Project Title: Post Gold King Mine Spill: San Juan River Health Monitoring

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Abstract:

One of the biggest mine-waste (Acid Mine Drainage or AMD) spills in the U.S. occurred on August 6, 2015, when 3 million gallons of AMD water was accidentally released into the Animas River from abandoned Gold King Mine located outside of Silverton, Colorado. The spill temporarily changed the color of the river to orange. The contaminated water flowed down the Animas River, into the San Juan River in New Mexico, was carried into the Colorado River and ended up in Lake Powell in Utah. We have conducted a desk-top evaluation of stream "health" in the San Juan River system that crosses the state lines of Colorado, New Mexico, Utah, and Arizona and flows through tribal lands. In 2016, benthic invertebrate surveys were conducted at San Juan River monitoring sites in the Navajo Nation, and those data are available to the public. Biological indices were calculated using these benthic invertebrates following the guidance of each states' regulatory agencies, and the results were compared to evaluate how the sites would be classified in terms of "impairment" by each state's biocriteria method. Our results showed the nature of resiliency from the microorganisms over the time and their recovery trend.

Introduction

While coal and mineral mining is an important revenue generating industry, several environmental consequences are associated with it. The formation of a metal-rich acid solution known as Acid Mine Drainage (AMD) is a major environmental problem associated with mining operations. Once exposed to AMD, the quality of adjacent surface water degrades drastically and eventually becomes unsuitable for sustaining biodiversity. Additionally, soils exposed to AMD become structurally unstable and highly prone to erosion (Ferguson and Erickson, 1988; U.S. Forest Service, 1993; Lapakko, 1993; USEPA, 1994). Mostly, AMD is produced due to the oxidation of pyrite (FeS2). In the presence of oxygen and water, pyrite oxidizes to form Fe^{2+}, SO_4^{2-} and H^+ ions (Stumm and Morgan, 1981).

$$FeS_2 + 3.5\ O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad [i]$$

The produced Fe^{2+} ion then reacts with O_2 to form Fe^{3+}. This reaction is facilitated by the sulfur oxidizing bacteria (*Thiobacillus thiooxidans*, *Thiobacillus ferooxidans*) as they utilize the produced energy from this reaction for their metabolism.

$$Fe^{2+} + 0.25\ O_2 + H^+ \longrightarrow Fe^{3+} + 0.5\ H_2O \qquad [ii]$$

In addition, the produced Fe^{3+} further oxidizes pyrite to form Fe^{2+}, SO_4^{2-} and H^+ ions.

$$FeS_2 + 14\ Fe^{3+} + 8H_2O \longrightarrow 15\ Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad [iii]$$

The abiotic rate of pyrite oxidation by Fe^{3+} is much higher than the oxidation by O_2 and water. Due to the production of H^+ ions the pH of the whole system drops drastically and becomes highly acidic. If the pH of the system remains over 3.5-4.0 standard units, Fe^{3+} precipitates in the form of $Fe(OH)_3$. The yellow-orange colored precipitation of iron hydroxide is known as "yellow boy."

$$Fe^{3+} + 3H_2O \longrightarrow Fe(OH)_3 + 3H^+ \qquad [iv]$$

The overall stoichiometric pyrite oxidation reaction can be written as (Stumm and Morgan, 1981):

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \longrightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ + heat \qquad [v]$$

Due to high acidity, the mobility of the metals in the environment increases significantly. Extensively acidic pH (as low as 2-4 standard units) coupled with metals toxicity can elicit severe impacts on aquatic biodiversity (Soucek et al. 2000; Hansen et al. 2002; Schmidt et al. 2002; Gergardt et al. 2004; Martin and Goldblatt 2007; Jennings et al. 2008; Trout Unlimited 2011). Abandoned mine sites often accelerate the AMD generation process and may require decades of proper management practices to reclaim. The adverse environmental impacts of AMD can exist forever if not addressed. The current number of abandoned mines in the US is estimated to be more than 557,000 (U.S. Forest Service, 2005); many of which are active sources of AMD. Approximately 15,000 to 23,000 kilometers of streams are currently impacted by AMD in the US (Kim et al. 1982; U.S. Forest Service 1993; USEPA 1994; Benner et al. 1997; Jennings et al. 2008; USEPA, 2011), which also represents a direct threat to human health. Due to its complex nature and wide array of consequences, AMD is termed a "multiheaded beast" (U.S. Forest Service, 2005), and taming this beast is a challenging task. According to the US Forest Service (2005), the estimated cost of cleaning up AMD impacted sites on National Forest System (NFS) land is around $4 billion. Between the years 1998 and 2003 around $310 million was spent on AMD impacted NFS land clean-up services (U.S. Forest Service, 2005).

One of the biggest AMD spills in the U.S. occurred on August 6, 2015, when 3 million gallons of AMD water was accidentally released into the Animas River from abandoned Gold King Mine located outside of Silverton, Colorado on Cement Creek in the upper Animas River basin. The upper Animas River basin is a heavily mineralized area that was extensively mined for metals, predominantly gold and silver, from the 1870s to the mid- 1990s. These extensive mining activities increased the exposure of mineralized rocks to the atmosphere, which resulted into production of AMD. The Animas River Spill incident occurred when the EPA crew was investigating the Gold King Mine to assess the on-going water releases from the mine, treat mine water, and assess the feasibility of site remediation. During the investigation, excavation by the EPA unexpectedly caused 3 million gallons of pressurized AMD- water to pour from the mine tunnel into Cement Creek, which feeds into the Animas River. The AMD spill temporarily changed the color of the Animas River to orange. The contaminated water was carried down the Animas and eventually entered the San Juan River system, which flows through the 4-Corners area before terminating in Lake Powell (UT) (Figure 1) (San Juan River fact sheet following 2015 spill at the upstream Gold King Mine (CO) (https://www.epa.gov/sites/production/files/2015-08/documents/goldkingminefactsheet15aug2015.pdf). The San Juan River System is upstream of lands owned by the Navajo Nation in NM, AZ, and UT.

The acid mine drainage released in the spill contained a number of metals and salts totaling about 190 tons of solids, including several forms of toxic metals such as lead, arsenic, mercury, and cadmium (Table 1). These solids were mixed in 3,043,067 gallons of water. This volume of water is approximately 9.3 acre-feet, or 9 football fields spread out at one foot deep (Chief et al., 2016).

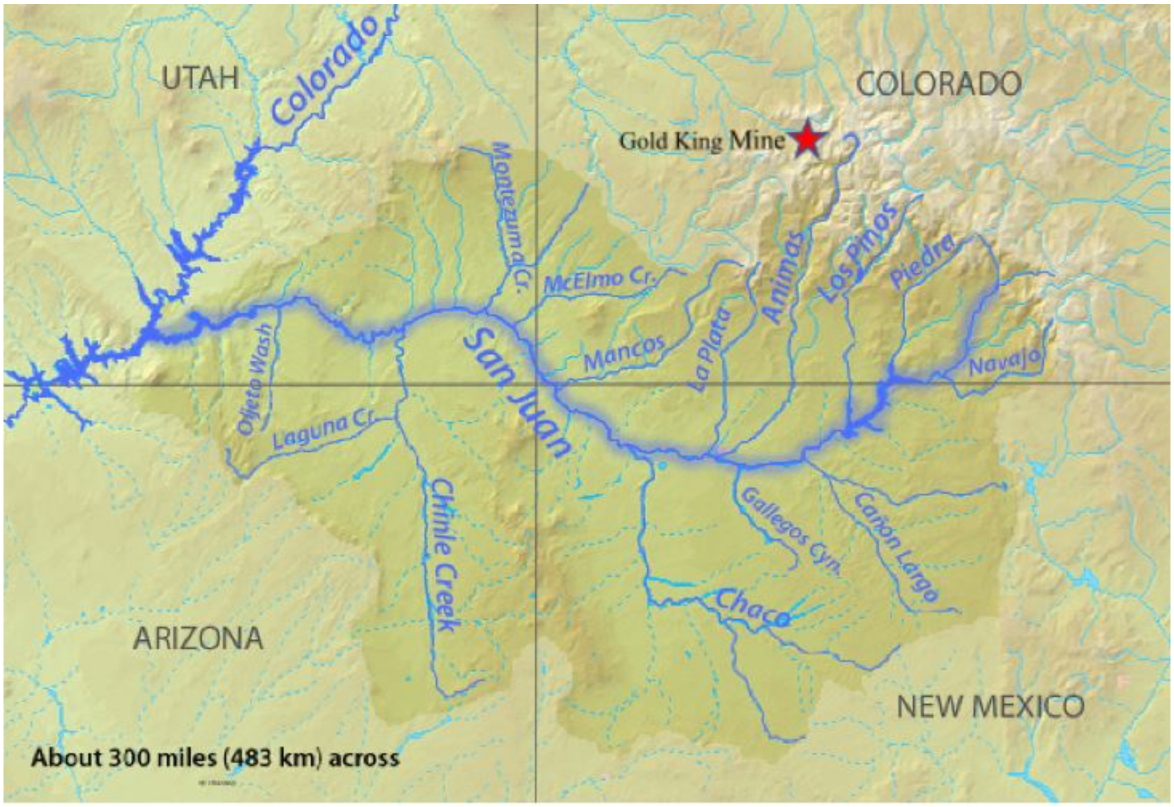

Figure 1: The San Juan River portion of the Colorado River Basin. The red star indicates the site of Gold King Mine spill (Chief et al., 2016).

Over the next month, EPA and partners, including the Colorado Water Quality Control Division (WQCD), carried out a number of activities to issue advisories to impacted communities, meet with and continue to inform community members, and collect and analyze water samples. Residents with wells in floodplains were told to have their water tested before drinking it or bathing in it. People were told to avoid contact with the river, including contact by their pets, and to prevent farmed animals from drinking the water. They were advised not to catch fish in the river. The Navajo Nation Commission on Emergency Management issued a state of emergency declaration in response to the spill. The effects of the Gold King Mine spill on the Navajo Nation have included damage to their crops, home gardens, and cattle herds which ceased irrigating their crops from the San Juan River. People living along the Animas and San Juan rivers were advised to have their water tested before using it for cooking, drinking, or bathing. The spill was also expected to cause major problems for farmers and ranchers who rely on the rivers for their livelihoods. The long-term impacts of the spill are unknown, as sedimentation is expected to dilute the pollutants as the spill cloud moves downstream. Research conducted by the New Mexico Bureau of Geology and Mineral Resources, New Mexico Game and Fish, Mountain Studies Institute, San Juan Basin Public Health and Colorado Parks and Wildlife clearly showed that the farming industry took a direct hit by the spill and the industry is still hurting. The farmers acknowledged that their sales are down by 25% from before the spill because the consumers do not want to buy food grown on the San Juan River basin. Figure 2 shows the change of metal levels in Animas River and San Juan River after the spill.

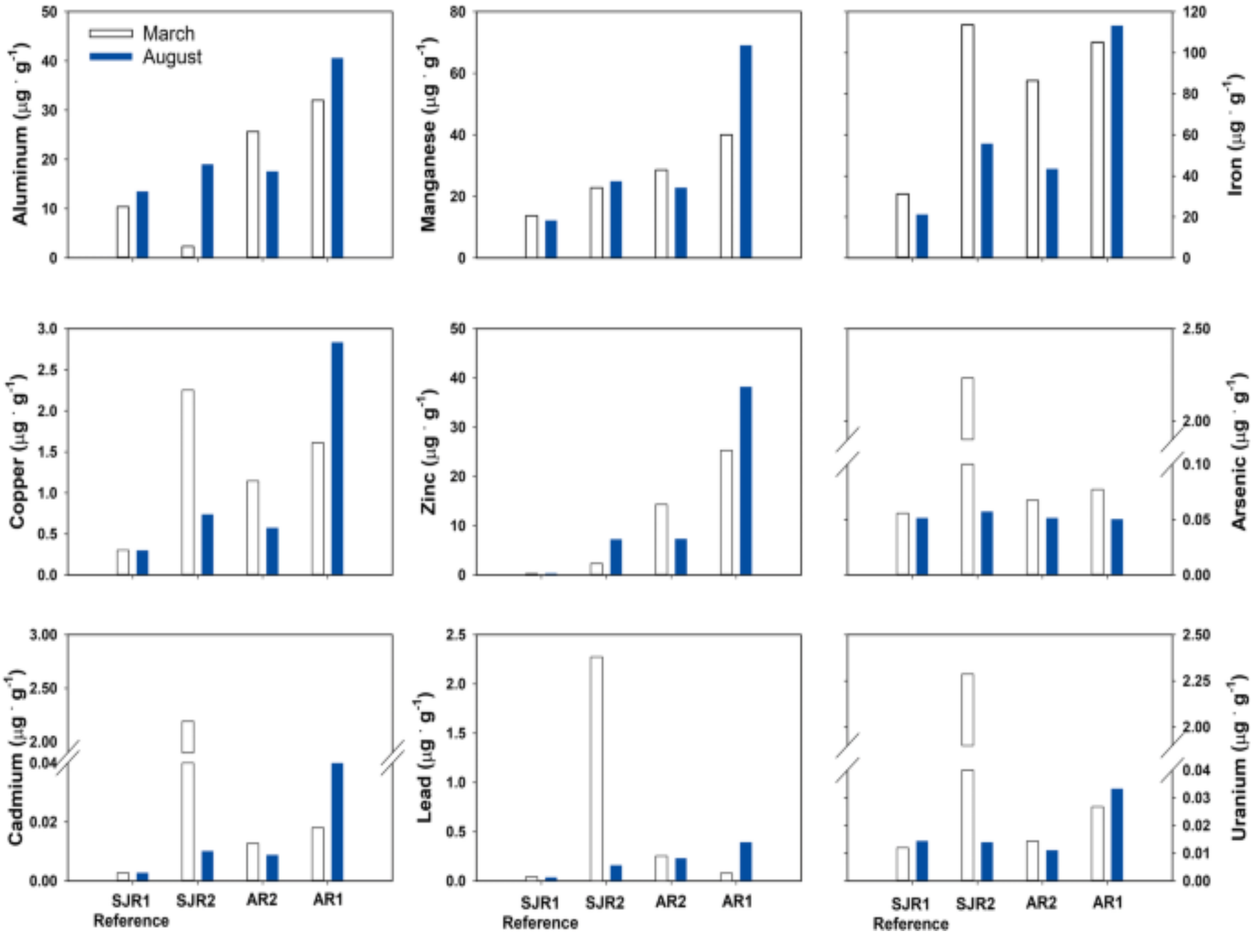

Figure 2. Effects of the Gold King Mine Spill on Metal Cycling through River and Riparian Biota across San Juan River (SJR) and Animas River (AR) basins. (Deval et al., 2020)

Table 1. Weight of metals (in pounds) released in 3,043,067 gallons of acid mine drainage from Gold King Mine; estimated by the University of Arizona from US EPA measurements at the Cement Creek 14th St. Bridge on Aug. 5, 2015 at 16:00 hours (US EPAb, Preliminary Analytical Data, 2015; Chief et al., 2016).

Metal	Pounds	Metal	Pounds	Metal	Pounds
Iron	248,582	**Copper**	919	**Cobalt**	10
Aluminum	23,657	**Sodium**	586	**Antimony**	8
Calcium	11,365	**Barium**	244	**Nickel**	7
Magnesium	6,984	**Arsenic**	206	**Mercury**	6
Potassium	5,307	**Vanadium**	137	**Cadmium**	4
Lead	4,481	**Molybdenum**	50	**Beryllium**	3
Manganese	1,953	**Silver**	28	**Selenium**	n.d.*
Zinc	1,101	**Chromium**	18	**Thallium**	n.d.*

n.d.= not detected

Several post-spill monitoring studies have been conducted in the San Juan River by state and federal agencies in the San Juan River since the spill. In 2016, benthic invertebrate surveys were conducted by the EPA at the San Juan River monitoring sites in the Navajo Nation, and those data are available to the public. (https://www.epa.gov/goldkingmine/follow-monitoring-data-gold-king-mine-incident)

The Clean Water Act requires that the U.S. Environmental Protection Agency establish "Designated Uses" for all of the waters of the U.S. The Agency, or the State or Tribal agencies delegated to act on EPA's behalf, must then determine which bodies of water are not meeting their designated uses and why. The Agencies responsible for these "Impaired Waters" must then go through a process to figure out how to turn things around.

Stream biological assessments (Biosurveys) are direct measures of the resident biota of a stream (fish, insect, algae, plants). Biosurveys help answer questions about whether a water body supports its designated uses and the desired biotic community. Biological criteria (Biocriteria) describe the expected biological community of a minimally impaired/ reference community. Biocriteria are regulatory-based measures that provide a benchmark to describe the desired condition of the system. They serve as a standard for direct comparison of the condition of the biota that live in aquatic systems. Biological Indices are developed as an aggregation of individual metrics that are most informative and relevant to the ecology of the streams within a region. Under the Clean Water Act (CWA), States, and Tribes with CWA §518 authority, are required to develop biological criteria, but they are given flexibility in how that is done. There is substantial variation in how states and tribes have approached this issue (https://www.epa.gov/sites/production/files/2015-10/documents/technical-components-factsheet.pdf).

The biota used in both Colorado and New Mexico biocriteria methods are benthic macroinvertebrates. In Colorado, the methodology used is a "Multi-Metric Index" (which varies by biotype), whereas New Mexico uses a "Stream Condition Index."

This project used data from the 2016 EPA benthic invertebrate surveys to calculate biological indices in accordance with the guidance of Colorado, New Mexico, (and Utah's) states' regulatory agencies. The study aims to identify how a selection of sites along the San Juan River would be classified in terms of "impairment" by each state's biocriteria method, and to examine similarities and differences in these "impairment" results across states.

Project Outcomes

This study used data which were collected by the EPA under its Gold King spill monitoring project, and which are available to the public (USEPA "Follow-Up Monitoring Data from Gold King Mine Incident"). The sampling data used in this study are from August and September 2016 and can be found at the EPA's Gold King Mine Spill website in the Benthic Biological Data 2016 spreadsheet. Benthic invertebrate taxonomy was not completed by a single contract lab; August samples were analyzed by Great Lakes Environmental Center, Inc. and September samples were analyzed by Rhithron Associates, Inc. There were no QA/QC results provided in the USEPA's benthic invertebrate dataset, therefore data quality cannot be determined.

The Navajo Technical University and FALCON research team selected four of the EPA sampling sites along the San Juan River for this study: SJAR, SJ4C, SJSR, and SJLP. SJAR is the EPA-designated "reference site" for the release incident. This sampling site is located immediately upstream of the Animas River confluence (SJAR) and was designated as the "reference site" because it would not have been subject to exposure of chemical inputs from the Gold King Mine spill. The other 3 study sites in the San Juan River were located downstream of the confluence with the Animas River in Farmington, NM (SJLP), Shiprock, NM (SJSR), and Four Corners, NM (SJ4C) (Figure 3). These sites were chosen because they are either: co-located with USGS stream gauges, are within the Navajo Nation, or are close to the Navajo Technical University campus.

<u>Figure 3. US EPA sampling sites along the San Juan River</u>

Bioassessment methods used in Colorado and New Mexico both rely on invertebrate datasets with taxonomic hierarchy, species count (from the EPA samples), regional tolerance values, functional feeding group designations, and habit/behavior assignments. In addition, 3 of the metrics that were calculated under the Colorado Method had to be adjusted for Summer Temperature. Water temperature data was found at the EPA's Gold King Mine Spill website, in the following sheet: August 2016 Follow Up Monitoring Data (XLSX). There were no QA/QC results provided in the USEPA's water quality dataset, therefore data quality cannot be determined. Water temperature (in degrees C) was recorded for each of the 8 sampling events (2 dates at each of the 4 sites).

If there were multiple entries of the same taxon in a given sample (same sample site, same date), it was assumed that 2 *different* species of that genus, tribe, or family were recorded. These were treated as distinct taxa in the analysis and were distinguished using "A," "B," "C" labels.

Regional tolerance values (TV), functional feeding group designations (FFG), habit/behavior assignments corresponding to each taxon were from in Barbour et al. 1999, Appendix B. The Regional Tolerance Value for the "Northwest (ID)" region was used based on the assumption that the sampling sites in New Mexico are more similar to Rocky Mountain habitats in Idaho than they are to habitats in the other ecoregions. When a TV or FFG was not listed for a taxon, best professional judgement was used to adopt an appropriate value based upon reported values for closely related taxa. Comments were made in the spreadsheet "Notes" column to identify when and how that was done.

All data entry and metric calculations were independently checked by a second investigator in order to verify data quality.

<u>Assumptions Made for Calculating Attainment/Impairment with the Colorado Method</u>:

This reach of the San Juan River is equivalent to "BioType 1" (i.e. Transition) based upon similar designation for nearby rivers (RioGrande, Mancos, McElmo Creek). Therefore, the relevant Aquatic Life Use Thresholds applicable to this study are: 45 (Attainment), 34 (Impairment) and Auxiliary Thresholds of HBI < 5.8 and Shannon Diversity Index > 2.1
Note: CO Guidance (2017 Appendices p. 13) states that in the San Juan River Basin "*Cluster analysis has demonstrated that the benthic macroinvertebrate composition….in those bigger rivers are statistically comparable to the benthic macroinvertebrate compositions in smaller sized tributaries within the same basins*."

For the metrics, it was assumed that "Intolerant Taxa" = Taxa with TV ≤ 3.

<u>Metrics Used (Colorado Method)</u>: For Biotype 1

- # EPT taxa in the sample – adjusted to reported temperature for the sampling date at each station
- % Non-Insect Individuals of all individuals
- % EPT excluding Baetidae of all individuals
- % Coleoptera Individuals of all individuals
- Intolerant taxa as a percentage of all taxa – adjusted to reported temperature for the sampling date at each station
- Number of Clinger Taxa (temperature adjusted) – not calculated due to substantial data gaps on "Habit" for the species
- # Facultative Predator or Shredder Taxa
- % increase indicator individuals in Biotype 1 – per lists of "Tolerant Increasers" for Mountain/Transitional sites in Table 8 and Mid-elevation Families in Table 9 (Jessup & Stribling, 2017, pp. 36-37)

Hilsenhoff Biotic Index Formula

$$= \sum \frac{n_i * t_i}{N}$$

Where, n_i is number of individuals of the i^{th} taxon
t_i is the tolerance value of that taxon and

N is the total number of individuals in the sample.

Shannon Weiner Index Formula

$$= \Sigma p_i \times \ln p_i$$

Where, p_i is the proportion of the entire community made up of species i

Assumptions Made for Calculating Attainment/Impairment with the New Mexico Method:

NM has two methods for determining biological use attainment in freshwater rivers & streams: the "reference condition" approach used in the Mountain Ecoregions and the "reference site" approach used everywhere else (NMED, 2019). The study area for this project falls within the San Juan/Chaco Tablelands and Mesas, Arid Canyonlands, and Shale Deserts and Sedimentary Basins ecoregions (Ecoregions 22i, 20d and 20b, respectively; Griffith et al, 2006) and is therefore subject to the Reference Site approach.

NMED (2019) describes their Reference Site approach as follows:

Based on identification and enumeration of the benthic macroinvertebrates present in the two samples, biological response indicators (i.e., benthic macroinvertebrate metrics) are calculated and compared between the two sites. Under this approach, the reference site serves as a quantitative control or yardstick to which a site may be compared and evaluated. The eight metrics and scoring criteria New Mexico uses for the reference site approach are recommended in Plafkin et al. (1989) Figure 6.3-4 as modified in Jacobi (2009), excluding the Standing Crop and Community Loss metrics. The ratio between the score for the study site and the reference site provides a percent comparability measure for each study site. The study site is therefore assessed on the basis of its similarity to the reference site and its apparent potential to support an acceptable level of biological health. The resulting score is placed in a condition category based on percent of reference: Non-Impaired (>83%), Slightly Impaired (54-79%), Moderately Impaired (21-50%), Severely Impaired (<17%). Sites in any of the impaired condition categories are considered to "Not Supporting" with respect to aquatic life use (see Table 3.3). Plafkin et al. (1989) recommends leaving 4% between each category to account for subjective judgment (e.g., BPJ) as to correct placement.

Table 2. Interpreting benthic macroinvertebrate data to determine Aquatic Life Use Support in wadeable, perennial streams

Type of Data	Fully Supporting		Not Supporting	Notes
Macroinvertebrate assemblages in Ecoregions 22, 24, 25, and 26[a]	Reliable data indicate functioning, sustainable macroinvertebrate assemblages not modified significantly beyond the natural range of reference condition (>83% of reference site(s)). [a]	[a]	Reliable data indicate macroinvertebrate assemblage with moderate to severe impairment when compared to reference condition (≤79% of reference site(s)). [a]	Reference condition is defined as the best situation to be expected within an ecoregion. Reference sites have balanced trophic structure and optimum community structure (composition & dominance) for stream size and habitat quality.
Macroinvertebrate assemblages in Ecoregions 21 and 23 using M-SCI[b]	Reliable data indicate functioning, sustainable macroinvertebrate assemblages not modified significantly beyond the natural range of reference condition (> 56.7 score).		Reliable data indicate macroinvertebrate assemblage with impairment when compared to reference condition (≤56.7 score).	

NOTES:
[a] Percentages and recommended 4% gap for BPJ are based on Plafkin et al. (1989).
[b] Percentages based on Jacobi et al. (2006).

The following eight metrics were calculated for each site:

Species Richness
Hilsenhoff Biotic Index
Ratio of Scrapers to Filtering Collectors
Ratio of Ephemeroptera+Plecoptera+Trichoptera to Chironomidae
Percent Contribution of the Dominant Taxon
Ephemeroptera+Plecoptera+Trichoptera Richness
Community Similarity (per the Community Loss Index)
Ratio of Shredders to Total Individuals

Percent comparability measures were then calculated for each metric, for each study site, and then compared to the reference site. An average comparability measure was calculated, and this average was compared to the state's "condition categories" to categorize the impairment status of each site. The one exception was the Community Similarity Index, since by definition it included a comparison of study site to reference site as part of the index determination. So, for that metric, instead of a percent comparability measure, the raw index was used in the tally for impairment determination (Table 3).

Table 3. Bioassessment Results

Site	Colorado Results	New Mexico Results
SJAR August	Impaired	
SJAR September	Not Impaired	
SJLP August	Impaired	Non-Impaired
SJLP September	Attainment	Non-Impaired
SJSR August	Attainment	Non-Impaired
SJSR September	Impaired	Non-Impaired
SJ4C August	Attainment	Non-Impaired
SJ4C September	Impaired	Moderately Impaired

Conclusion

The ecological health of streams and rivers is often assessed by looking at freshwater invertebrates. RIVPACS models are based on a database of reference samples from streams and rivers across the San Juan River which flows into three states on the Navajo Reservation, these were collected between 2014 and 2019. The information collected was put into a spreadsheet then categorized to Class, Order, Phylum, family, Tribe, and Genus and it was done for the New Mexico and Colorado since the river runs through the three states also Utah. The information was broken down into a final draft report to analyze the samples of species that were affected. The need to define a target community of what type of species were affected and to create a baseline for comparing results. Analyzing the data was a factor since no other information was available. The river has been impacted by disturbance from the chemicals, the flow and destroyed certain species.

Student Involvement

One NTU Environmental Science and Natural Resources undergraduate student, Darlene Wilson, got trained under this project. Darlene worked along Dr. RoyChowdhury and FALCON project team members Dr. Judy Dudley and Claire Doyle. Darlene attended AISES Region 3 conference in Albuquerque from April 1-2, 2022. Darlene presented (poster presentation) her research at 9th Annual NTU Research Day Competition on March 4, 2022, and N^4WPP Water Symposium on April 22, 2022.

Ongoing Work

As mentioned earlier one of the four sampling sites used in this study, SJAR, is located immediately upstream of the Animas River confluence. We have identified the exact location of SJAR sampling site (Figure 4) and are in the process of collecting the water samples and analyze them to assess the current state of the problem.

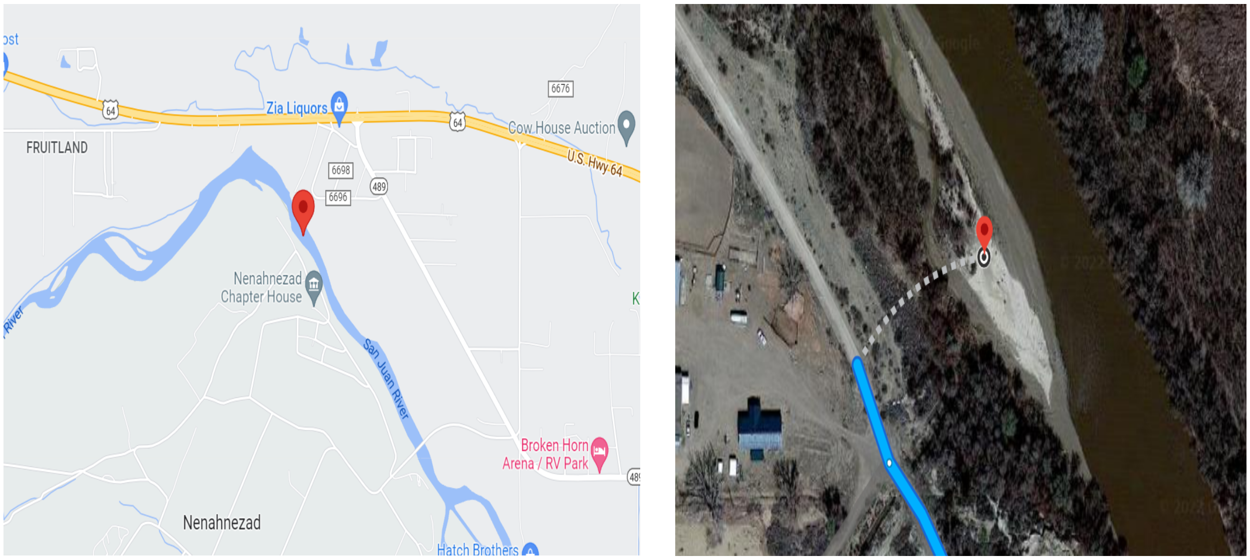

Figure 4. Sampling site SJAR near Farmington, NM