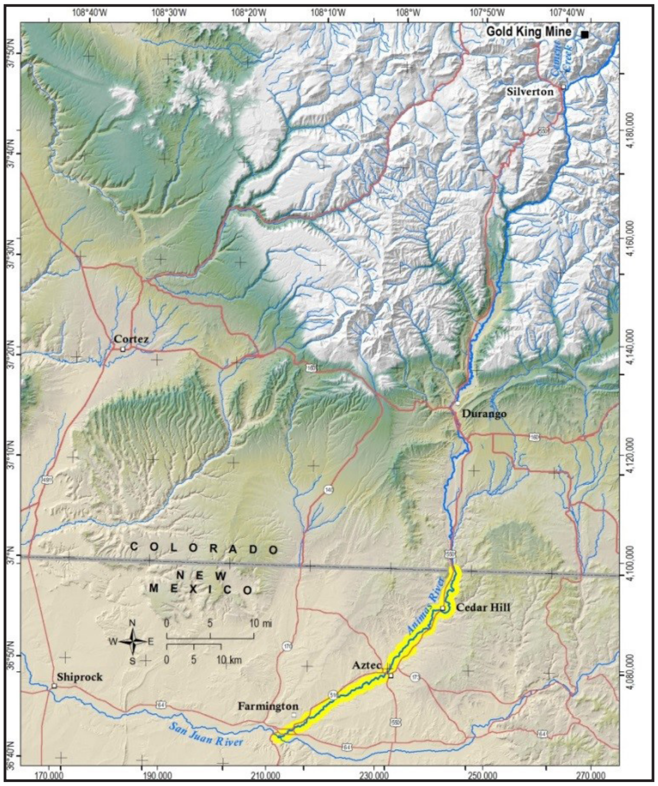

Figure 1.The study focused on the reach of the Animas River outlined in yellow, from the Colorado-New Mexico state line to Farmington. The location of the Gold King Mine, the source of the contaminant spill is also shown.

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

THE GOLD KING MINE SPILL AND RESPONSE

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

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

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

REGIONAL GEOLOGY

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

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

THE ANIMAS RIVER

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

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

GROUNDWATER FLOW CONDITIONS

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

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

METHODS

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

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

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

GEOCHEMISTRY OF THE ANIMAS RIVER ALLUVIAL AQUIFER

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

Groundwater Recharge Assessment

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

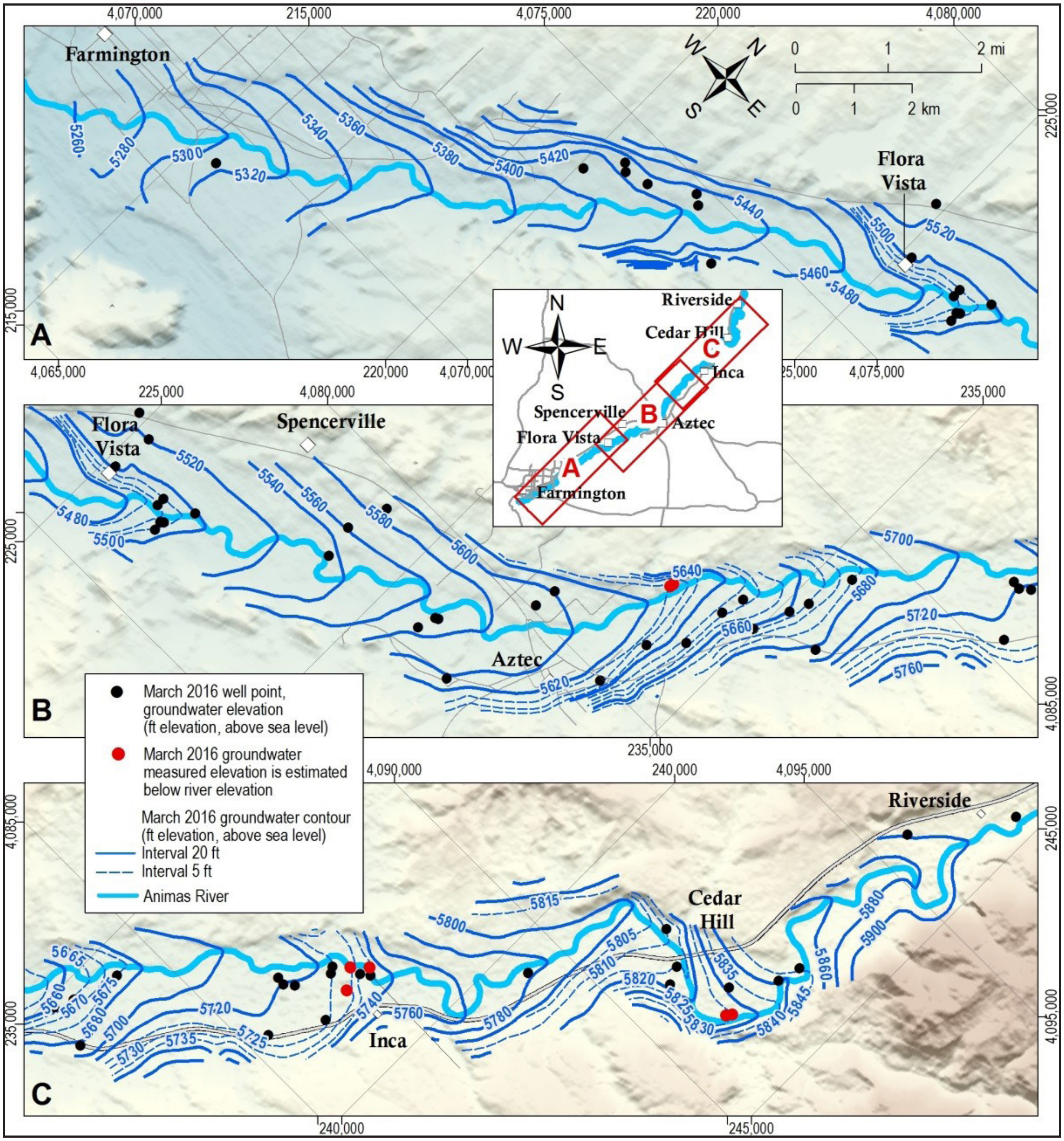

Figure 2. Water table map based on water level measurements during March 2016. Red points designate wells that exhibited water level elevations below the estimated river stage elevation at the time, indicating that in these areas the river water is recharging the alluvial aquifer. The losing stream condition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

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

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

Groundwater Contaminants

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

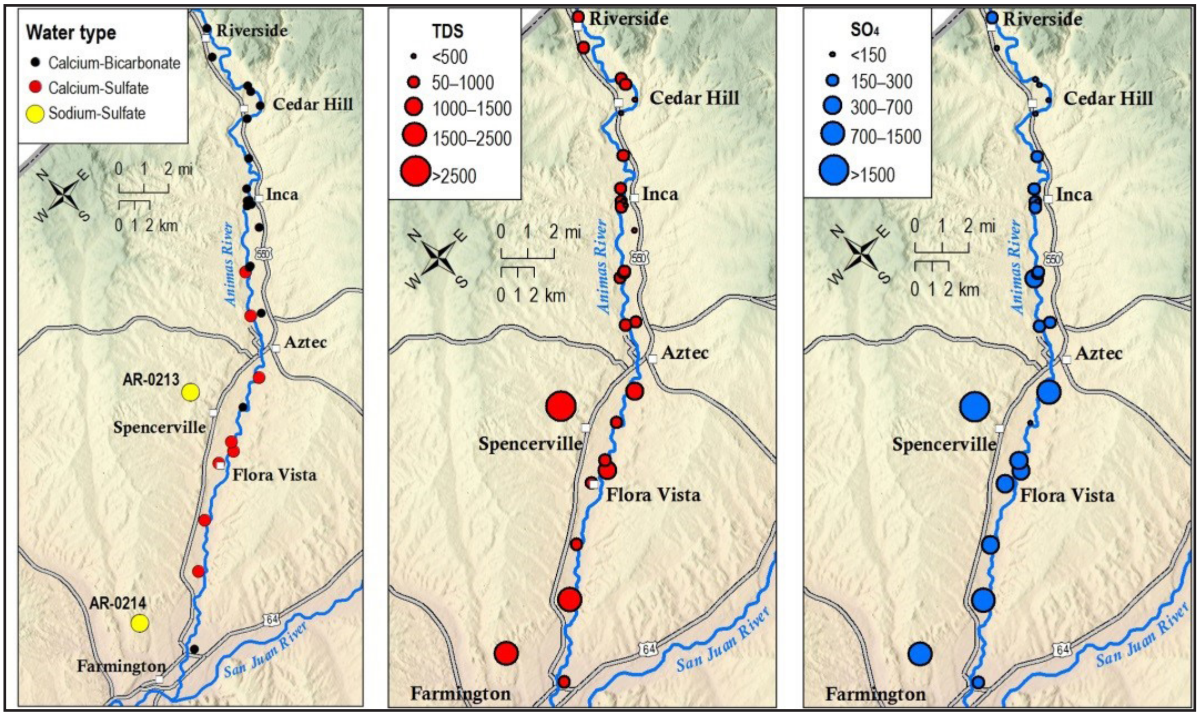

Figure 3. Trends for water type, total dissolve solids, and sulfate concentrations. Left panel: Water type as defined by relative cation and anion concentrations. Center panel: Average total dissolved solids concentrations show a general trend of increasing in the downstream (southwest) direction. Right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

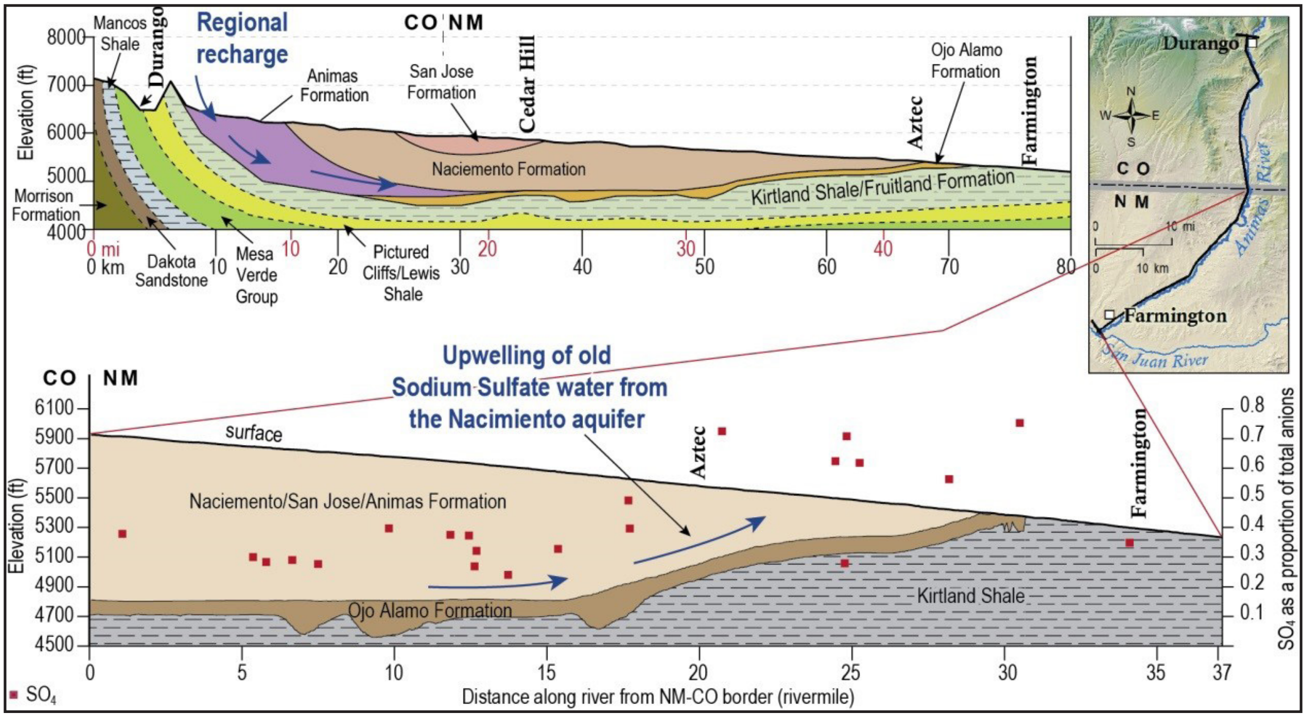

Figure 4. Schematic regional cross-sections showing groundwater flow paths in regional bedrock. Regional groundwater recharge to the Nacimiento/Ojo Alamo/San Jose aquifer occurs in the San Juan Mountains near Durango, at the northern edge of the San Juan Basin. Increased sulfate (red data points and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

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

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

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

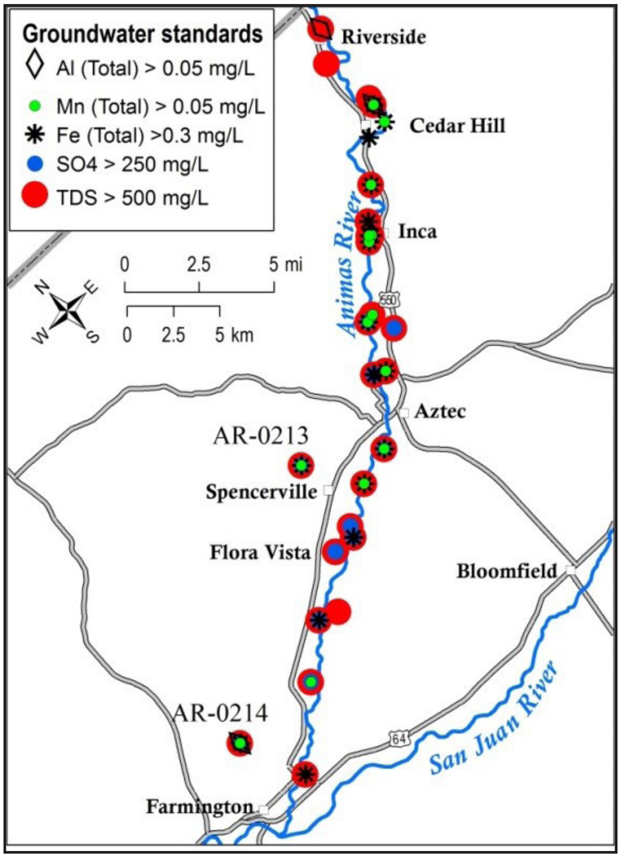

Figure 5. Location of wells that produced water exceeding US EPA secondary contaminant levels for total dissolved solids, total iron, total manganese, and total aluminum.

CONCLUSIONS

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

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

ACKNOWLEDGMENTS

This project was successful only because of the generosity and cooperation of well and land owners along the Animas Valley who allowed us to access their wells to collect these essential data. Funding for this study was provided by the U.S. Environmental Protection Agency through the New Mexico Environment Department under MOU16-667-2000-0004. The authors thank our colleagues and collaborators at the New Mexico Environment Department including Dennis McQuillan and Diane Agnew for feedback and support on this project. We would like to thank Dr. Patrick Longmire for taking time to meet with us and helping review the geochemistry data. We also kindly thank the USGS New Mexico Water Science Center staff contributions for assistance in water level measurements in August 2015, including Jesse Driscoll, Lauren Sherson, Nicole Thomas, and Amy Gallanter. During the August 2015 water level measurements, we had cooperation and assistance also from New Mexico Office of the State Engineer's Office staff Doug Rappuhn, Rob Pine, and Shawn Williams. We also thank Miriam Wamsley, formerly with the New Mexico Department of Health, for her help on water quality concerns related to private domestic wells. Finally, we thank Dr. Geoffery Rawling and Scott Christenson from the New Mexico Bureau of Geology for reviewing and providing constructive comments on this report.

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Book Review

Clifford J. Villa[1]

RIVER OF LOST SOULS: THE SCIENCE, POLITICS, AND GREED BEHIND THE GOLD KING MINE DISASTER.

By Jonathan P. Thompson. (Torrey House Press, 296 pages; 2018)

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I. Introduction

On August 5, 2015, contractors for the U.S. Environmental Protection Agency (EPA) investigating the Gold King Mine in southwestern Colorado accidently released some three million gallons of contaminated water to the Animas River, triggering weeks of front-page headlines, months of Congressional hearings, and now years of litigation. *River of Lost Souls: The Science, Politics, and Greed Behind the Gold King Mine Disaster*,[2] a new book by Jonathan P. Thompson, suggests by its title a human folly behind this "disaster" much broader and deeper than one tragic accident wrought by EPA contractors. On this thesis, Thompson certainly delivers. However, what we get from the book is both less and so much more. Less, because one can finish the book and walk away wondering who really is to blame for the Gold King Mine spill. So much more, because *River of Lost Souls* is not really the story of a spill, but the story of a place: the Four Corners country of Colorado, New Mexico, Arizona, and Utah.

The story of this place is cause for celebration and despair: despair as Thompson chronicles one trauma after another visited upon this breathtaking country of mountains and desert; but celebration too as readers could not hope for a writer more capable and better situated than Thompson to explain these traumas to us. Thompson, who was born and raised in the Animas River valley, with family reaching back generations, returned to the area in 1996 to write for local newspapers and eventually the *High Country News*. On the fateful day of the Gold King Mine blowout in August 2015, Thompson—already an accomplished, award-winning writer—was at home in Durango, Colorado, working on another piece, when the story of a lifetime *literally* came to him. Hearing news of the spill on his Twitter feed, Thompson jumped into his car and drove upstream to confront the "[t]urbid, electric-orange water, utterly opaque, sprawl[ing] out between the sandy banks…."[3] Hours after dark, the sickly "slug" of orange water moving down the Animas River would reach Durango and continue on its long journey through four states, three tribal lands, and innumerable towns, villages, farms, and lives along the way. Thompson, the *writer*, would become part of the story. As national media descended on Durango and began reporting on the spill,[4] Thompson was already there and among the first to get the story and get the story *right*.[5]

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[1] Associate Professor, University of New Mexico School of Law. J.D., Lewis & Clark Law School. B.A., University of New Mexico. The author wishes to thank the faculty of the UNM Professional Writing Program (1990) for introducing me to Edward Abbey, Joan Didion, Annie Dillard, John McPhee, Wallace Stegnar, and so many other great writers who have immeasurably enriched my perspectives on the American West and the world.

[2] JONATHAN P. THOMPSON, RIVER OF LOST SOULS: THE SCIENCE, POLITICS, AND GREED BEHIND THE GOLD KING MINE DISASTER (2018).

[3] Thompson, *supra* note 1, at 7.

[4] *See, e.g.*, David Kelly, *River Spill Is a Toxic Blast from the Past*, L.A. TIMES A-1, Aug. 10, 2015; Julie Turkewitz, *Environmental Agency Uncorks Its Own Toxic Spill*, N.Y. TIMES, Aug. 11, 2015; Richard Parker, *A River Runs Yellow*, THE ATLANTIC, Aug. 21, 2015.

[5] *See, e.g.,* Jonathan Thompson, *When Our River Turned Orange*, HIGH COUNTRY NEWS, Aug. 9, 2015; Jonathan Thompson, *Gold King Mine Water Was Headed for the Animas, Anyway,* HIGH COUNTRY NEWS, Aug. 28, 2015.

Importantly, Thompson remained in place after the media frenzy faded, digging deeper, continuing to explore both the causes and consequences of the spill.[6] In *River of Lost Souls*, Thompson's collective writings after the spill plus 20 years of local reporting before the spill[7] come together and expand into one heartbreaking whole. With the instincts of an old-time newspaperman[8] and the engagement of a New Journalist,[9] Thompson plunges into the story and emerges with an astonishing work of natural history, investigative reporting, and memoir. In the end, *River of Lost Souls* may not answer every question readers have about the Gold King Mine spill, but it will help readers see the spill in a new light: the spill as both a creature of place and a consequence of politics and greed.

Chapter 1 of *River of Lost Souls*, "Blowout," opens appropriately on the morning of August 5, 2015, when the EPA contractors investigating the flow of mine drainage from the Gold King Mine accidently poked through a plug in the mine portal and released some three million gallons of contaminated water into the watershed of the Animas River.[10] The Gold King Mine blowout in August 2015 frames Thompson's book, but does not dominate it. Instead, with equal parts Wallace Stegnar[11] and Edward Abbey,[12] Thompson gives us a sense of place "with a capital *P*,"[13] shaped by natural forces and the people who explored, settled, lived, and lost. We begin with geology, imagining "a land of ancient lakes of bubbling lava," where a "vast chamber of magma collapsed" 27 million years ago, leaving behind a region of mountains with natural mineral wealth.[14] In these same places today, we see a "community of McMansions" springing up north of Durango,[15] serving those drawn to the Purgutory Ski Resort and the new recreational economy of the San Juan Mountains. In Chapter 2, "Holy Land," we jump back in time 210 years to the first Spanish explorers standing on the bank of the Animas River and declaring its name.[16] And finally, of course, we consider the original inhabitants of this country, two thousand and ten thousand years ago.[17]

Most of the history recounted in *River of Lost Souls*, however, begins with Chapter 3, which takes us back to the 1870s or so when small farms began to sprout in the Animas River Valley and mining began in earnest in the high country of the San Juan Mountains. Encouraged by agreements with local tribes and passage of the

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[6] *See* Jonathan Thompson, *Silverton's Gold King Reckoning*, High Country News (May 2, 2016), available online at https://www.hcn.org/issues/48.7/silvertons-gold-king-reckoning

[7] Thompson, *supra* note 1, at Acknowledgements.

[8] Among Thompson's strongest apparent influences are small-town newspapermen such as David F. Day, editor of the *Durango Democrat*, who dared to speak up in 1900 against the pollution of the Animas River by local mining companies. Thompson, *supra* note 1, at 67-74. Thompson's influences also obviously include his father, Ian Thompson, who wrote for the *Silverton Standard*. *See* Jonathan Thompson, *Silverton's Gold King Reckoning*, High Country News (May 2, 2016). In tribute to this tradition, Thompson writes lovingly of the old newspaper office in Silverton, Colorado, that Thompson assumed in 1996 from generations of prior newspapermen including his own father. Thompson, *supra* note 1, at 241 ("It was a newspaper nostalgic's dream"). When asked about other writing influences, Personal Communication, Bookworks, Albuquerque, New Mexico (April 18, 2018) (book reading), Thompson mentioned David Lavender, One Man's West (Doubleday, 1943). Lavender has been described succinctly as a "Colorado rancher and miner who … became one of the most prolific chroniclers of the American West." Wolfgang Saxon, *David Lavender, 93, Whose Books Told the Story of the West*, N.Y. Times, April 30, 2003. Lavender's influence on Thompson and *River of Lost Souls* is readily apparent in the concern shown by each author for people, livelihoods, and the impacts of industry on the natural world.

[9] For the manifesto of New Journalism, a movement from the 1960s in which nonfiction writers began to occupy more visible roles within their long-form stories, see Tom Wolfe, The New Journalism (1975). For a more recent take on this literary genre, see Robert S. Boynton, The *New* New Journalism: Conversations with America's Best Nonfiction Writers on Their Craft (2005).

[10] *Id*. at 5.

[11] Wallace Stegnar (1909-1993), known as the "Dean of Western writers," is often recognized for ushering in the modern tradition of Western literature with his groundbreaking work of nonfiction, Beyond the Hundredth Meridian: John Wesley Powell and the Second Opening of the West (1953). *See* Charles F. Wilkinson, *The Law of the American West: A Critical Bibliography of the Nonlegal Sources*, 85 Mich. L. Rev. 953, 959-960 (1987) (placing *Beyond the Hundredth Meridian* at the front of the essential reading list of works on the American West). Stegar later won the Pulitzer Prize for the fiction Angle of Repose (1972) and the National Book Award for Spectator Bird (1977). For an encompassing review of Stegnar's life, last work, and continuing influence on Western writers, see Janet C. Neuman and Pamela G. Wiley, *Hope's Native Home: Living and Reading in the West, A Review of Wallace Stegnar's* Where the Bluebird Sings to the Lemonade Springs: Living and Writing and the West., 24 Envtl. L. 293 (1994).

[12] *See, e.g*., Edward Abbey, Desert Solitaire: A Season in the Wilderness (1968). In the unlikely case that any reader would miss the influence of Edward Abbey, Thompson directly quotes Abbey in the frontmatter: "Contempt for the natural world is contempt for life. The domination of nature leads to the domination of human nature."

[13] Thompson, *supra* note 1, at 132. As Wallace Stegnar famously observed in his essay, *The Sense of Place*, "If you don't know where you are …, you don't know *who* you are." Wallace Stegnar, *The Sense of Place, in* Where the Bluebird Sings to the Lemonade Springs: Living and Writing in the West (1992) (paraphrasing author Wendell Barry).

[14] Thompson, *supra* note 1, at 3.

[15] Thompson, *supra* note 1, at 7.

[16] Thompson, *supra* note 1, at 15.

[17] Thompson, *supra* note 1, at 19.

General Mining Act of 1872,[18] settlers from Europe, China, and the post-Civil War United States flooded into the region, founding Silverton, Colorado, in 1873.[19] The Old West flourished and faltered and began its cycles of boom and bust.

Much of the important context for comprehending the Gold King Mine spill begins here, in the mountains around Silverton, with prospectors trying their luck and on rare occasions finding something worth finding. In Chapter 5, "Olaf and the Gold King," Thompson brings one of those prospectors vividly to life: Olaf Arvid Nelson, who staked the claim on Bonita Peak in 1887 that would become the Gold King Mine.[20] Chapter 6, "Perfect Poison," provides a healthy dose of the "science" promised in the book title, explaining with the ease of a seasoned STEM teacher how water draining from old mines such as the Gold King can combine "three innocent ingredients – oxygen, water, and iron pyrite" together to form sulfuric acid that can kill fish and bugs, and eat a shovel overnight.[21] This "acid mine drainage," which remains a staggering problem for aquatic life throughout mining districts of the West,[22] became a particularly voluminous problem for the Gold King Mine, drawing the attention of EPA in 2014 and setting off the chain of events that led to the blowout on August 5, 2015.[23] Chapter 7, "Slime Wars I," rounds out our introduction to contamination from the mining industry with a look at how the milling process extracts only a fraction of the metals from the mined ore and resulted historically in massive releases of mill wastes, or "tailings," into nearby waterways.[24] The story here is how the Animas River, supposedly devastated by the carelessness of EPA's crew in August 2015, was already "rapidly being destroyed … by the absolute and unlawful recklessness of Silverton mill men" by the year 1900.[25] Drawing from newspaper accounts and other sources, Thompson colorfully depicts the "wars" between the upstream mills in Silverton and the downstream denizens of Durango, who in 1902 "surrendered" in this war and elected "to get its drinking water from elsewhere."[26]

To this point in *River of Lost Souls*, readers could find most of the same major plot points in Thompson's original reporting on the "Gold King Mine Disaster" published in the *High Country News*.[27] But the detail that we find in *River of Lost Souls* is deeper and richer. For example, where one earlier article briefly mentions the violence of the local miner's union toward the Chinese-American population of Silverton in 1906,[28] the book allows pages to expand upon this dark, racist history that could otherwise be lost to nostalgia for the "good old days."[29] The book also allows Thompson room to develop his thesis of the Gold King Mine spill as a consequence of politics and greed. Thompson gives us, for example, the story of Lena and Edward Stoiber, who became fabulously wealthy around 1900 thanks to Lena's management skills and Edward's expertise in metalurgical science. Nevertheless, this educated power couple of the Silverton mining district would not "devote just a fraction of their considerable talents to coming up with ways to mitigate mining's damages … rather than aiming all of their innovation toward increased profits."[30] At some points, Thompson himself becomes a part of this unfortunate history. In one of the most remarkable passages late in the book, we see Thompson in 1996, "as the only member of the local press" corp, invited by a mine manager to venture underground and observe a "boxcar-sized concrete plug" installed a mile deep into the American Tunnel,

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[18] General Mining Act of 1872, 17 Stat. 91 (1872), codified at 30 U.S.C. §§ 22-54 (2015). Enacted in 1872, the General Mining Law remains in effect and virtually the same today, providing that "all valuable mineral deposits in lands belonging to the United States … shall be free and open to exploration and purchase." 30 U.S.C. § 22 (2015). For a thorough review of the General Mining Law in the context of modern mining contamination, see John Seymour, *Hardrock Mining and the Environment: Issues of Federal Enforcement and Liability*, 31 Ecology L. Q. 795, 825-832 (2004).

[19] Thompson, *supra* note 1, at 33-35.

[20] Thompson, *supra* note 1, at 58.

[21] Thompson, *supra* note 1, at 61-63.

[22] To pick one example, the Gold King Mine itself is just one of more than 30 inactive mines in the Animas River watershed which together discharge a daily average of 5.4 million gallons of mine; that is, *every day*, the district produces a greater discharge of mine water than the infamous day of the Gold King Mine spill. U.S. EPA, *One Year After the Gold King Mine Incident* 6 (Aug. 1, 2016).

[23] Thompson, *supra* note 1, at 274-275.

[24] Thompson, *supra* note 1, at 67-70.

[25] *Id*. at 67.

[26] *Id*. at 77.

[27] *See supra* notes 4-5.

[28] *See* Jonathan Thompson, *Silverton's Gold King Reckoning*, High Country News (May 2, 2016) (noting briefly, "In 1906, a union-led mob drove the entire Chinese-American population from town").

[29] Thompson, *supra* note 1, at 88-90.

[30] *Id*. at 76-80.

theoretically shutting off the flow of acid mine drainage to the surrounding watershed.[31] Readers by this point will realize that the installation of these underground "bulkheads" will prove a massive hydrological mistake leading directly to the Gold King Mine blowout nearly 20 years later.

As a story of Place, much of *River of Lost Souls* really has little to do with the Gold King Mine blowout. In Chapter 9, "Hard Rain's Gonna Fall," we learn all about a torrential rainfall that led to massive flooding in the Animas River valley in 1911. In Chapter 10, "the Blackest Week," we learn about the Spanish Flu epidemic which raced through San Juan County in the fall of 1918 and claimed at least 150 lives. In later chapters, we learn about the rise of industry and politics in the production of oil and natural gas in the Four Corners country. We learn about the Four Corners Methane Hot Spot,[32] uranium mill tailings dumped straight into the Animas River,[33] and an experiment with cloud-seeding known as Project Skywater.[34] At times, some readers could tire of the tangents to the story of the Gold King Mine.[35] At other times, the string of tragedies befallen this country can feel overwhelming. Thankfully, Thompson makes these tragedies bearable by maintaining throughout both his sense of empathy and sense of humor.[36]

And then there is the gorgeous language. Thompson looks up one wintery night and sees snowflakes "swarm[ing] the streetlights like a million falling moths."[37] For Thompson, there is the potential for beauty everywhere, even on blustery spring days when "the yellow and gray dust lifted off the tailings piles and fluttered so lightly through the bright blue sky."[38] It is probably no wonder that some of the most affecting passages from *River of Lost Souls* come in the recurring moments of memoir. In Thompson's voice, Durango, Colorado, transforms from a town on a map in the nightly news to a scene from our own childhood memories:

> I remember the soothing rhythmic sound of my mom's loom, the staccato of my dad's typewriter; racing our bikes around the block in the dark; playing hide-and-seek with all the neighborhood kids on summer nights and the euphoric feeling you get just as day slips into night and you're running for base with all you've got and your feet leave the ground and for a second you're flying, really flying.[39]

From front cover to back, we grow up with Thompson, see our parents age, find new people in our lives, and wonder what is next.

What is next for the Gold King Mine spill remains open to speculation, but it will involve lawyers and lawsuits. Environmental law forms another frame of reference for considering the same sets of facts examined in *River of Lost Souls*. The applicability of this frame is not lost on Thompson, who unerringly surveys a range of federal environmental statutes designed to prevent or remedy the string of ecological tragedies visited upon the Four Corners country. Thompson gives us the Wilderness Act[40] and the Federal Land Policy and

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[31] *Id*. at 247-48.

[32] *Id*. at 170.

[33] *Id*. at 178, 183.

[34] *Id*. at 205.

[35] At one point in *River of Lost Souls* (124), a fleeting reference to "William 'Big Bill' Haywood" may remind some readers of one of the most tedious works of Western literature in the last quarter-century: J. Anthony Lukas, Big Trouble: A Murder in a Small Western Town Sets Off a Struggle for the Soul of America (1997). At 880 pages, the plot could be fairly summarized as this: "A former state governor of Idaho is murdered and labor organizer Bill Haywood is accused of the crime but acquitted with the help of attorney Clarence Darrow." Along the way, readers of *Big Trouble* are treated to hundreds of pages of the history of baseball and everything that happened in the early 1900s. Fortunately, compared to *Big Trouble*, Thompson's *River of Lost Souls* is only one-third the length, so wherever we are in the book, we are never too far afield from the Gold King Mine spill.

[36] Thompson's fine sense of irony shines through in Chapter 13, where after examining the staggering environmental impacts from a coal-fired power plant near Farmington, New Mexico, Thompson gazes up at a massive ash impoundment pile and then notes a sign stuck in the base: "No Trash Dumping. Walk in Beauty." Thompson, *supra* note 1, at 153. After another long stretch of histories and tragedies, Thompson delivers the comic relief with a bit about sitting in a Durango coffee shop in 1996, getting charged extra by the proprietor for complaining about home-baked cookies full of egg shells. Thompson, *supra* note 1, at 240.

[37] Thompson, *supra* note 1, at 291.

[38] Thompson, *supra* note 1, at 188.

[39] Thompson, *supra* note 1, at 210.

[40] Wilderness Act of 1964, 16 U.S.C. § 1131-1136.

Management Act,[41] two federal statutes designed to protect our public lands from the overreaches of human industry. We see the Endangered Species Act of 1973,[42] which should protect listed species of native fish in the Animas River watershed including the Razorback sucker and giant Colorado pikeminnow.[43] We see the Clean Water Act of 1972,[44] with its lofty goal "to eliminate the discharge of pollutants to navigable water by 1985,"[45] which might have been handy 72 years earlier to stop the direct discharge of tailings from Silverton mills into the Animas River. Perhaps most significantly, we see the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA),[46] better known as Superfund. We see how community interest in protecting the local mining industry led to local opposition to Superfund designation.[47] We also see how the Gold King Mine spill drove the local community to drop their opposition to Superfund, leading to formal Superfund designation in September 2016.[48]

Beyond the environmental statutes, we also find in *River of Lost Souls* regular references to legal proceedings concerning the impacts of mining activity to the environment and private property. Thus, we see the case of the owners of a hydroelectric plant near Telluride, Colorado, suing "an upstream mill operator because the latter's tailings were mucking up its operations," with a Colorado appeals court in 1897 upholding an injunction against the continued dumping.[49] We see a similar case from Jefferson County, Colorado, brought by downstream farmers against upstream mill operators, with the Colorado Supreme Court in 1935 upholding an injunction to prohibit further dumping of mill tailings into Clear Creek.[50] One thing we do not see in *River of Lost Souls* is the proper legal citation that every good law review editor will demand. The absence of proper legal citation is fine here, of course, for at least two reasons. First, Thompson is not writing a legal treatise.[51] Second, compared to the judicial decisions themselves, Thompson's descriptions of the people and conflicts behind the reported cases are often far richer.[52]

Beyond the question of who was truly at fault for the Gold King Mine spill, Jonathan Thompson is clearly aiming for something bigger in *River of Lost Souls*. From beginning to end, *River of Lost Souls* is a story of Place, and as Wallace Stegnar wrote, "No place is a place until things that have happened in it are remembered in history."[53] Thompson has done some mighty fine remembering for us in *River of Lost Souls.* And the book is not just about looking backwards. The book is very much a contemporary comment on the Donald Trump era, where racism rises again,[54] where "alternative facts" are spewn with impunity,[55] and where "oil, coal, automobile, and utility executives knowingly steer us all headlong toward irreversible climate catastrophe..."[56] If *River of Lost Souls* is ultimately about Place, that place may be as broad as our nation – or as near as our soul.

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[41] Federal Land Policy and Management Act of 1976, 43 U.S.C. §§ 1701-1782.

[42] Endangered Species Act of 1973, 16 U.S.C. §§ 1531-1542.

[43] Thompson, *supra* note 1, at 228-229.

[44] 33 U.S.C. §§ 1251-1387.

[45] Thompson, *supra* note 1, at 223. *See also* Clean Water Act Sec. 101(a), 33 U.S.C. § 1251(a)(1) (goal of eliminating discharge of pollutants by 1985).

[46] 42 U.S.C. §§ 9601-9675.

[47] Thompson, *supra* note 1, at 251-252, 272-273.

[48] Thompson, *supra* note 1, at 279-280. The designated Superfund site is now formally known as the Bonita Peak Mining District site. 81 Fed. Reg. 62,397, 62,401 (Sept. 9, 2016).

[49] Thompson, *supra* note 1, at 72-73. Suffolk Gold Mining & Milling Co. v. San Miguel Mining & Milling Co., 9 Colo. App. 407 (1897).

[50] Thompson, *supra* note 1, at 118. Wilmore v. Chain O'Mines, 96 Colo. 319 (1935).

[51] For proper legal citations and analysis concerning the Gold King Mine spill, *see, e.g.*, ______, 90 Colo. L. Rev. ___ (2018); Clifford J. Villa, *The Gold King Mine Spill: Environmental Law and Legal Protections for Environmental Responders*, 2018 Utah. L. Rev. __ (2019).

[52] For one excellent example, Chapter 11, "Slime Wars," begins with the tale of Hugh Magone, a farmer in Montana who brought suit in 1903 against upstream mining companies near Butte, Montana, to stop the dumping of mill tailings into Silver Bow Creek. Thompson, *supra* note 1, at 111-113. While Thompson brings colorful detail to this conflict between farmers and miners at the turn of the century, the only reported judicial decision in this case available via Westlaw deals exclusively with the minutae of the court's authority to require the deposition of a witness outside the State of Montana. *See* Magone v. Colorado Smelting & Mining Co., 135 F. 846 (1905).

[53] Stegnar, *supra* note 11, *A Sense of Place*.

[54] Thompson, *supra* note 1, at 128.

[55] Thompson, *supra* note 1, at 268.

[56] Thompson, *supra* note 1, at 80.

Application of Solar-Atmospheric Connections Towards Improved Forecasts of the Animas River and other Streams in the Western US

Michael Wallace
Hydrologist, MW&A
Albuquerque, NM
mwa@abeqas.com

ABSTRACT

Considerations of connections between modern solar cycles, Hadley and Walker circulation patterns, along with streamflow characteristics of several mid latitude, high altitude watersheds have pointed to the potential for improved multi-annual to sub-decadal forecasting of streamflows in targeted locations. Such conditions appear to apply to watersheds of the southern Rocky Mountains of the western United States.

In this exploration, correlations and linear regressions were developed for key sequential features that have been provisionally identified. The resulting forecasting approach focused on streamflow time series for prime candidate streams of the Southern Rocky Mountains, including the Animas and Pecos Rivers. A third stream, the Gila River in the Mogollon Mountains was included in the comparative study because of its marginal candidacy with respect to geopotential height and latitude.

The forecasts based upon the new regression method were the most accurate of all featured methods, for the series considered under a five-year trailing average. Through a sequence of solar, trade wind and streamflow cross-regression exercises, forecasts for the Animas and Pecos Rivers were advanced as far as six years into the future.

INTRODUCTION

This paper is associated with two oral presentations and a poster by this author at the 1st and 2nd Annual Conferences on *Environmental Conditions of the Animas and San Juan Watersheds with Emphasis on Gold King Mine and Other Mine Waste Issues*, sponsored by the New Mexico Water Resources Research Institute in 2016 and 2017. Material here also summarizes a paper submitted to the *Hydrological Sciences Journal* which is in a closing stage of review (Wallace, 2018). Accordingly, extensive text from that paper has been condensed and consolidated by the same author to produce this complementary product.

Many hydrologists must at some point address the challenges of forecasting the long-term future states of streams associated with their study domains. To date most researchers have relied primarily upon stochastic approaches, which depend on records of the history of the subject stream system for estimating that system's future. Accordingly, the nominally predictive solutions are based on autocorrelation (AC) and/or autoregression moving average (ARMA) strategies, such as described in Wei (2006).

These strategies are typically parametric, given that they are often geared to develop best estimates of the first several moments (mean, variance, skew) for a given time series. Moreover such parametric results are typically cast into "climatological" products, including the mean flow for a given season or month, or as estimates of extreme events such as a "probable maximum flood." A more desirable type of forecast would for example project the arrival of a period of drought, with a certain lead time, span, and intensity across a given region, hopefully with acceptable accuracy for planning purposes.

Accordingly, if independent and reliable precursors were available over multi-season to multi-decadal scale time frames, then hydrologists would likely employ them in other regression based approaches towards improved forecasting. Some independent precursors to regional climatologic atmospheric moisture patterns have been described. These generally are limited to temperatures and/or pressure differentials associated with locations or regions within the Pacific Ocean, including the widely cited El Niño pattern. This sea surface temperature time series for a stationary location within the eastern equatorial Pacific Ocean is often lumped into a broader compendium of patterns termed the El Niño Southern Oscillation Index (ENSO) (NOAA 2017).

To date, the ENSO suite of precursors have not proven to be consistently reliable for hydrologic forecasting beyond a few months lead span. Deterministic numerical global circulation models (GCMs) have also been frequently deployed towards these same forecast objectives but none so far have been able to accurately simulate extended periods of integrated climate for the globe or any sub-region, at least with regard to hydroclimatology.

In the goal of improving hydrologic forecasting skill, researchers continue to experiment with the adoption of various combinations of selected precursors. As opposed to the conventional adoption of precursors that are primarily temperature or pressure based, this paper focuses on those indexes that exemplify high masses of atmospheric moisture. Moreover, this work contemplates the possibility that solar radiant forcing can drive the underlying precursor parameters.

The sun is indisputably the primary driver of our weather. However explicit and physically consistent correlations between longer term surface climate patterns and solar cycles, including the 11 year cycle (Schwabe 1844), have yet to be fully verified or widely documented. In contrast to this contemporary lack of evidence, older studies from the 19th and early 20th centuries produced extensive products that purported to show high correlations between solar cycles and climatic features, including for example global temperature estimates (Koppen 1914) and cyclone frequencies in the Indian Ocean (Meldrum 1885). Notably, the apparent persistence of these synchronous correlations had faded by the middle of the 20th century (Hoyt and Schatten 1997).

Ultimately new connections between the solar irradiance and climate signatures were identified by researchers such as Labitzke and Van Loon (1995) in the upper atmosphere by the late 20th century. However the establishment of lower atmospheric and near surface moisture and temperature correlations to SSNs has remained elusive to date. Many researchers have nonetheless recognized the potential to connect SSNs to surface water hydrology. This was considered a productive study area because streamflow records are commonly understood to represent an integrated signature of climate over their watershed footprint.

In addressing this objective, the recent work of Wallace (2018) included the development of a conceptual model in which the global hydrosphere undergoes energy changes over time and within its Hadley and Walker circulatory limbs as a result in part of slight changes in the total solar irradiance (TSI) of approximately 0.17 W/m^2 on average. The TSI can be represented as an index in numerous variations, including the published monthly Sunspot Numbers (SSN) as archived at the Royal Observatory of Belgium (WDC-SILSO).

From this work, new correlations between solar cycles and atmospheric parameters have been found over the Western Equatorial Pacific (WEP) region. That work identified for the WEP region that solar cycles express pervasive lagged correlations to multiple components of the atmosphere. These correlations were identified across that footprint from the surface via trade winds (TWWP), through the core via latent heat, and up to the top of the atmosphere (TOA) via outgoing longwave radiation.

As featured in that study by several maps of the geopotential height, the overlying weight of the full atmosphere drops significantly over major high altitude land masses in middle latitudes, and those indentations are routinely indicative of enhanced atmospheric moisture. The study accordingly extended the exploration to streams originating from such regions. The initial results were suggestive that significant lagged correlations between those streams and the TWWP could be identified.

Given the lagged correlation between the solar signature and the atmospheric parameters overlying the WEP, it appeared possible to apply a cross-regression moving average (CRMA) approach towards their prediction. Moreover, given the lagged correlation between those atmospheric parameters and the streamflow signatures within the Southern Rocky Mountains (SRM), it also appeared possible to apply a CRMA approach towards streamflow prediction. In essence, these two correlative pairings represent the potential for an accurate, two step CRMA analysis connecting solar cycles to streamflow records.

APPROACH AND METHODOLOGY

Three SRM streamflow records were selected for the CRMA analysis as identified in Table 1 and the map of Figure 1. The three SRM gages are represented in the map by the solid blue dots. Within that domain the Animas is the northernmost gage, the Pecos is the central gage to the east and the Gila gage is at the southern end of the cluster. The positions of the selected streamflow gages with respect to the geopotential height depressions, which can also be identified in the figure and that were developed from the routine satellite ERA-Interim resource were expected to impact the performance of this forecasting approach.

The first featured site is the Pecos near Pecos, New Mexico gage (PnP). It captures water from a catchment which reaches over 4 km in elevation and resides within the noted geopotential indentation at a middle latitude (approximately 37 degrees N). This gage lies largely upstream of any significant human operations such as reservoirs and irrigation. The Pecos River drains ultimately to the Gulf of Mexico within the greater Atlantic Ocean. The second featured site is the Animas River gage near Farmington, New Mexico. The Animas gage shares nearly all of the same characteristics as the Pecos. However its flow rates are roughly 5 to 10 times higher than those of the Pecos, and it drains ultimately to the Upper Colorado River, which reaches the Pacific Ocean.

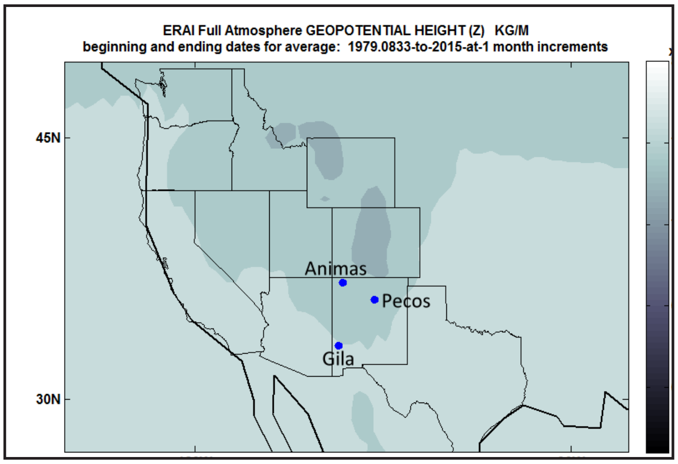

Figure 1. Geopotential height contours across the SRM and stream gages.

Table 1. Stream Gages Utilized.

River, State and Country	Streamflow Gage ID	Decimal Longitude	Decimal Latitude	drainage area (km^2)	Elevation of highest edge of catchment (km amsl)	Years of continuous records available
Pecos River	PnP	254.31730	35.70835	490	4.0	86
Animas River	Animas	251.79825	36.72250	3522	4.2	85
Gila River	GnG	251.46261	33.06150	4828	2.7	88

Sources:
USGS 08378500 Pecos River near Pecos, NM accessed online at http://www.usgs.gov/water/
USGS 09364500 Animas River at Farmington, NM accessed online at http://www.usgs.gov/water/
USGS 09430500 Gila River near Gila, NM accessed online at http://www.usgs.gov/water/

The third site, the Gila River near Gila, New Mexico was chosen primarily due to its marginal qualities with respect to the candidate criteria. As noted, the other two catchments reach above 4 km in elevation but the Gila's watershed only reaches to slightly below 3 km in elevation. Moreover, the Gila watershed is further to the south of the middle latitude target (at approximately 33 degrees N). The Gila also drains ultimately to the Pacific Ocean.

An exploration of the autocorrelations for each time series is helpful in targeting some of the most useful moving averages and lags for the forecasting exercises. Figure 2 outlines a series of autocorrelation functions (ACFs) associated with the SSN and TWWP indexes along with the selected streams. The maximum lag considered was 11 years, specifically because that is the primary period of the SSN index. Many notable features of this chart stand out. For example, the ACFs of the Sun and the Animas River are congruent for the most part. Moreover, to a greater or lesser extent, each ACF shows a cyclostationary behavior, with a dip to low or negative autocorrelations near the five-year lag followed by a return to higher and more positive ACFs near the 11-year lag.

The proposed method is subsequently shown to produce a promising yet variable degree of forecasting span and accuracy improvement across the study region. The first step of the process developed and applied the lagged correlations between each stream gage and the satellite era TWWP for a five-year trailing averages (5yta) streamflow forecast with a lead time of three years into the future.

As part of this initial step, those correlations are applied to the customary linear regression solution as Equation 1.

$$y = Ax + B \qquad (1)$$

Where:

x is the independent variable (TWWP for the first CRMA regression step or simply the appropriate streamflow value for the ARMA case),

y is the dependent variable (streamflow for the first regression step),

A is the dimensionless regression coefficient calculated from a linear fit of a scatter plot between historical values of y and x, and

B is the intercept (the value of y when x is equal to zero).

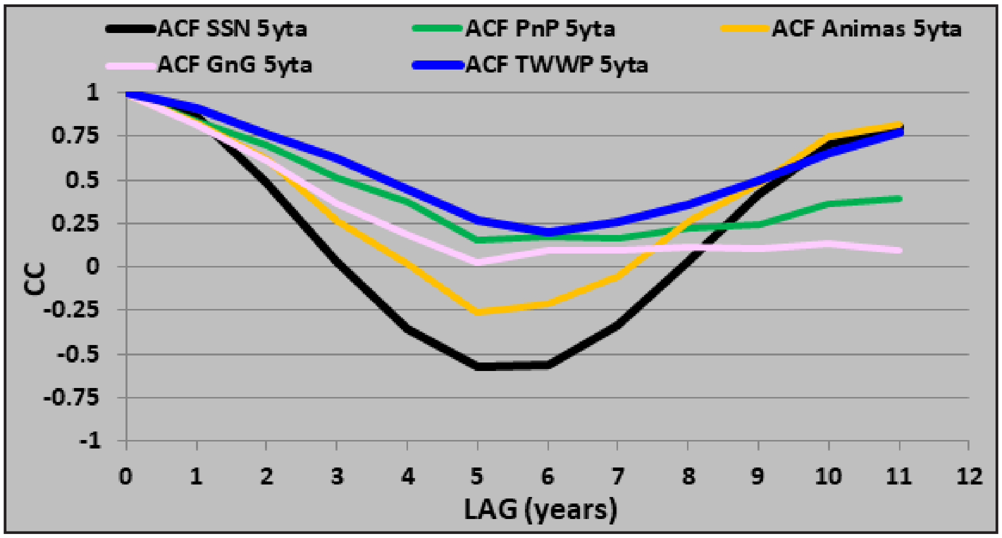

Figure 2. Autocorrelation functions (ACFs) for five-year trailing averages (5yta) of the SSN, TWWP and selected streamflow observation time series.

Accordingly, Pearson correlation coefficients were calculated between the TWWP and each SRM stream in the Wallace study (2018). This exercise demonstrated that for all streams, the TWWP correlations were consistently the highest. Moreover the TWWP correlations generally showed the highest significance scores. The resulting ARMA and CRMA calculations produced the dependent time series for the three SRM streamflow gages.

The second step of the analysis was largely identical to the first step in structure but was limited to extending the three year lead forecasts for the 5yta CRMA cases an additional three years. Moreover, it was limited to the two stream gages associated with the Pecos and Animas Rivers, as opposed to the more marginal Gila River case. This second step was motivated by the correlations indicated between the TWWP and solar cycles. It was additionally informed by the fact that solar cycles themselves are routinely (if not always accurately) forecast in advance by one or more years, as documented for example at the WDC-SILSO site. Accordingly the step entailed first obtaining a record of 5yta SSN values to the current time, and then adding the projected SSN values for the subsequent year. Next, the Pearson correlation coefficient was calculated between the SSN record and the TWWP for a two year lag. The resulting regression coefficients were calculated and those were used to forecast the 5yta TWWP for three additional years into the future.

These projected TWWP values were then utilized, again through the regression relation of Equation 1 and the coefficients corresponding to each stream, to predict the 5yta streamflows of the Pecos and Animas rivers for an additional three years into the future. For those specific cases therefore, streamflows were quantitatively predicted for a total of six years beyond the year 2016. The results of this final step were simply appended to the results from the previous step for the two relevant cases.

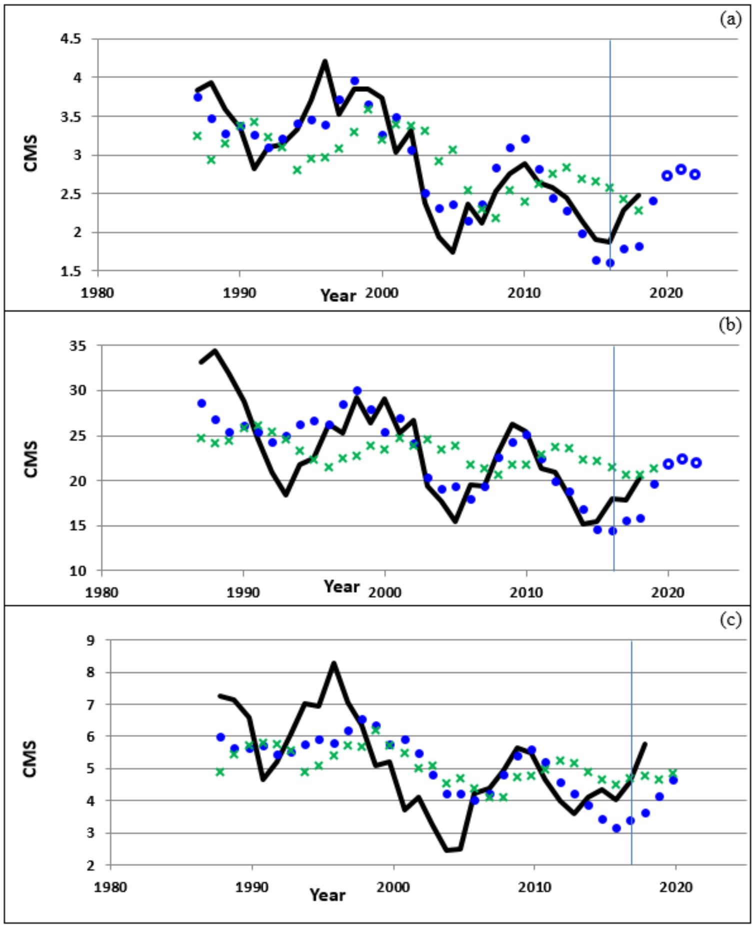

Figure 3. Comparisons of three year-lead predictions to observed values for the featured streams. (a) PnP (b) Animas (c) GnG. All values are for five-year trailing averages (5yta) in cubic meters per second (CMS).

RESULTS

As noted in the previous section, the results documented here include specific cases from application of the widely used Cross Regression and Auto Regression Moving Average (CRMA and ARMA) approaches towards time series predictive analyses. A graphical overlay of observations to the simulated time series is helpful if not essential as a first order assessment of the skill of each exercise. Figure 3 accordingly highlights these overlays for the 5yta cases for each of the three stream gages in this study. In this figure set, the solid black line represents the observed series and dotted lines represent the simulations. The green Xs define the ARMA solutions and the blue dots define the CRMA solutions. The thin vertical line for each subfigure defines the transition from the so-called training period to the test period. In other words, the regressions were developed based upon observation records through for the most part the end of the year 2015.

For most cases the TWWP results exhibit lower errors across the range of streamflow values. Naturally, the closer the fit to both mean and extreme flow values, the better the overall performance of the method. Also, most of the methods show nominally good performance at estimating mean values. Skill performances are routinely quantified through the common Root Mean Squared Error (RMSE). However a greater sensitivity in comparing results was desired and accordingly two Goodness of Fit (GOF) measures were adapted from common significance and hypothesis testing resources. Those measures were the well known Chi squared (χ2) and Kolmogorov Smirnov (K-S) tests. These quantified skill measures of the ARMA and CRMA regression calculations are featured in Table 2. Figure 3 and Table 2 therefore document that among the three approaches explored, the TWWP CRMA exercises produce the most accurate forecasts, particularly for the two streams located well within the main target domain identified.

SUMMARY AND CONCLUSIONS

Considerations of past research regarding solar cycles, Hadley and Walker circulation patterns, and streamflow characteristics of several mid latitude, high altitude watersheds have pointed to the potential for improved multi-annual to sub-decadal forecasting of streamflows in targeted locations. Such conditions appear to apply to the SRM of the Western United States.

In the development of this conclusion, sets of correlations were explored for key sequential features based upon previous published research and currently available solar cycle, and trade wind observations. Equivalent exercises were applied towards potential connections of some of those parameters to streamflow data sets for candidate streams of the SRM. A two staged cross-regression based forecasting approach (CRMA) was then applied to forecast streamflows up to six years into the future. The skill of the CRMA forecasts for the training period were compared to forecasts for the same stream sets via a conventional autocorrelation technique (ARMA).

Table 2. Performance Results.

Forecast Case	Root Mean Squared Error (RMSE)	χ Squared ρ Value	Chi Test Significance at ρ <.1 ?	Kolmogorov Smirnov ρ Value	Auto-correlation of residuals
SSN 2 yr lead forecast of TWWP 5 yta	0.71	2.94E-03	N	0.6	0.581
TWWP 3 yr lead forecast of PnP 5 yta	0.3182	0.999	Y	0.652	0.054
AC 3 yr lead forecast of PnP 5 yta	0.6022	0.036	N	0.200	na
TWWP 3 yr lead forecast of Animas 5 yta	3.1279	0.438	Y	0.781	-0.123
AC 3 yr lead forecast of Animas 5 yta	5.0446	3.94E-14	N	0.011	na
TWWP 3 yr lead forecast of GnG 5 yta	1.1188	5.64E-04	N	0.211	0.089
AC 3 yr lead forecast of GnG 5 yta	1.3550	2.43E-04	N	0.109	na

”na” means not applicable to this exercise. “yta” means year trailing average. “AC” means autocorrelation. “PnP”, “Animas”, and “GnG” are streams as defined in text.

The training forecasts of flows in the Animas River, the Pecos River and the Gila River at the selected observation gages, based upon the CRMA approach were the most accurate of all featured methods. Given the three- to six- year forecast span, several years remain for subsequent review and evaluation. Should these forecasts continue to show high fidelity, they may point the way to a more routine, longer span and higher accuracy approach to streamflow and general drought forecasting to the benefit of all.

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SOURCE DATA

Animas River Source: USGS 09364500Animas River at Farmington, NM Available from https://waterdata.usgs.gov /

ENSO including TWWP Sources: Available from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

NOAA (National Oceanic and Atmospheric Administration) National Climate Data Center (NCDC) 2017

https://www.esrl.noaa.gov/psd/cgi-bin/data/testdap/timeseries.pl

Gila River Source: USGS 09430500 Gila River near Gila, NM. Available from https://waterdata.usgs.gov

Pecos River Source: USGS 08378500 Pecos River near Pecos, NM Available from https://waterdata.usgs.gov

UCAR ERAI Source: Available from https://climatedataguide.ucar.edu/climate-data/era-interim

SSN Source: WDC-SILSO, Royal Observatory of Belgium, Brussels. Available from http://www.sidc.be/silso/