AN EVALUATION OF WATER AND SEDIMENT QUALITY IN A MINE-IMPACTED WATERSHED: CASE STUDY OF ELM CREEK, PICHER, OKLAHOMA

By

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Dissertation approved:

Major Professor

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Introduction

Abandoned mining sites have been widely documented to be hazardous to the environment, both physically and chemically. Such hazards include sediment and water contamination, which can harm local biota and downstream urban and rural communities (Gutierrez et al., 2020; Johnson et al., 2016; Juracek & Drake, 2016). Specifically, lead (Pb) and zinc (Zn) mining has occurred for centuries due to Pb-Zn ores being widely dispersed and found in most countries, leading to mine waste being left behind after abandonment (Gutierrez et al., 2016). These abandoned Pb and Zn mines, and the left behind waste, contribute to the degradation of usable land and water through environmental contamination (Gutierrez et al., 2016; Gutierrez et al., 2015; Johnson et al., 2016; Juracek & Drake, 2016).

Legacy sediment has also been widely documented in the United States. These sediments are earth materials - primarily alluvium or colluvium - deposited following human disturbances, such as mining or deforestation (James, 2013). Legacy sediment includes spoils (waste and mining debris) from mines and construction sites that deliver material downstream from the source (James et al., 2020). For example, hydraulic gold mining in California caused an increase of approximately 1 billion m^3 of sediment into the environment from 1853-1884, which led to widespread historical aggradation (James, 1997, 2013). Denudation, the process of erosion, leaching, stripping, and reducing the mainland due to removal of material from higher to lower areas with a permanent filling of lowlands, took effect at a rate of approximately 1 cm per year across a 1,000 km^2 area known as Bear

Basin within northeastern California due to the hydraulic mining, leading to greater floods downstream (Haldar & Tisljar, 2014; James, 1997, 2013).

Contamination of river sediments can result from nearly every conceivable human activity within a drainage basin (Wohl, 2015). The historic Tri-State Mining District (TSMD) of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma has a history of metal contamination from mining that extended over 100 years (Gutierrez et al., 2016; Gutierrez et al., 2020; Gutierrez et al., 2015; James, 2013; James et al., 2020; Johnson et al., 2016; Juracek & Drake, 2016; Manders & Aber, 2014). This region was among the world's foremost providers of Pb and Zn from 1850-1970 (Gutierrez et al., 2020). Overall, 23 million tons of zinc concentrate and four million tons of lead concentrate were extracted from TSMD across the three states (Brosius & Sawin, 2001; Johnson et al., 2016). As the ores were extracted, chat, or waste rock separated from economically viable ore, was piled up to heights estimated at 200 feet in some places within towns and near mining infrastructure across TSMD (Johnson et al., 2016). The chat piles consisted mainly of chert, limestone fragments, and small portions of zinc and lead sulfide minerals (Gutierrez et al., 2020; Johnson et al., 2016). Proximity to the chat piles and various construction that used chat, such as children's sandboxes and paving roads, caused human health problems within the local populaces, in part due to elevated blood lead levels (Johnson et al., 2016; Malcoe et al., 2002). These included behavioral abnormalities, decreased cognitive function, delayed puberty in children, decreased fertility in adults, and increased risk for hypertension and death (Breysse, 2020; Johnson et al., 2016; Malcoe et al., 2002; Shriver et al., 2008).

While the chat piles within the TSMD are not *sensu stricto* classified as legacy sediment, the environmental damages and human health concerns resulting from sediment being leached from the chat piles prompted the United States Environmental Protection Agency (USEPA) to initiate remediation within TSMD as four superfund sites (Cherokee County, Oronogo-Duenweg Mining Belt, Newton County, and Tar Creek) beginning in 1983 (EPA, 2023, see Figure 1). Superfund is the common name for CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act), which was enacted in 1980 to direct the cleanup of abandoned or uncontrolled hazardous waste sites, or known as superfund sites, within the U.S. (EPA, 2023b). Currently there are 1336 Superfund sites spanning all fifty states and nine specifically in Oklahoma (EPA, 2023a, 2023b).

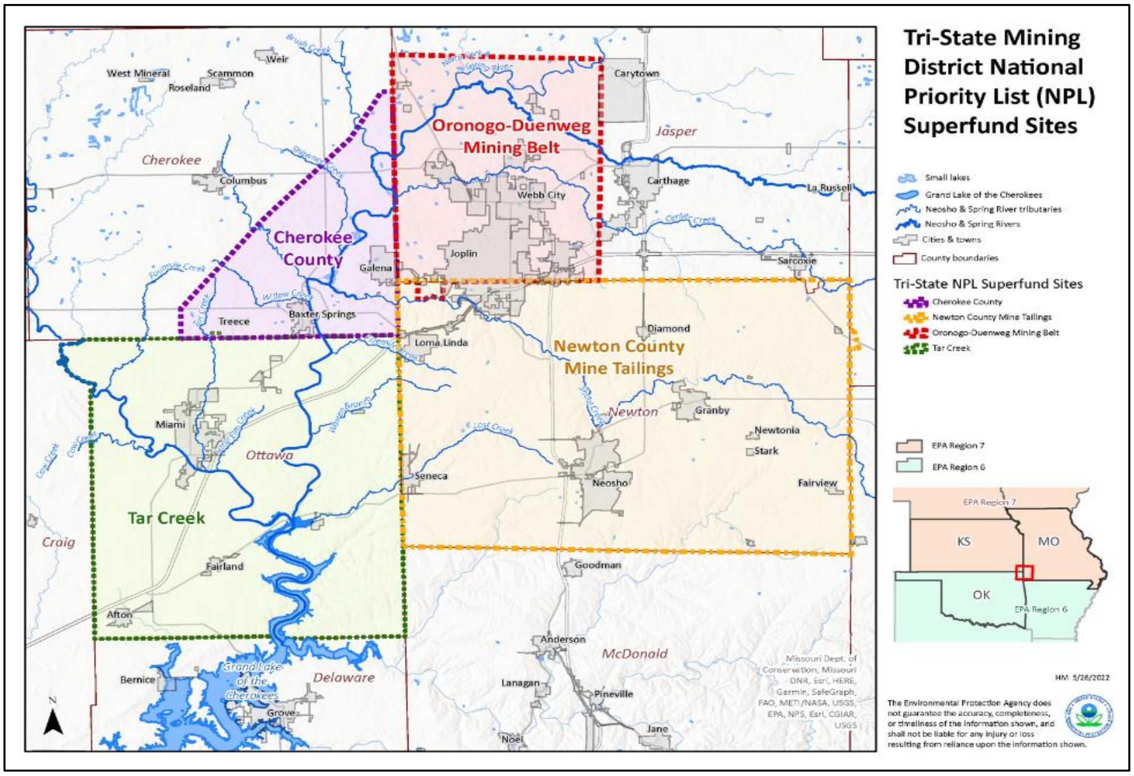


Figure 1: Map of Tri-State Mining District's Superfund sites. Image: epa.gov

The region of focus for this study is that of the Tar Creek Superfund site (TCSS) within Oklahoma (OK). The most intense mining operations occurred in and around Picher, OK with 130,410 tons of lead and 749,254 tons of zinc produced annually (EPA, 2023c; Mathews & Wood, 2011). Ore was first discovered near the town of Picher in 1914 and was a major national center of lead and zinc mining until 1970 when the mines began to dry up along with many others in the TSMD (EPA, 2023c).

The local mines in Picher were above two aquifers, the Boone and Roubidoux. The Boone aquifer is classified as a minor aquifer due to the low water yield of less than 10 gallons per minute (gpm) and sits above the Roubidoux aquifer, which is classified as a major aquifer because of having an average yield of at least 50 gpm (*Boone and Roubidoux Aquifers Study*, 2017; Osborn, 2001). Due to the Boone aquifer's karst nature, it is more susceptible to groundwater contamination, but also has a high recharge rate from surface water (Osborn, 2001). Both aquifers are important resources for public use groundwater and the Roubidoux aquifer is also used for agriculture and industry (*Boone and Roubidoux Aquifers Study*, 2017). The Boone aquifer can discharge into the Roubidoux aquifer by way of water moving through pores and fractures thus increasing the risk for cross contamination (*Boone and Roubidoux Aquifers Study*, 2017).

The Boone aquifer's groundwater would seep into the mine shafts during operation leading to pumping devices being installed to dry the shafts for use (ITRC, 2017). Once the mining operations ceased, the pumping ceased as well leading to the groundwater chemically reacting with the leftover mineral deposits forming acid mine water that, ultimately, reached the surface (Gutierrez et al., 2016; ITRC, 2017). This overland flow eliminated most of the local biota within Tar Creek and stained the bottom of the riverbed red due to the ferrous hydroxide deposition (EPA, 2023c; ITRC, 2017). This prompted the EPA and Oklahoma to investigate and subsequently add the Tar Creek site to the national priority list (NPL) in September 1983 (EPA, 2023c). The superfund site does not have a preset boundary; rather, it comprises wherever chat piles exist, which covers approximately 330 piles within Ottawa County, OK (EPA, 2023c).

Barrett (2022) conducted a study along an approximately 1-mile reach of Elm Creek within TCSS, using two sample sites: Bird Dog North and Bird Dog South (see

Figure 2). The goal of Barrett's work was to determine the origin of the heavy metal concentrations within Elm Creek and to document whether metal concentrations were above EPA cleanup targets for local water and sediment. Of the fifteen water samples tested by Barrett, from 2/22/2020 to 10/1/2021, for the following metals: Arsenic (As), Cadmium (Cd), Iron (Fe), Lead (Pb), Manganese (Mn), and Zinc (Zn), all but As had samples with detectable levels above the EPA cleanup targets and the background concentrations (Tables 1 and 2). Barrett (2022) noted increases of 8 times the EPA target concentration for Cd, 11 times for Fe, 5 times for Pb, 24 times for Mn, and 23 times for Zn downstream of the chat piles in Elm Creek indicating contamination because of the mining operations. For the sediment samples, Barrett had 3 times the EPA target concentration for As, 20.5 times for Cd, 33.7 times for Pb, and 6.4 times for Zn downstream of the chat pile, although Fe and Mn did not have EPA cleanup targets regarding sediment. The sampling regimen of Barrett (2022) – namely, collecting water and sediments upstream and downstream of the chat piles – confirmed that the contamination was due to sediment originating off the chat piles proximal to the stream channel.

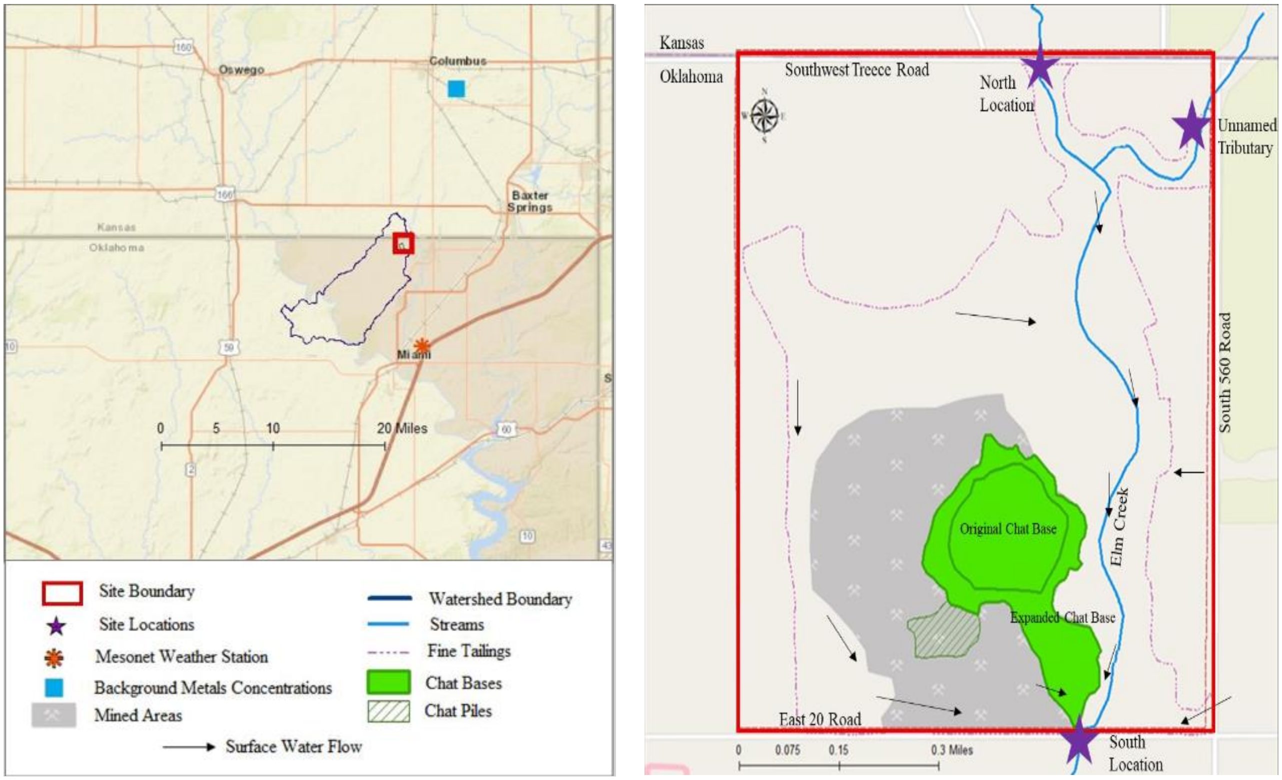


Figure 2: Tar Creek Superfund Site study area for investigating heavy metal concentrations within water and soil at field sites Bird Dog North (North Location), Bird Dog South (South Location) and unnamed tributary. (Barrett, 2022)

Aims and Objectives

This thesis focuses on the ongoing remediation of Tar Creek and the efficacy of the cleanup protocols being employed within the watershed. The study continues the work of Barrett (2022) by extending the temporal record of in-channel contamination to understand the changes in contamination over a longer time span, but also adds a spatial component by monitoring and documenting sediment transport further downstream. The study has two broad research aims: (1) to assess the magnitude and extent of mining-related sediment contamination in the study area within the TSMD, and (2) to quantify the transport and environmental fate of contaminated sediment from the headwaters of TCSS to downstream watersheds.

Study Area

The study site encompasses approximately 1.5 miles of Elm Creek that drains the TCSS near the town of Picher, OK (see Figure 3). The site is known as Distal10a by the remediating party, namely the Quapaw Tribe (Nation, 2023). Elm Creek flows through TCSS diagonally from north to southwest and eventually joins with Tar Creek which, in turn, connects downstream with the Neosho River. The headwaters for Elm Creek are located approximately 1.9 miles north of the study site, which is part of the 22.7 sq. mile Elm Creek Watershed, see Figure 5 (CH2M Hill, 2016). The Elm Creek watershed, as measured using GIS from the USGS gauging site as the outlet, is 18.6 sq. miles, and the Distal West watershed, using the outlet labeled in Figure 6, is 6.4 sq. miles. Elm Creek itself flows past the remediated chat pile and through a culvert located beneath E20 road, then flows southwest through the study site for about 1.5 miles before exiting the study site via a culvert located on S550 road (see Figure 3). Directly upstream and downstream of Bird Dog South, retention ponds were placed at varying stages of the ongoing remediation which resulted in flow being cut off from downstream systems for extended periods of time.

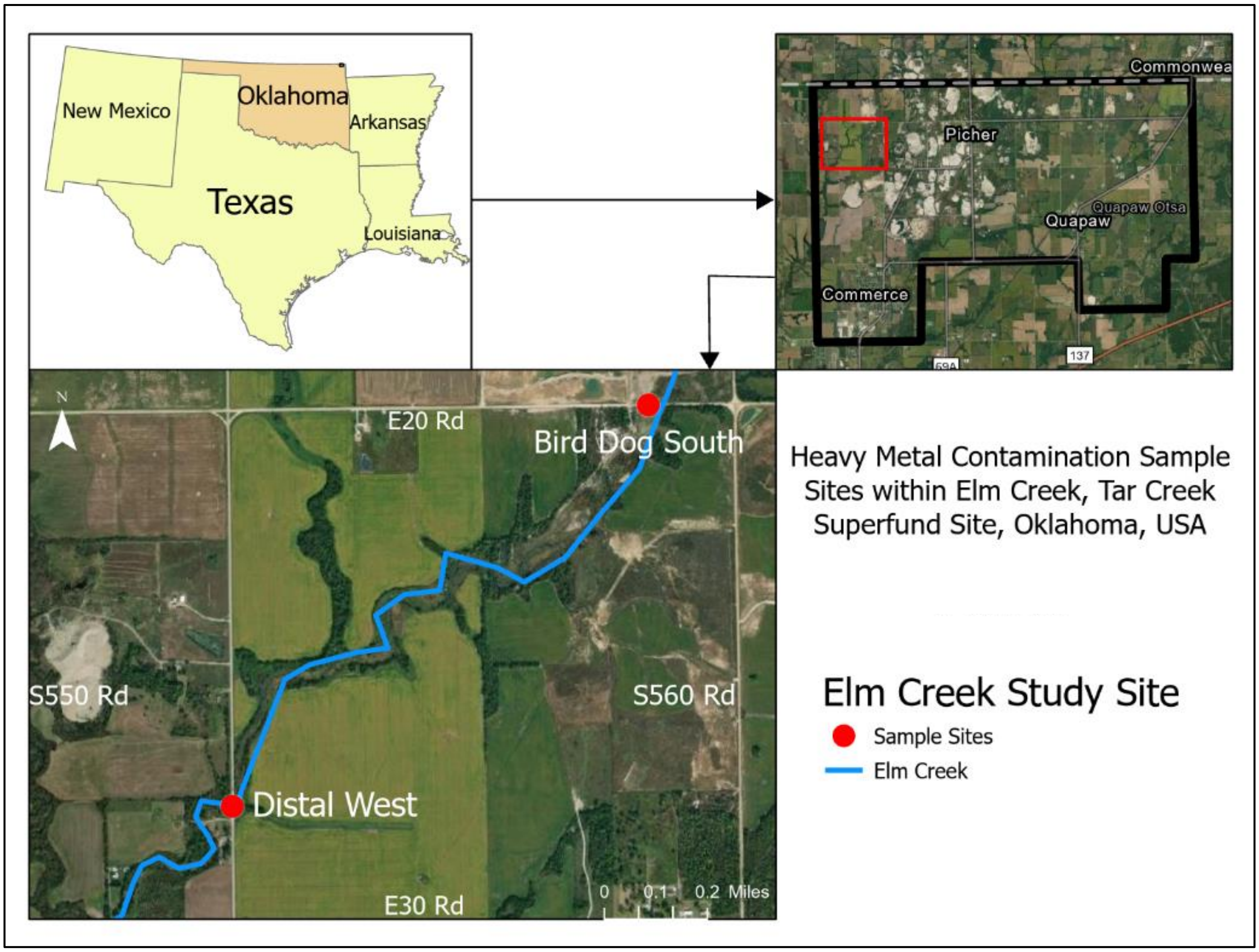
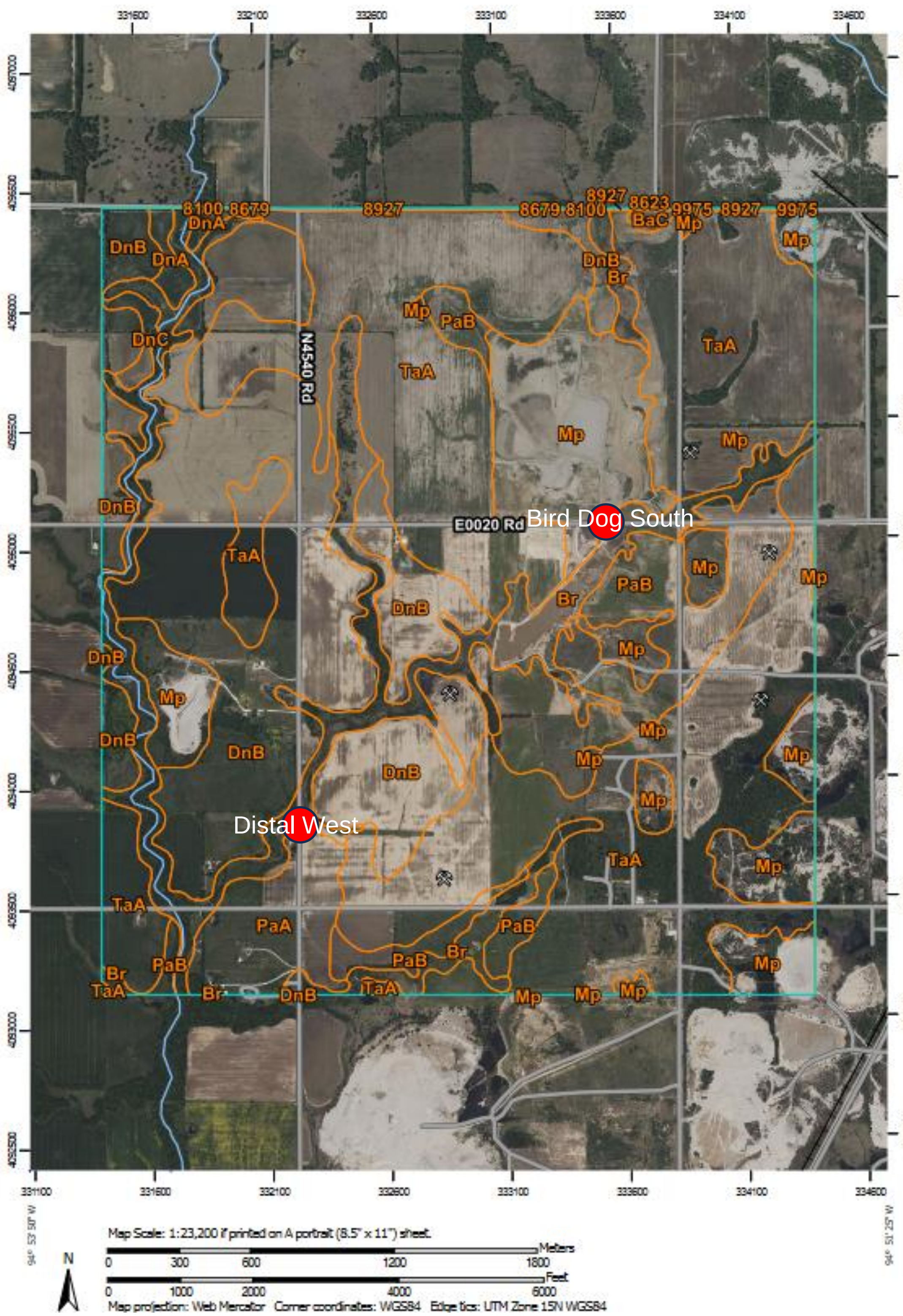


Figure 3: Elm Creek Study Site

To monitor water and sediment within Elm Creek, two sampling sites were chosen: (1) Bird Dog South at the culvert under E20 road, and (2) Distal West at the culvert under S550 road (see Figure 3). These two locations were chosen as continuous monitoring equipment could be installed and secured within the channel at a culvert and bridge crossing. These two sites also allowed us to establish measurement points both immediately downstream of the remediated chat pile (i.e., Bird Dog South, as a continuation of Barrett's 2022 work) and at a location that drained into the larger river systems downstream (i.e., Distal West), thereby establishing a spatial context to the contamination of sediment within Elm Creek.

The geology of the study area is primarily weathered sandstone and loess over Pennsylvanian shale (Johnson et al., 2008; Shepherd et al., 2022). Below the shale layer is karst dolomite and limestone (Johnson et al., 2008; Shepherd et al., 2022). Soils within TCSS are generally silt loams (USDA, 1964; USDA & NRCS, 2024). Within the study area itself, the Dennis silt loam series and Taloka silt loam series dominate, as seen in Figure 4. In these soils, the water table is approximately 12-24 inches from the surface (USDA & NRCS, 2024). The Dennis silt loam (DnB) is somewhat poorly drained after storm events and occurs on gentle slopes of 1-3% average slope. The Dennis silt loams belong to hydrologic group C/D indicating low infiltration and high runoff potential (USDA & NRCS, 2024). The Taloka silt loam (TaA) is also somewhat poorly drained on lower slopes, generally around 1% (USDA & NRCS, 2024). The Taloka silt loams belong to hydrologic group D indicating that it has very low infiltration and higher runoff potentials than the Dennis silt loam series (USDA & NRCS, 2024).


Bird Dog South
Distal West
N4540 Rd
E0020 Rd
8100 8679
8927
8679 8100
8927
8623
9975 8927 9975
DnA
DnB
DnC
BaC
Mp
Br
PaB
PaA
TaA
331100
331600
332100
332600
333100
333600
334100
334600
94° 53' 50" W
94° 51' 25" W
N
Map Scale: 1:23,200 if printed on A portrait (8.5" x 11") sheet.
Meters
0 300 600 1200 1800
Feet
0 1000 2000 4000 6000
Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 15N WGS84

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
8100	Hepler silt loam, 0 to 3 percent slopes, frequently flooded	0.3	0.0%
8623	Bates loam, 3 to 7 percent slopes	0.4	0.0%
8679	Dennis silt loam, 1 to 3 percent slopes	0.8	0.0%
8927	Taloka silt loam, 0 to 1 percent slopes	2.3	0.1%
9975	Dumps, mine	0.5	0.0%
Subtotals for Soil Survey Area		**4.3**	**0.2%**
Totals for Area of Interest		**2,439.9**	**100.0%**

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
BaC	Bates loam, 3 to 5 percent slopes	3.5	0.1%
Br	Eram-Verdigris complex, 0 to 20 percent slopes	272.3	11.2%
DnA	Dennis silt loam, 0 to 1 percent slopes	14.6	0.6%
DnB	Dennis silt loam, 1 to 3 percent slopes	575.2	23.6%
DnC	Dennis silt loam, 3 to 5 percent slopes	9.0	0.4%
Mp	Dumps, mine	297.7	12.2%
PaA	Parsons silt loam, 0 to 1 percent slopes	75.8	3.1%
PaB	Parsons silt loam, 1 to 3 percent slopes	205.2	8.4%
TaA	Taloka silt loam, 0 to 1 percent slopes	982.4	40.3%
Subtotals for Soil Survey Area		**2,435.5**	**99.8%**
Totals for Area of Interest		**2,439.9**	**100.0%**

Figure 4: Project site soil map with detailed legend. The red dots indicate the two field sites Bird Dog South and Distal West. Websoilsurvey.com

Land use is an important component in any study such as this as varying types can have significant effects on storm runoff generation, sediment erosion and transport, and decreased water quality (EPA, 2022). Land use, as defined by the EPA, is “the human use of land” which “represents economic and cultural activities that are practiced” at certain locations (EPA, 2022). Much of the land used near the study area is utilized for hay/pastures (59%), cultivated crops (11%), deciduous forests (15%), and human settlements (15%) within northeastern OK (USGS, 2019).

Climate is also a fundamental component for understanding basin response as it relates to the continual cleanup of TCSS, particularly Elm Creek. Climate is defined as “the long-term pattern of weather in a particular area” which is measured as an average for the area for at minimum 30 years (Society, 2022). The climate of Oklahoma, which houses all of the TCSS, ranges from humid subtropical in eastern Oklahoma to semi-arid in western Oklahoma. The eastern climate type, within which the study area lies, is impacted by proximity to the Gulf of Mexico which transports moist (mT) air northward, thereby increasing precipitation and humidity. Summer periods in Oklahoma are long and hot, while winter periods are short and more mild than other areas of the U.S. (Survey, 2010). Average yearly precipitation varies from region to region in Oklahoma, such as an average of approximately 44.8 inches in the east and an average of approximately 29.5 inches in the west (Osborn, 2020). The study area experiences an average annual rainfall of 45.6 inches, statistically indistinguishable from the average rainfall for the eastern portion of Oklahoma (Mesonet, 2023).

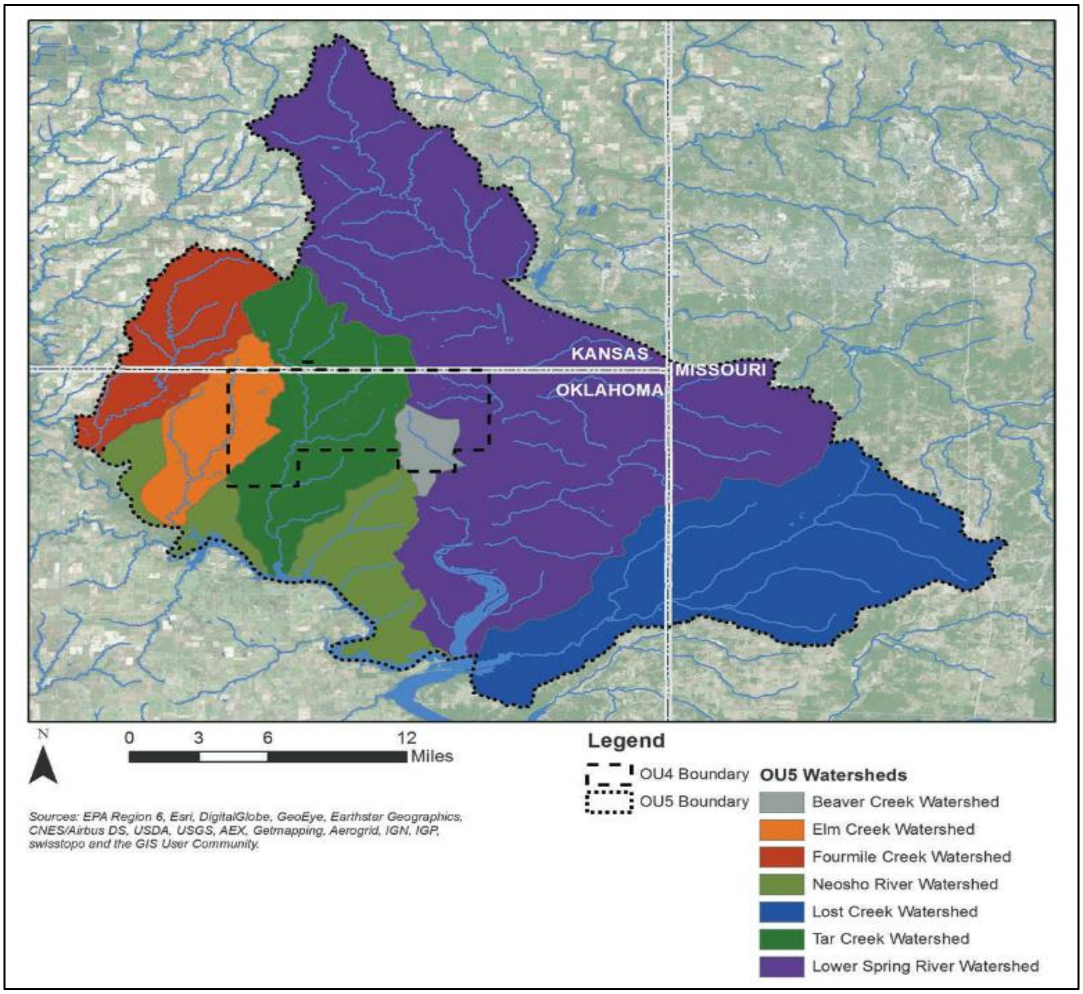


Figure 5: Watersheds of the Tar Creek Superfund Site. epa.gov

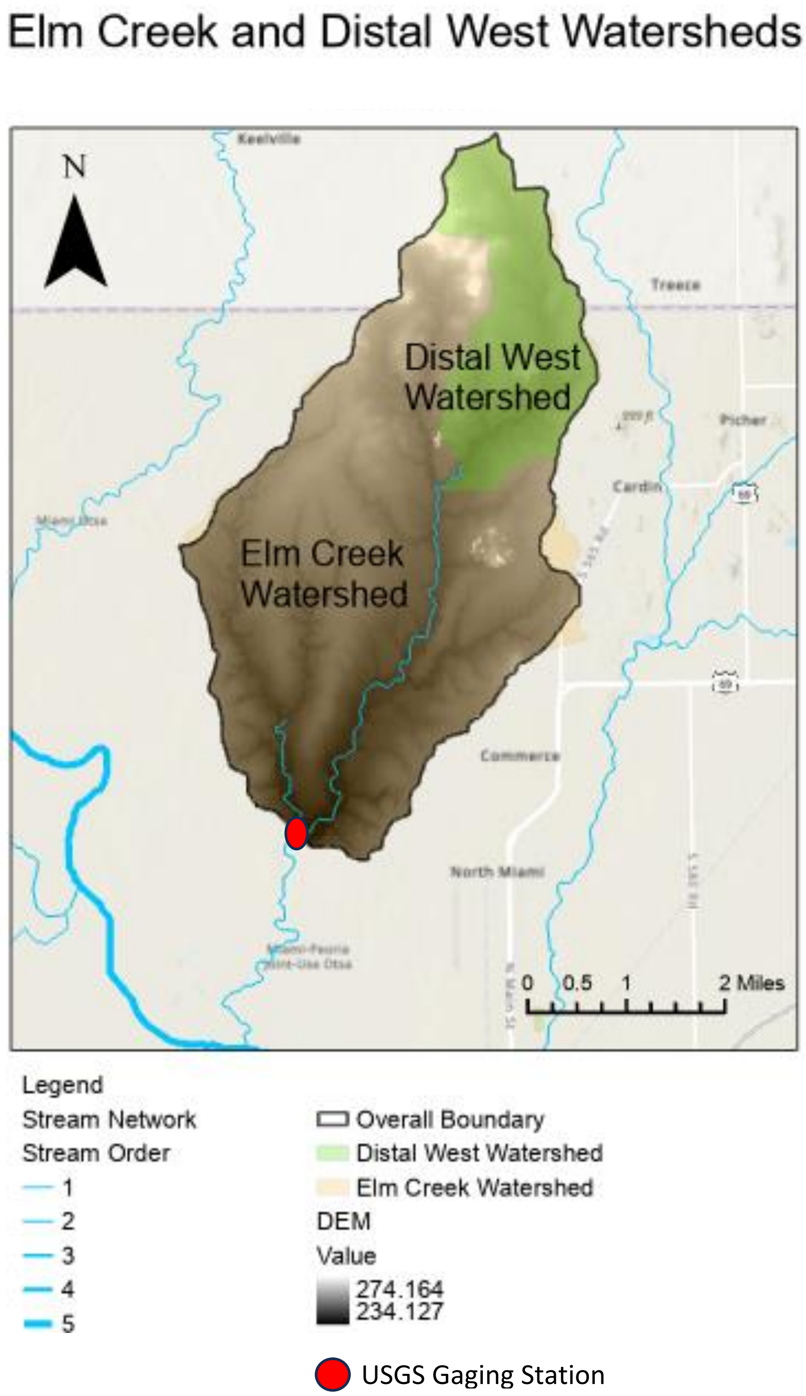


Figure 6: Elm Creek and Distal West Watershed Boundaries. The red dot is for the USGS gaging station 07185030.

Methods

Water and sediment sampling

Quarterly sampling was performed at the study site over 16 months (September 2022 - January 2024) to ensure that one full water year was captured [(1)]. Water and bed sediment samples were collected at both Bird Dog South and Distal West during these quarterly site visits and sent to the Meridian Laboratory in Wichita Falls, Kansas for analysis of the metal content. The first quarterly sampling involved installing the continuous monitoring equipment, as discussed below. The following sampling protocol was used:

1. Water samples were collected at both sample sites and stored in lab-supplied, preserved (nitric acid) containers. This was achieved by inserting the bottle into the middle of the creek in the upstream direction with a slight tilt to allow the flow of water to slowly fill the bottle (EPA, 2016). The samples were used to detect heavy metals (Cd, Fe, Mn, Pb, Zn, and As).
2. Sediment samples were obtained via shovel from the middle of the creek, drained of excess water, and placed into a plastic Zip lock bag using a smaller plastic shovel to take a portion of the sediment from the larger shovel to prevent cross-contamination (after collection the Zip lock bag is placed into another Zip lock bag to prevent spillage) (Division, 2020). The samples were used to detect heavy metals (Cd, Fe, Mn, Pb, Zn, and As).

1. Water Year: 12-month period, for any given year through September 30, of the following year. https://water.usgs.gov/nwc/explain_data.html

3. The samples were labeled with the date, time, sample location, and sample number, then listed on chain-of-custody documents and transported in a cooler by the Quapaw Tribe to Meridian Analytical Labs, LLC for metals analysis using EPA method 6010 in accordance with SW846 (Solid Waste: Physical/Chemical Methods Compendium). Method 3005A was used to prepare the water samples and method 3050B was used for the sediment samples. Method 3005A heats the sample with dilute HCl and HNO_3 before metal determination, and method 3050B vigorously digests the sample in HNO_3 and H_2O_2 followed by dilution with either HNO_3 or HCl (EPA, 2018b). Method 6010 uses inductively coupled plasma-optical emission spectrometry (ICP-OES) to convert analytes to an excited state of gaseous atoms or ions. When the atoms or ions return to their ground state, they emit energy in the form of wavelengths that correspond to a specific element and the intensity of that energy determines the concentration of that element within an analyzed sample (EPA, 2018a). The laboratory followed quality control (QC) and quality assurance (QA) guidelines instituted by the EPA in SW-846, including multiple blind quality control samples to ensure accurate results. Meridian Labs also is certified under the National Environmental Laboratory Accreditation Program through the state of Kansas, and are accredited in Oklahoma (Meridian Analytical Labs, 2023).

Hydrology and sediment transport

Continuous sampling at both sites (see Figure 3) was done using installed environmental probes as described below. The probes were programmed to collect data on turbidity and water depth at 5- and 15-minute intervals over the study year, respectively. Turbidity was collected as a proxy for suspended sediment concentration at Distal West (see discussion below). Water depth was collected in order to compute expected discharge at Distal West. A tipping bucket rain gage was also installed at the study site. Inspection of the installed equipment also occurred during quarterly visits along with the data being downloaded.

The continuous monitoring equipment installed at the two sample sites were an RG 600 tipping bucket rain gauge (installed only at Bird Dog South), two multi-parameter YSI EX01 Sondes, and Keller DCX-22 water level loggers (see Figure 7). The rain gauge was installed on 09/23/2022 and programmed to measure 0.01 inches of rainfall summed at five-minute intervals. The rain gauge was installed on top of a fence post devoid of any nearby vegetative cover and has an accuracy of +/- 1% at one inch per hour. Additionally, rainfall data was gathered from the weather monitoring station (MIAMI65) in Miami, OK, which is approximately 9.5 miles from the study site, but only about three miles outside of the watershed's boundary, making it potentially useful as a regional check on rainfall intensities. Monthly data and daily rainfall totals were downloaded from mesonet.org.

YSI EX01 multiparameter Sondes and Keller DCX-22 water level data loggers were installed at the sample sites (see figure 7) to measure turbidity and water depth, respectively. The Sondes were calibrated according to the manufacturer's guidelines for turbidity (Finegan, 2018). The water data loggers measured water depth in inches and were calibrated by measuring atmospheric pressure in a depth of 0 inches of water to 12 inches of water in the laboratory. Because the Keller DCX-22 water level loggers proved unreliable, and because flow depth was *the* critical hydrologic parameter needed to compute discharge, a second water level system was installed at Distal West. This comprised a YSI WL16 data logger and submersible pressure transducer combination.

Channel cross sections and channel slope at each culvert were surveyed using a TruPoint 300 Total Station. These survey data were then used in the calculation of channel velocity (and, ultimately, stream discharge) via the Manning equation, discussed below.

We were not able to sample suspended sediment directly due to the seven-hour travel time to the study site. Rather, in-stream turbidity, which is an optical indicator of water clarity, was measured and then calibrated against twelve suspended sediment samples retrieved during two site visits, the first on 8/3/2023 and the second on 11/4/2023. During these two site visits, turbidity readings were taken while the author stirred up sediment within the channel across a range of turbidity values while concurrently taking depth-integrated water samples by hand. The suspended sediment samples were then returned to the lab and vacuum filtered through Whatman 0.45-micron filter paper, as described in Richard & Feist (2010), Goh et al. (2016), and Sandstrom (1995). A suspended sediment-turbidity relationship was then established, and the resulting equation was used to predict suspended sediment concentrations (see Figure 14). We note that the coefficient of determination in the turbidity-suspended sediment relationship was notably higher than typically reported in the literature. This can be attributed primarily to the artificial method employed for collecting the suspended sediment samples. The higher coefficient of determination can also be attributed to both the relatively small sample size and the retrieval of samples predominantly from the lower end of the flow regime.

Figure 7: Continuous Monitoring Equipment. YSI EX01 Sonde (Left), Keller DCX-22 water level Data Logger (Middle), and RG 600 Tipping Bucket Rain Gauge (Right)

Data Processing

Heavy metals:

Processing the Meridian Analytical Labs' data on the sediment and water samples involved aggregating the metal types (Cd, Pb, Zn, Fe, Mn and As) detected separately onto scatterplot graphs to visualize concentrations upstream and downstream to determine if those metal concentration values, in mg/kg, were above the EPA thresholds (See Tables 1 and 2). The scatterplots were then used to evaluate the degree to which the metal concentrations changed over time.

Table 1: EPA target concentrations for heavy metals.

EPA remediation plan target concentrations for heavy metals						
Heavy Metal	Cadmium	Iron	Manganese	Lead	Zinc	Arsenic
Target Concentration (mg/kg) (Sediment)	10	N/A	N/A	500	5500	5
Target Concentration (mg/L) (Water)	0.0061	0.3	0.05	0.303	0.287	0.34

Table 2: Safe Drinking Water Act contaminant levels for heavy metals.

Safe Drinking Water Act maximum and secondary contaminant levels for heavy metals			
Heavy Metal	Arsenic	Iron	Manganese
Maximum Contaminant Level (mg/L)	0.01	N/A	N/A
Secondary Contaminant Level (mg/L)	N/A	0.3	0.05

Because the sampling protocols were quarterly (i.e., four measurements per metal per year), small sample sizes meant we were limited in terms of the robustness of statistical testing. In lieu of this we used notched box plots to visually demonstrate potential statistical differences between the samples (See McGill et al., 1978).

Hydrologic/sedimentologic data

The continuous data from the installed probes, along with the on-site rainfall data and that from mesonet.org and the local weather monitoring station data in Miami, were downloaded into excel spreadsheets for analysis.

For each storm event (defined here as any rainfall total ≥0.5 inches) we calculated 15-min, 30-min and 60-min rainfall intensities to quantify the intensity-duration-frequency characteristics of storms during the water year (USDC & NOAA, 2019).

The two key variables at each sampling site are discharge and sediment flux. Because stream velocity could not be continuously monitored, we used Manning's Roughness to determine the theoretical stream velocities at a range of culvert and channel depths. The Manning's Roughness coefficient was calculated for both Bird Dog South and Distal West using the protocol outlined in Bengtson (2019) and Service (2007). At Bird Dog South, the following values were computed: n_1 (Base Roughness Coefficient) = 0.02; n_2 (Irregularity Modifier) = 0, n_3 (Cross Section Modifier) = 0, n_4 (Obstruction Modifier) = 0, n_5 (Vegetation Modifier) = 0.005, and n_6

(Meandering Modifier) = 0. Adding all the n values together produced a Manning's Roughness Coefficient of 0.025 for the channel at Bird Dog South. At Distal West, the values were: $n_1 = 0.02$; $n_2 = 0$; $n_3 = 0$, $n_4 = 0.01$; $n_5 = 0.005$; $n_6 = 0$. This totaled to 0.035 for Distal West's Manning's Roughness Coefficient.

This allowed us to construct a depth-velocity relationship which was then used to predict discharge. The equations are as follows:

$$A = D * W \tag{1}$$

Where D = depth (m), W = width (m), and A = cross-sectional area (m^2)

$$R = A/P \tag{2}$$

Where P = wetted perimeter (m) and R = hydraulic radius (m)

$$V = (R^{\frac{2}{3}} * S^{\frac{1}{2}})/n \tag{3}$$

Where S = slope (0.00026), n = manning's coefficient (0.035) and V = velocity (m/s)

$$Q = V * D * W \tag{4}$$

Where Q = discharge (ft^3/s)

$$Q * SS = SF \tag{5}$$

Where SS = suspended sediment concentration (mg/L) and SF = sediment flux (g/s)

The hydrologic analysis included generating hydrographs and sedigraphs for the flow record, computing storm-based runoff and sediment flux, and the calculation of basin response, including lag times, basin flashiness, and runoff volumes (see Dingman, 2015). Lag time means 50% of the total rainfall for a storm event to the peak of that storm event. Basin flashiness means how quickly flow within a river or stream increases or decreases during a storm event (Center, 2023). Runoff volumes mean the volume of water flowing over the land during a storm event.

Results

Heavy Metal Contamination

Figures 8 A-F and 9 A-F show the time series plots for each of the six heavy metals in water and sediment across the 18-month study period from 09/23/2022 to 02/03/2024. Note that the data collected by Barret (2022) both upstream and downstream of the remediation site is highlighted in blue with the data collected in this study extending the temporal record to 02/03/2024.

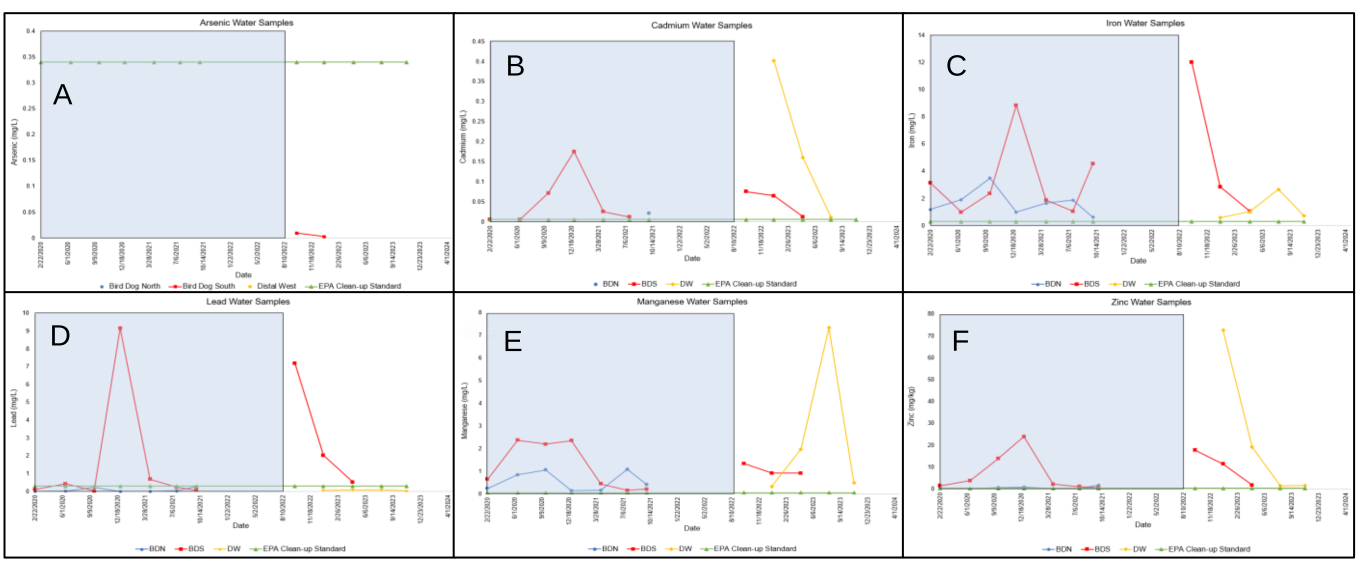


Figure 8: Water Metal Analysis for Arsenic (A), Cadmium (B), Iron (C), Lead (D), Manganese (E) and Zinc (F). Metal concentrations, measured in mg/L, are plotted for three sites (Bird Dog North (BDN, Blue), Bird Dog South (BDS, Red), and Distal West (DW, Yellow)) along with the EPA Clean-up Standard (Green). The light blue box indicates Barrett's (2022) collected sample data.

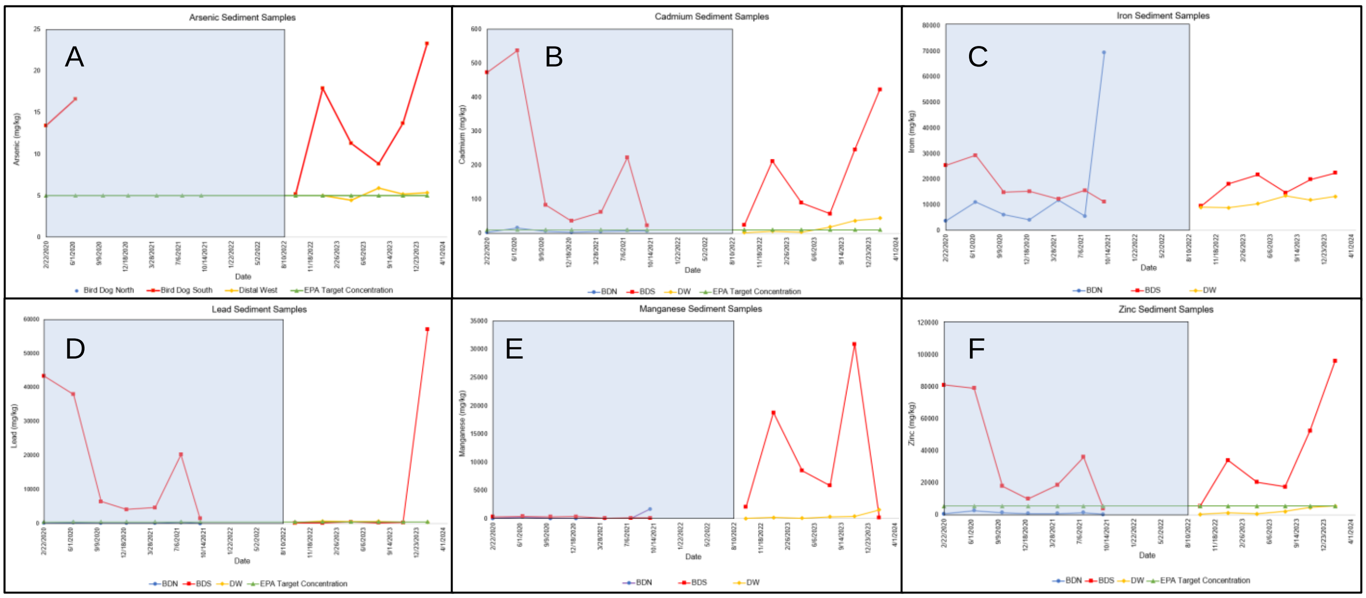


Figure 9: Sediment Metal Analysis for: Arsenic (A), Cadmium (B), Iron (C), Lead (D), Manganese (E), and Zinc (F). Metal concentrations, measured in mg/kg, are plotted for three sites (Bird Dog North (BDN, Blue), Bird Dog South (BDS, Red), and Distal West (DW, Yellow)) along with the EPA Clean-up Standard (Green). The light blue box indicates Barrett's (2022) collected sample data.

The average concentrations per site visit for the metals found within the water samples are given in Table 3 along with identifying whether concentrations exceed the EPA limit. At Bird Dog South, three quarterly samples exceeded the EPA target concentration for the following metals: Cd, Fe, Pb, Mn, and Zn. No quarterly samples exceeded the EPA target concentration for As at Bird Dog South. For Distal West, Fe, Mn, and Zn had four sample exceedances, Cd had three sample exceedances and Pb had two samples exceed the EPA target concentration. Like Bird Dog South, As did not have any quarterly samples exceeding the EPA target concentration at Distal West.

Overall, the extent to which EPA limits were exceeded at Bird Dog South for the water samples are summarized as follows: 8.4 times the EPA limit for Cd, 17.7 times for Fe, 10.7 times for Pb, 21.1 times for Mn, and 35.8 times for Zn. For Distal West the EPA limit exceedances are summarized as follows: 31.3 times the EPA limit for Cd, 4.1 times for Fe, 6.2 times for Pb, 14.3 times for Mn, and 82.5 times for Zn.

Table 3: Water Analysis Results. The numbers provided are the average concentrations for a particular site visit for each of the six metals.

Water Results								
Sample ID	Date	As (mg/L)	Cd (mg/L)	Fe (mg/L)	Pb (mg/L)	Mn (mg/L)	Zn (mg/L)
EPA Target Concentration		0.34	0.0061	0.3	0.303	0.05	0.287
Bird Dog South	9/23/2022	0.0095	**0.0754**	**12**	**7.18**	**1.34**	**17.7**
Distal West	9/23/2022	XX	XX	XX	XX	XX	XX
Bird Dog South	1/4/2023	0.0026	**0.065**	**2.86**	**2.02**	**0.916**	**11.4**
Distal West	1/4/2023	ND	**0.402**	**0.585**	**0.0627**	**0.325**	**72.6**
Bird Dog South	4/21/2023	ND	**0.0127**	**1.06**	**0.524**	**0.914**	**1.71**
Distal West	4/21/2023	ND	**0.16**	**1.02**	**0.0898**	**1.97**	**19.1**
Bird Dog South	8/3/2023	XX	XX	XX	XX	XX	XX
Distal West	8/3/2023	ND	**0.0111**	**2.65**	0.0868	**7.34**	**1.47**
Bird Dog South	11/3/2023	XX	XX	XX	XX	XX	XX
Distal West	11/3/2023	ND	ND	**0.704**	0.0263	**0.482**	**1.56**
Bird Dog South	2/3/2024	XX	XX	XX	XX	XX	XX
Distal West	2/3/2024	XX	XX	XX	XX	XX	XX
Bolded Values exceed EPA Target Concentration. ND = Non Detectible, XX = No Water Present							

The average concentration per site visit for the metals found within the sediment samples is given in Table 4 along with identifying if concentrations exceeded the EPA limit. At Bird Dog South all six quarterly samples exceeded the EPA target concentration for As and Cd. Zn had five quarterly samples exceed, while Pb had one quarterly sample exceed. For Distal West, As had four quarterly samples exceed, Pb had three quarterly samples exceed, and Cd had two exceedances for its EPA target concentration.

Bird Dog South's EPA exceedances for the sediment samples are summarized as follows: 2.7 times the EPA limit for As, 17.5 times for Cd, and 6.8 times for Zn. Distal West's exceedances are summarized as follows: 1.0 times the EPA limit for As, 1.9 times for Cd and 1.0 times for Pb.

Table 4: Sediment Analysis Results. The numbers provided are the average concentrations for a particular site visit for each of the six metals.

Sediment Results							
Sample ID	Date	As (mg/kg)	Cd (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Mn (mg/kg)	Zn (mg/kg)
EPA Target Concentration		5	10	N/A	500	N/A	5500
Bird Dog South	9/23/2022	**5.2**	**24.4**	9480	135	2070	5310
Distal West	9/23/2022	ND	1.6	9000	259	47.6	263
Bird Dog South	1/4/2023	**17.9**	**212**	18100	151	18800	**34000**
Distal West	1/4/2023	**5**	6.3	8770	**683**	235	1180
Bird Dog South	4/21/2023	**11.3**	**89.7**	21700	429	8500	**20400**
Distal West	4/21/2023	4.47	3.47	10400	**559**	75.7	597
Bird Dog South	8/3/2023	**8.81**	**57.7**	14700	218	5870	**17400**
Distal West	8/3/2023	**5.89**	**18.1**	13500	**653**	352	2130
Bird Dog South	11/3/2023	**13.7**	**246**	19900	280	30900	**52400**
Distal West	11/3/2023	**5.17**	**37.1**	11800	444	412	4490
Bird Dog South	2/3/2024	**23.3**	**423**	22400	**57000**	230	**95900**
Distal West	2/3/2024	**5.36**	**44.5**	13200	420	1590	5410
Bolded Values exceed EPA Target Concentration. ND = Non Detectible							

To test for differences between the metal concentrations in both the water and the sediment samples across the three sites (i.e., Bird Dog North, Bird Dog South, and Distal West), notched box plots were constructed using the collected data from this study as well as that of Barrett (2022) (see Figures 10 A-E and 11 A-F). Notched box plots feature a "notch" that narrows around the median. These notches serve as a rough indicator of the significance of the difference between medians. When the notches of two boxes do not overlap, it suggests a statistically significant difference between the medians.

For the water samples, the Pb data suggested a difference between Bird Dog South and Distal West. Zinc concentrations were also different between Bird Dog North compared to the other two field sites. For Cd, Fe and Mn, all notches overlapped suggesting no difference between the three field sites.

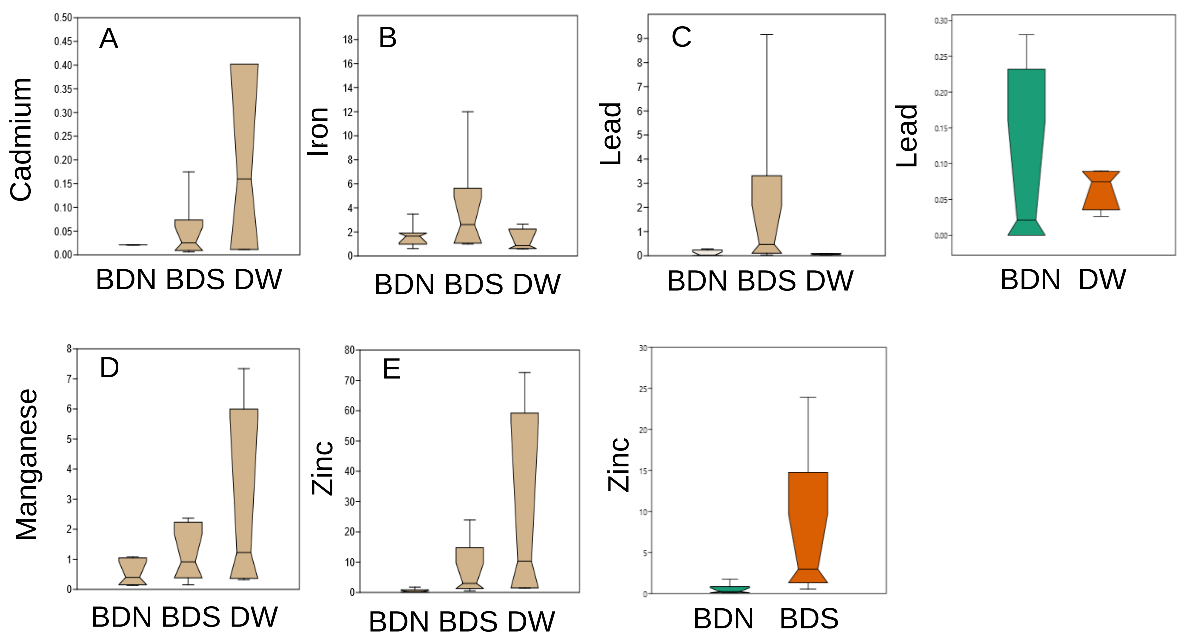


Figure 10: Water Sample Notched Box Plots: Cadmium (A), Iron (B), Lead (C), Manganese (D), and Zinc (E). Heavy Metals, measured in mg/L, across three sample sites (Bird Dog North (BDN), Bird Dog South (BDS), and Distal West (DW)) are plotted via the Box plots and suggests a difference if the notches on the box plots do not overlap. Additional box plots for Pb and Zn are plotted to show if

two of the field sites overlap that are not easily recognizable in the three-field site box plot due to large value ranges.

In terms of sediment, we found that As was elevated at Bird Dog South relative to Distal West. Cd, Fe and Zn also indicated differences between Bird Dog South compared to Bird Dog North and Distal West. The Pb samples indicated all three field sites were different. Mn showed a difference only between Bird Dog North and Bird Dog South.

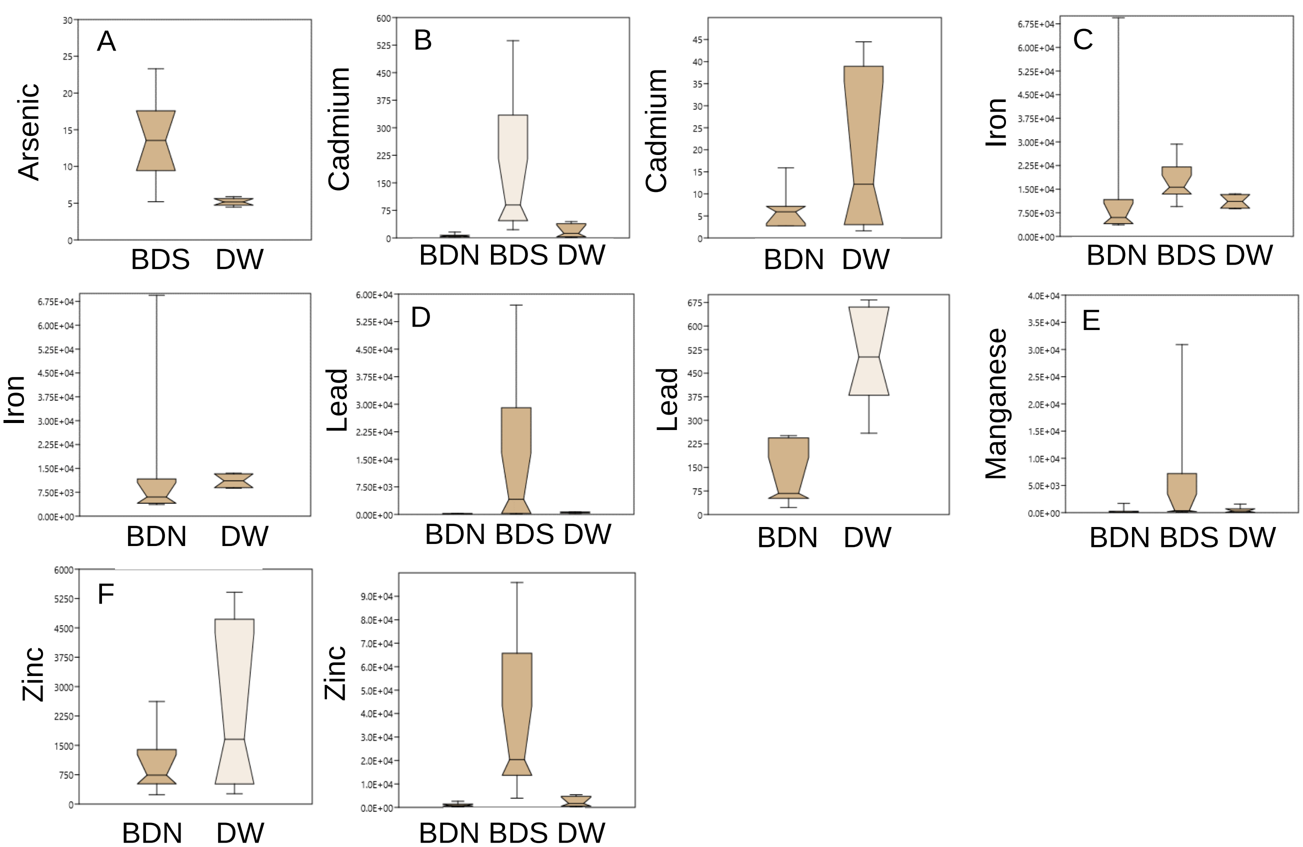


Figure 11: Sediment Sample Notched Box Plots: Arsenic (A), Cadmium (B), Iron (C), Lead (D), Manganese (E), and Zinc (F). Heavy Metals, measured in mg/kg, across three sample sites (Bird Dog North (BDN), Bird Dog South (BDS), and Distal West (DW)) are plotted via the Box plots and deemed different if the notches on the Box plots do not overlap. Additional box plots for Cd, Fe, Pb, and Zn

are plotted to show if two of the field sites overlap that are not easily recognizable in the three-field site box plot due to large value ranges.

Basin hydrology and sediment response

No flow was measured at Bird Dog South during the study period. Channel sediments were being continually excavated both upstream and downstream of the culvert as part of the remediation process, resulting in significant changes to the channel geometry. In addition, two large retention ponds were dug either side of the culvert (see Figure 12 A-B). Because there was no detectible flow at Bird Dog South, sediment flux could not be calculated for this section immediately downstream of the chat pile. Thus, Distal West became the primary focus for the hydrology and sediment response, in terms of Tar Creek, for this study.

The resolution of discharge was achieved via equations 1-5, as discussed in the methods section, using the calculated Manning's Roughness coefficient. Although the equations predicted volumetric flow as water level increased, observations in the field on 8/3/2023 showed minimally flowing water in the channel with a measured depth of 37.5 cm on that date. This is because the channel here is characterized by a deep pool and very low energy slopes as seen in Figure 13. Because the equations predicted a discharge of 18.8 cfs at a flow depth of 37.5 cm, we felt a reasonable approach would be to use the predicted 18.8 cfs as a starting point for flow (i.e., Q = 0). All discharge values were therefore reduced by 18.8 cfs. An additional reduction of 6.2 cfs was made to better align our values with observed measurements to reduce the overestimation of discharge that appeared within the data at the original 18.8 cfs reduction (see discussion).

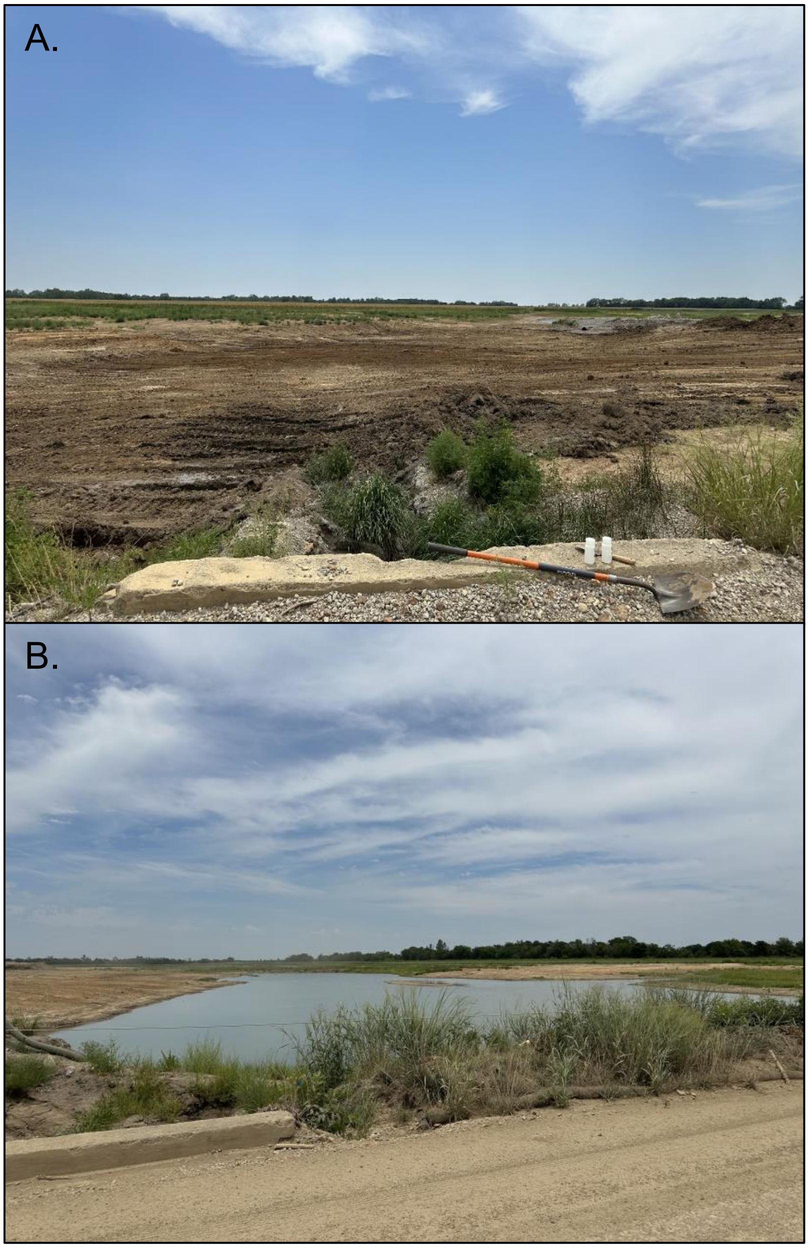


Figure 12: A. Bird Dog South with lack of downstream flow due to ongoing remediation, B. Retention pond upstream of culvert (08/03/2023).

Figure 13: Deep Pool, low energy slope, at Distal West site.

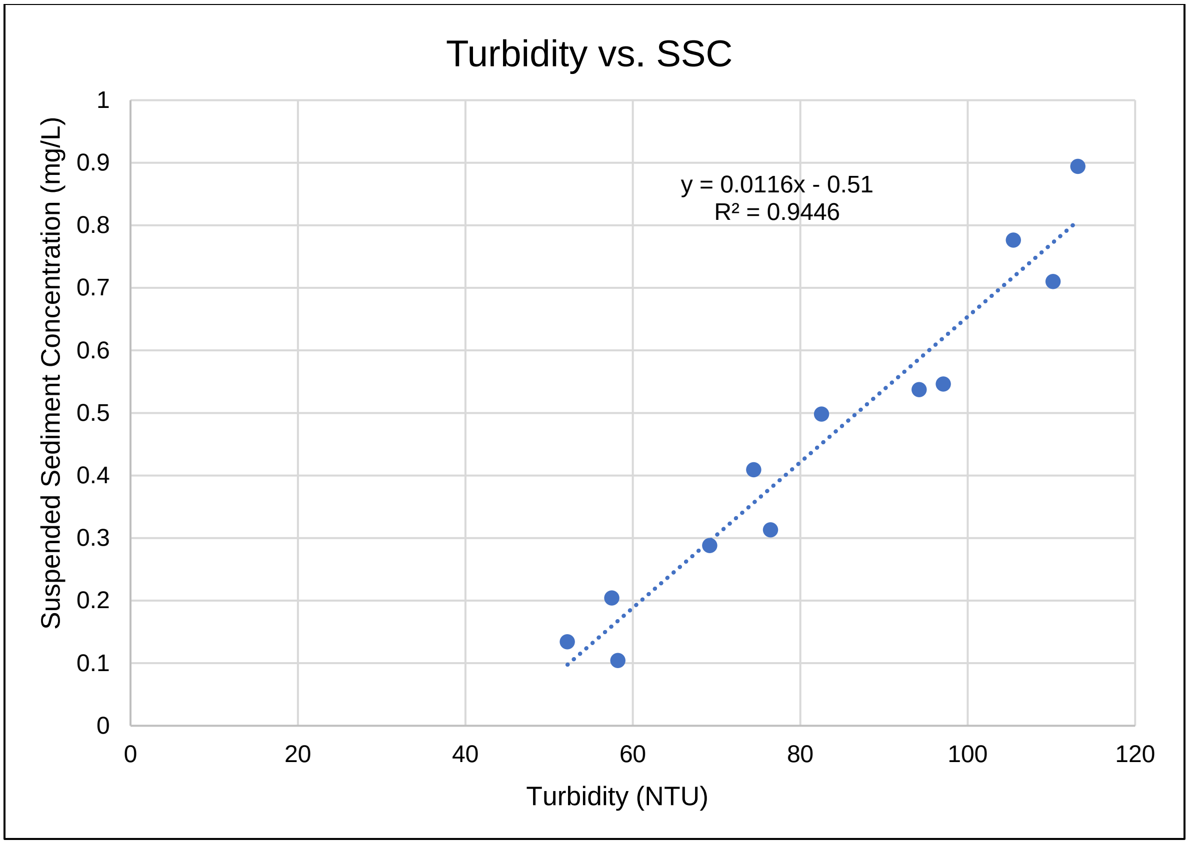


Figure 14: Relationship between Turbidity and Suspended Sediment Concentrations using twelve samples.

The suspended sediment concentration (SSC)-turbidity relationship determined from field sampling and laboratory filtration is shown in Figure 14. SSC calculated using this relationship appeared as negative values that were under a turbidity of 44 NTUs. Thus, the values were corrected to appear as zero for all values under 44 NTUs (Smolders et al., 2003). Using the calculated discharge and the corrected suspended sediment concentrations, instantaneous sediment flux was calculated, via equation 5, for Distal West (see Figure 15).

Ten storm events (rainfall ≥ 0.5 Inches) were identified during the study period. Rainfall data corresponding to the days in which the storms occurred, as well as sediment flux data, were plotted alongside discharge (see Figure 15) to clarify the relationship between the three variables and articulate basin storm dynamics. Daily onsite rainfall measurements, the CoCoRaHS daily rainfall measurements, along with the 15- minute, 30-minute, and 1-hour intensities for the field basin are given in Table 5 [(2)]. CoCoRaHS data was added due to equipment failure for the onsite rain gauge, so for 11/3/2023 onwards, this public data was used as a surrogate for the storm calculations of storms #7-10.The hydrograph for Distal West was plotted alongside the record at the USGS gaging station at Elm Creek to both compare the hydrologic response and compute the relative contribution from Distal West to the downstream watersheds such as Elm Creek (Figure 16). A monthly average discharge graph was also plotted to compare Distal West and Elm Creek to better visualize the relationship between the two sub-basins (Figure 16).

2. CoCoRaHS is an acronym for the Community Collaborative Rain, Hail and Snow Network. CoCoRaHS is a unique, non-profit, community-based network of volunteers of all ages and backgrounds working together to measure and map precipitation (rain, hail, and snow). By using low-cost measurement tools, stressing training and education, and utilizing an interactive Website, our aim is to provide the highest quality data for natural resource, education, and research applications. We are now in all fifty states.

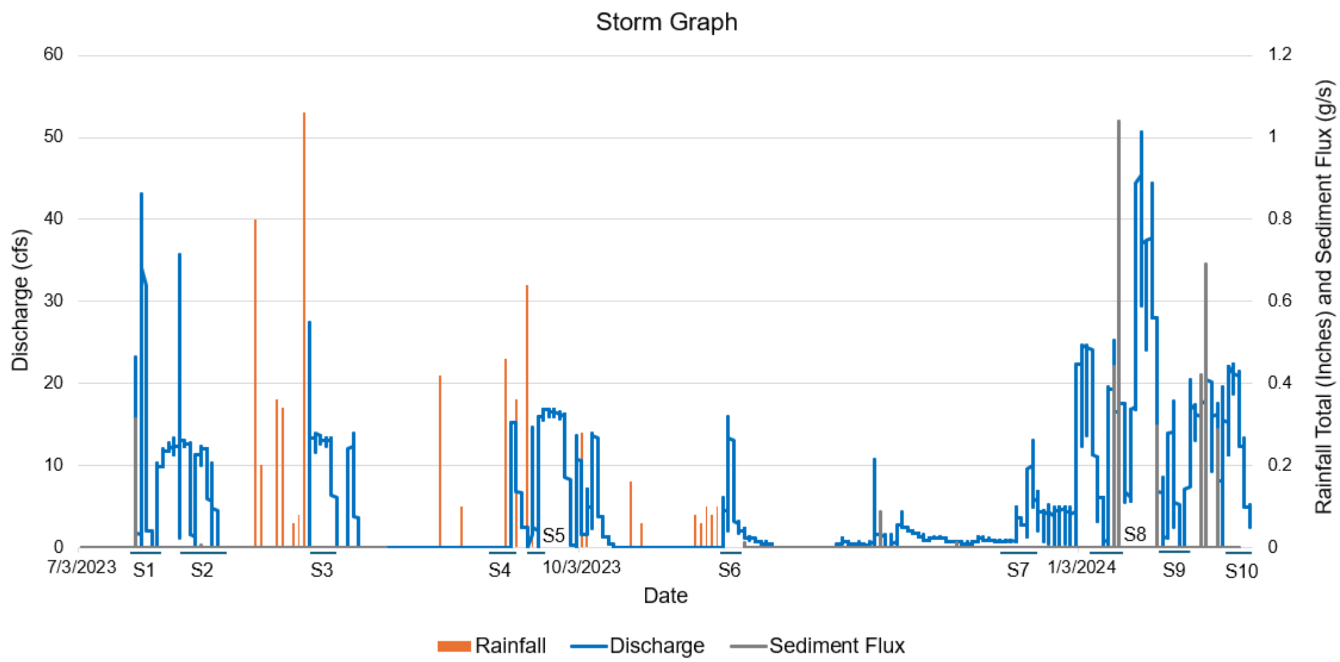


Figure 15: Discharge displayed over an eight-month timeframe with an additional axis for corresponding sediment flux data measured in g/s and rainfall data measured in inches (right axis).

Table 5: Rainfall Daily Totals, CoCoRaHS Rainfall Daily Totals, and Rainfall Intensities (15 min, 30 min, 1 hr.) from Storm Events (≥0.5 Inches).

Rainfall Date	On-site Rainfall Total (Inches)	CoCoRaHS Rainfal Total (Inches)	15 min max	30 min max	1 hr max	Rainfall 15-minute intensity	Rainfall 30-minute intensity	Rainfall 1-hour intensity
10/24/2022	2.8	XX	0.52	0.84	1.28	2.08	1.68	1.28
10/25/2022	1.34	XX	0.18	0.32	0.5	0.72	0.64	0.5
11/11/2022	0.92	XX	0.42	0.5	0.56	1.68	1	0.56
11/24/2022	0.62	XX	0.08	0.14	0.18	0.32	0.28	0.18
11/26/2022	0.9	XX	0.22	0.28	0.3	0.88	0.56	0.3
12/8/2022	0.58	XX	0.04	0.08	0.14	0.16	0.16	0.14
12/10/2022	1.24	XX	0.16	0.28	0.48	0.64	0.56	0.48
12/13/2022	2.08	XX	0.22	0.28	0.48	0.88	0.56	0.48
1/18/2022	1.18	XX	0.14	0.22	0.4	0.56	0.44	0.4
2/7/2023	1.74	XX	0.3	0.48	0.72	1.2	0.96	0.72
2/8/2023	1.16	XX	0.18	0.24	0.42	0.72	0.48	0.42
2/14/2023	1.04	XX	0.3	0.36	0.5	1.2	0.72	0.5
2/22/2023	0.86	XX	0.12	0.2	0.34	0.48	0.4	0.34
3/2/2023	0.56	XX	0.2	0.28	0.28	0.8	0.56	0.28
3/3/2023	0.52	XX	0.06	0.1	0.18	0.24	0.2	0.18
3/16/2023	0.76	XX	0.2	0.32	0.4	0.8	0.64	0.4
3/23/2023	1.32	XX	0.14	0.24	0.46	0.56	0.48	0.46
4/5/2023	0.84		0.76	0.84	0.84	3.04	1.68	0.84
8/5/2023	1.94	0.81	0.9	1	1.12	3.6	2	1.12
8/9/2023	0.82	0.56	0.36	0.38	0.38	1.44	0.76	0.38
8/14/2023	2.76	1.49	1.44	2	2.34	5.76	4	2.34
9/8/2023	0.98	0.86	0.42	0.56	0.7	1.68	1.12	0.7
9/11/2023	0.52		0.12	0.18	0.32	0.48	0.36	0.32
9/19/2023	1.28		0.46	0.74	0.86	1.84	1.48	0.86
9/20/2023	2.1	2.69	0.38	0.58	0.94	1.52	1.16	0.94
9/22/2023	1.3		0.4	0.6	0.64	1.6	1.2	0.64
9/24/2023	0.64	0.82	0.64	0.64	0.64	2.56	1.28	0.64
10/4/2023	1.48	0.64	0.34	0.5	0.74	1.36	1	0.74
10/13/2023	0.82		0.22	0.26	0.5	0.88	0.52	0.5
10/29/2023	1.82	0.73	0.12	0.16	0.26	0.48	0.32	0.26
11/20/2023		0.51	XX signifies CoCoRaHS data was not used for those dates. Blank spaces are for zero rainfall recorded by CoCoRaHS.					
12/1/2023		0.57						
12/22/2023		1.1						
1/23/2024		0.72						
2/4/2024		0.98						

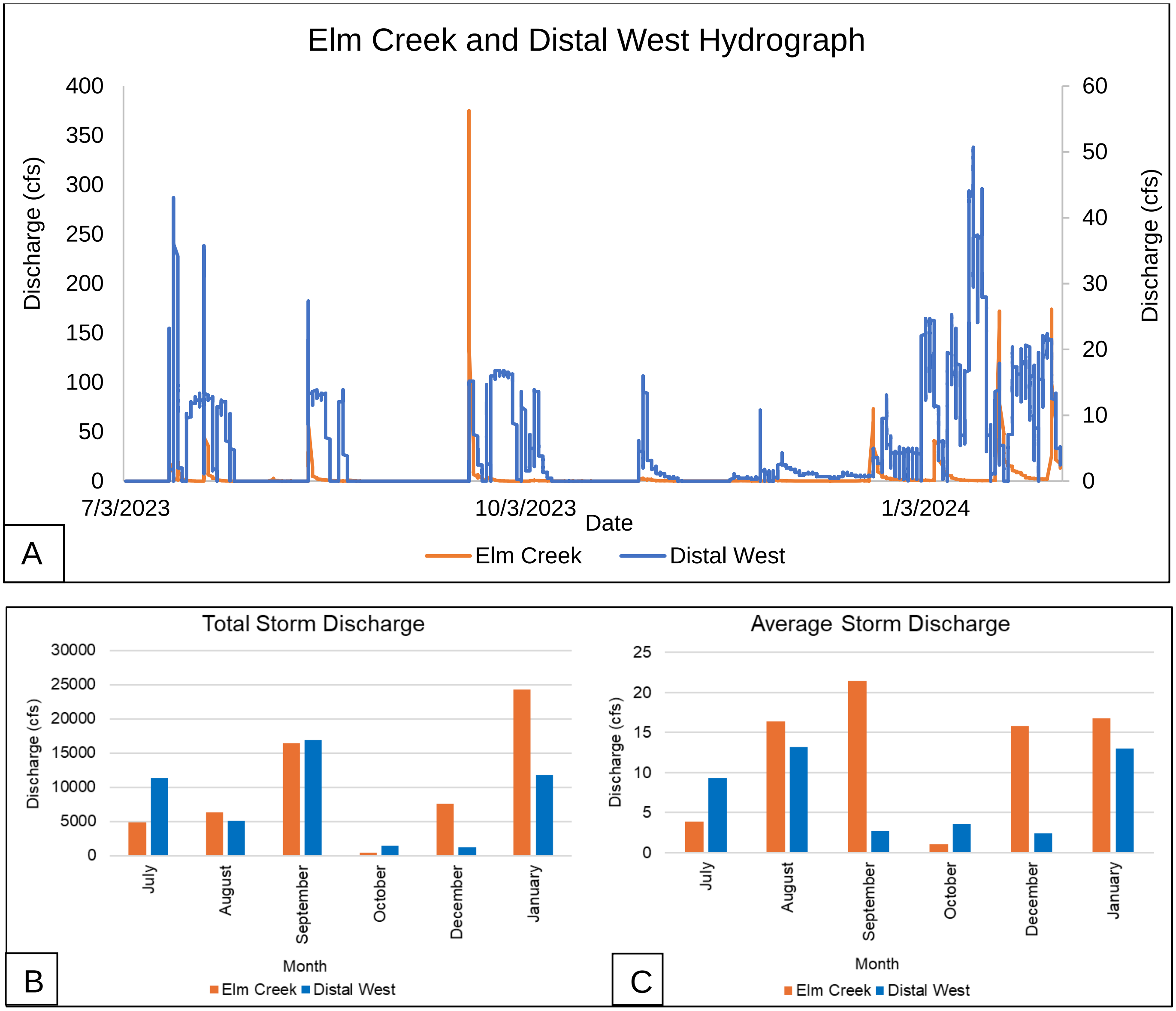


Figure 16: Elm Creek and Distal West Hydrograph Comparison. Elm Creek uses the left axis and Distal West uses the right axis for their respective discharge values (A). Monthly total discharge comparison between Elm Creek and Distal West (B) and monthly average discharge comparison between Elm Creek and Distal West (C).

It should be noted that the rain gauge lost power leading to rainfall data from May to July and November (2023) to February (2024) to be lost. In addition, the turbidity probe failed to record data from 12/14/2022 to 7/3/2023 and 8/29/2023 to 11/2/2023. The ten storms, from 7/13/2023 to 2/3/2024, were analyzed to determine hydraulic variables, such as lag time and runoff coefficient, to better evaluate the basin response (see Table 6). Average discharge was computed as the mean flow across each storm event. The runoff volume was calculated using the equation $((x_1 + x_2)/2)*900$ with X_1 and X_2 representing discharge readings at 15-minute intervals (USDA, 2021). The runoff coefficient was calculated by dividing the runoff volume by the storm volume. The average rainfall total across all storms was 1.7 inches, the average storm discharge was 7.7 cfs, and the average peak storm discharge was 23.1 cfs. The average runoff coefficient for the Distal West basin was 15.4% and the average time to peak and lag time were 58 hours and 68 hours, respectively.

Table 6: Storm variables for basin analysis.

	Storm Dates	Storm Rainfall Total (Inches)	Average Discharge (cfs)	Peak Discharge (cfs)	Runoff Volume (cf)	Runoff Coefficient	Time to Peak (hr)	Lag Time (hr)
Storm #1	7/13-19/2023	XX	9.1	43.0	4,717,489.4		43	
Storm #2	7/21-26/2023	XX	10.6	35.8	5,466,144.6		12	
Storm #3	8/14-17/2023	XX	13.2	27.4	4,550,114.8		8	
Storm #4	9/17-20/2023	3.4	1.3	15.2	435,740.7	1.5%	95	37
Storm #5	9/22-25/2023	0.7	4.1	16.0	1,407,837.6	22.2%	95	62
Storm #6	10/28-11/1/2023	1.9	3.4	16.0	1,464,062.8	8.9%	70	51
Storm #7	12/20-24/2023	1.3	2.4	9.5	1,033,029.6	9.1%	120	96
Storm #8	1/5-10/2024	XX	11.1	25.3	5,716,746.2		104	
Storm #9	1/19-23/2024	1.0	7.1	20.4	3,039,094.9	35.4%	114	42
Storm #10	1/31/-2/3/2024	XX	14.3	22.4	4,135,134.0		18	
Cocorahs daily rainfall data was used in place of the on-site daily rain data for Storms 7-10. XX means no rainfall was recorded.								

Discussion

Water and Sediment

For the quarterly sampling, several key findings emerged across the multi-year study period, as shown in Figures 8 and 9. Overall, metal concentrations in both the water and sediment samples were very low at Bird Dog North – that is, upstream of the chat pile as indicated by Barrett's (2022) results. However, at Bird Dog South, immediately downstream of the chat pile, heavy metal concentrations for five of the six metal types in the sediment samples increased over time, while the water samples, like Barrett's (2022) data, all indicated decreasing metal concentrations over time. At Distal West, metal concentrations in the sediment were less than at Bird Dog South, although post chat pile removal (i.e., 9/23/2022 onwards), the concentrations began increasing. This suggests that contaminated sediment from the upper basin (i.e., proximal to the chat pile) is likely beginning to migrate downstream through the fluvial system toward the outlet at Distal West. The water samples at Distal West did show considerable variability over the sampling period, but we did note a decrease over time in the latter half of 2023.

For the water samples, metals at Bird Dog South showed a high degree of variability in the concentration values during both Barrett's (2022) sampling regime through to this study's sampling period. Nevertheless, metal concentrations at Bird Dog South were elevated in relation to Distal West and the EPA target concentrations. While metal concentrations in the water samples at Distal West were much lower than those at Bird Dog South, as noted above, the decrease at the downstream location suggests that the mobilized metals are now being effectively contained within the retention basins.

The sediment samples tell a somewhat different story in that (1) there is less variability in the data compared to the water samples, and (2) heavy metal concentrations appear to be increasing over time, specifically downstream at Distal West. Compared to Barrett's Bird Dog South samples, which suggested an overall decrease over time, the data in this study suggests increasing contamination post remediation for most of the tested metals. The chat pile upstream of Bird Dog South was removed in November 2021, but the base was not fully removed until August 2023.

For example, Fe samples ranged between 0 and 22400 mg/kg, while Cd ranged between 24.4 and 423 mg/kg. Bird Dog South is obviously a highly disturbed site (see Figure 12) with sediments being excavated and reworked during both the removal of the chat pile and the construction of the retention basins upstream and downstream of the culvert. There is simply no way to know the likely residence time of the sediments within the culvert at Bird Dog South or whether the material we sampled is redeposited particles from the chat pile itself or freshly exposed sediment that was never actually contaminated due to downcutting through the culvert (see Figure 17).

Figure 17: Downcutting of the stream channel upstream (A.) and downstream (B.) of the Bird Dog South Culvert.

Distal West presents similar findings as the water samples in that metal concentrations are lower than those at Bird Dog South. However, the sediment samples diverge from the water samples for both Bird Dog South and Distal West by showing a rapid increase over time for Bird Dog South and a relatively gentle yet steady increase in concentrations over time for Distal West. We speculate here that some contaminated sediment is likely being mobilized and transported downstream from Bird Dog South which, of course, is immediately downstream from the former chat pile. Although this downstream increase in metal concentrations is only beginning to emerge (and may likely continue to do so), the contamination levels already exceed the EPA cleanup targets for several contaminants. For example, in the last samples taken on 2/3/2024, As (5.36 mg/kg) and Cd (44.5 mg/kg) were above their respective EPA target concentrations of 5 mg/kg and 10 mg/kg, respectively.

The notched box plots for the water samples suggest no difference between the sites for four out of the six metals. The three-month time intervals likely caused a large spread in values for the field sites creating large notch regions that allow for more overlap, such as the Distal West notched box plots for Cd, Mn, and Zn. For the sediment sample notched box plots, similar spreading of value ranges to the water box plots were observed for most of the samples. Thus, no solid assertions could be made on if the remediation process has caused these sites to be different or not.

Basin Hydrology

Ten storm events were identified and analyzed to determine how much runoff of metal contaminants occurred to the downstream sections of the basin, and to better understand the hydrology and sedimentology of Elm Creek as a basin and tributary for Tar Creek which flows into the Neosho River (36.853233, -94.859073). Five storms – namely, storms #1-3, #8 and #10, did not have preceding rainfall data greater than zero, so the runoff coefficients and the lag times could not be calculated.

Average peak discharge across the studied storms was 23.1 cfs and the average discharge was 7.7 cfs. The runoff coefficients varied between 1.5% and 35.4% with an average across the ten storms of 15.4%. This means that, on average, less than 20% the rain falling across the Distal West drainage basin becomes storm runoff, indicating considerable storage of water within the system, either as groundwater recharge or rainfall being retained within the two excavated basins. In total, the Distal West watershed contributed approximately 28% of the runoff to downstream Elm Creek watershed (refer to Figure 6) This contribution is proportional to the basin area for Distal West in relation to the basin catchment.

The average time to peak (i.e., time of rise or basin response) for Elm Creek at Distal West was approximately 68 hours and the average lag time was approximately 58 hours. This confirms that Elm Creek is hydrologically sluggish with slow response times. Runoff generation is impeded within this basin and routed relatively slowly through the channel network to the outlet at Distal West. The range in peak lag times, plotted in Figure 18, suggests a basin with response characteristics dominated by subsurface storm flow. Indeed, lag times are about an order of magnitude longer than for 'average' saturation overland flow, and well above those for Hortonian (i.e., infiltration-excess) overland flow. While we did not take direct measurements of the channel these subsurface lag times suggest increased infiltration into the subsurface aquifer or the surface sediments.

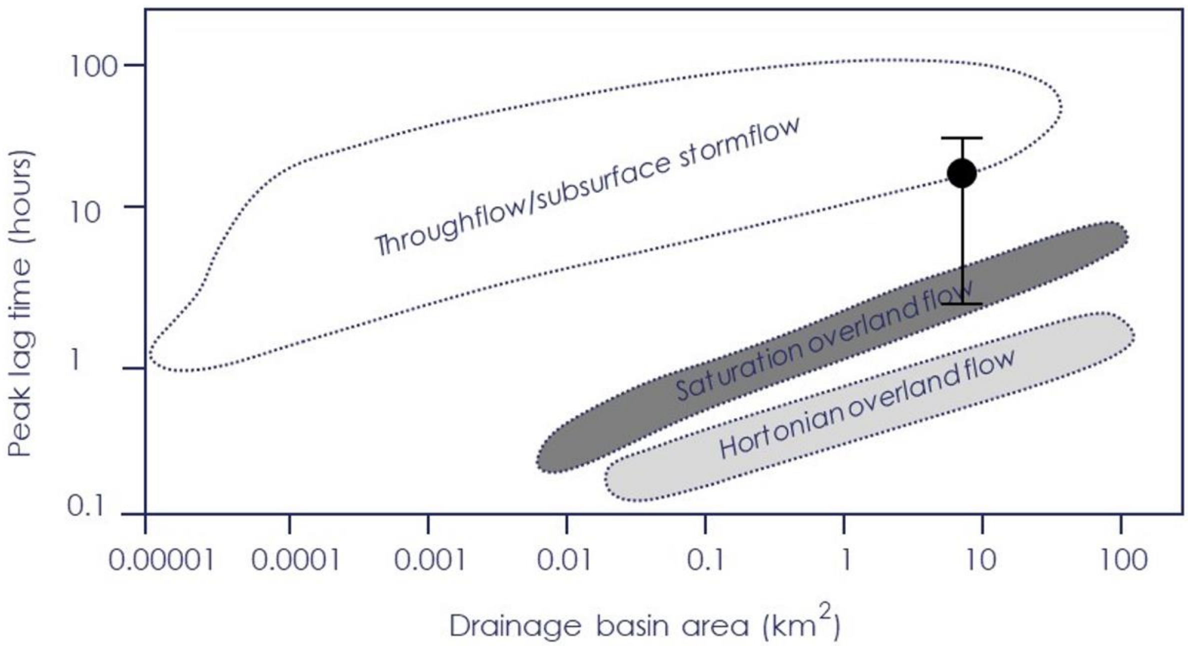


Figure 18: Ranges of peak lag times for hillslope processes (Slattery et al., 2006). The mean and range in peak lag time for this current study are also plotted on the diagram.

Storms #1 lower runoff coefficient could be attributed to the hottest summer in recorded history (2023) leading to the local environment drying out and the subsequent rainfall being used to recharge the soil and potentially groundwater instead of becoming runoff as the ground was unsaturated. Storm #9's runoff coefficient of 35.4% was the highest during the period of record and occurred during the largest collection of storm events during this research leading to greater rates of runoff.

Sediment transport within Elm Creek is highly episodic and variable in magnitude as seen in Figure 15 [3]. Generally, sediment concentrations were low, and because Elm Creek in this upper section of the basin (i.e., the Distal West basin) is sluggish, sediment flux was correspondingly low. There were certainly sporadic peaks, such as during storms #8 to #10 where sediment transport was most prominent. The highest instantaneous sediment flux occurred during storm #8 between 1/8 and 1/11 2024 at a rate of 1 g/s, equivalent to just 0.09 Mg/day. However, for much of the eight-month period, there was no measurable sediment transport for the months where data was available. This suggests that the flow within the channel at Distal West was not normally turbid, and that sediment mostly remains in storage rather than delivered downstream. Thus, outside of storm #8 with multiple peaks after the storm event, sediment potentially containing heavy metals did not travel downstream in large quantities. The lack of sediment transport could certainly be linked to the remediation project and be associated with the retention ponds which stored water and trapped sediment thereby impeding sediment.

3. Chat pile was removed upstream of Bird Dog South by November 2021, but the base of the pile was not removed until August 2023.

Conclusions and Future Research

This study set out with the following aims: (1) to assess the magnitude and extent of mining-related sediment contamination in Tar Creek within the TSMD, and (2) to quantify the transport and environmental fate of contaminated sediment from the headwaters of TCSS to downstream watersheds. While there were several setbacks during the study period in the form of equipment failure, we were able to address both aims in terms of discerning changes in downstream contamination and the overall efficacy of the remediation process.

The major findings of this study were as follows: Firstly, despite variability in metal concentrations for the water and sediment samples, due in part to the timespan between sample collection and the fact that sediment at Bird Dog South was heavily manipulated and impacted by excavation, the metals at Bird Dog South were higher in concentration than both Bird Dog North upstream and Distal West downstream within the sediment. This suggests that very little of the sediment being excavated proximal to the chat pile at Bird Dog South actually makes its way to the basin outlet at Distal West on an event time frame. Second, at Distal West, heavy metal concentrations appear to be slowly increasing with time post remediation, indicating that at least some of the finer-grained sediments are making their way through the sediment delivery system. Third, metals found within the water column were elevated in terms of their concentrations compared to the metals within the sediment samples, suggesting there was greater flushing of contaminants through the system than those being transported via sediment transport. Thus, there are higher concentrations of metals present at Distal West in the water column rather than the channel bed. Fourth, while no large storms (i.e. >0.3 inches per hour of rainfall) occurred during the study period, several events larger than 0.5" revealed long, delayed response and lag times indicating that Elm Creek is hydrologically sluggish and likely dominated by subsurface storm processes. Fifth, the Distal West watershed contributes approximately 28% of the discharge to Elm Creek, which is proportional to the basin's area in relation to the Elm Creek watershed. And sixth, low rates of instantaneous sediment flux suggests that sediment storage is again the dominant process within this fluvial system along with low conveyance of contaminated sediments (Ahrens & Henson, 2018). The storage of sediment behind beaver dams (Pavlowsky, pers. comm.) and retention ponds reduces contamination downstream at least in the short term. We do acknowledge that this study focused on one chat pile that was remediated in the Elm Creek channel upstream of Bird Dog South. Nevertheless, the storage of sediment noted here does not preclude the potential for significant contamination downstream to water systems like the Neosho River in the longer-term.

Future studies could include sampling the Elm Creek watershed on a more consistent and timelier basis to avoid long periods between sample collection and mitigate against potential equipment failure. We acknowledge this is an expensive process but would undoubtedly lead to a better understanding of the hydrology and sedimentology of these upstream watersheds in relation to larger nearby watersheds of eastern Oklahoma. Although we did not look at subsurface hydrology during this research, the hydrologic system might be losing groundwater to subsurface seepage through various mine shafts located within the Tar Creek watershed (Shepherd et al., 2022). Thus, additional research farther downstream could elucidate how much groundwater loss is occurring via seepage to better understand the hydrology of Tar Creek and its watershed. Furthermore, additional studies connecting remediation activities within the Tar Creek and Tri-State Mining District superfund sites to local health outcomes will better determine the efficacy of the remediation over time. Additional studies related to the local Roubidoux and Boone aquifers and larger surrounding aquifers, such as the Ogallala aquifer, would greatly benefit farmers and consumers alike with determining best practices for protecting aquifers, their recharge zones, and river systems connected to them from contamination originating from superfund sites.

Appendix

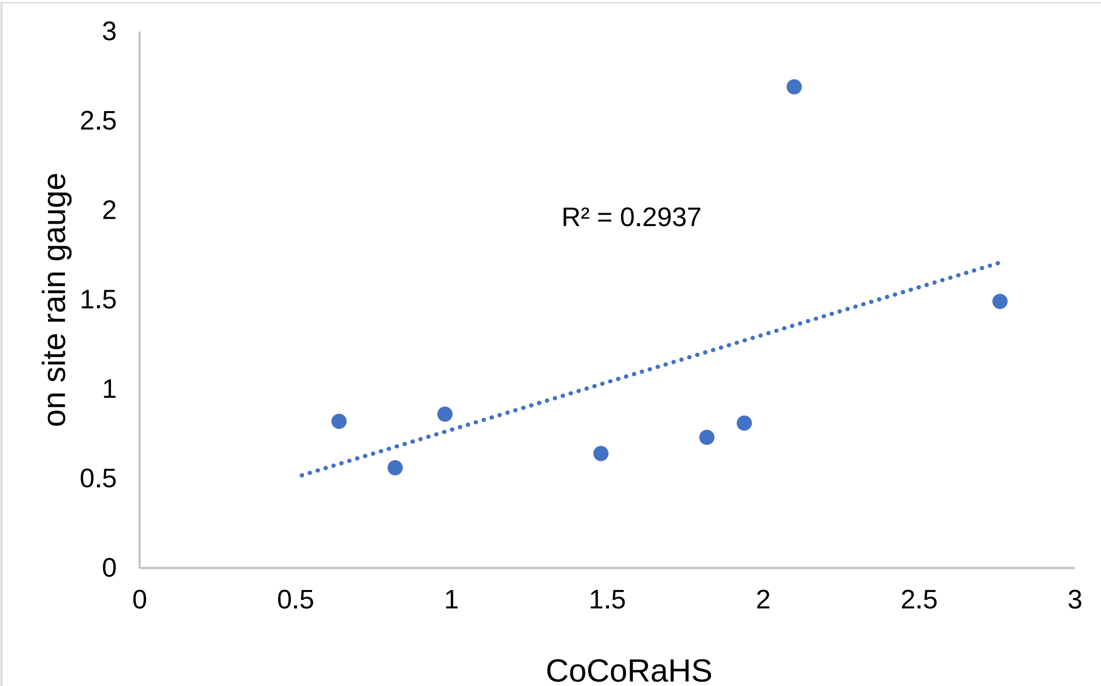


Figure 19: CoCoRaHS and on-site regression curve with eight data points.

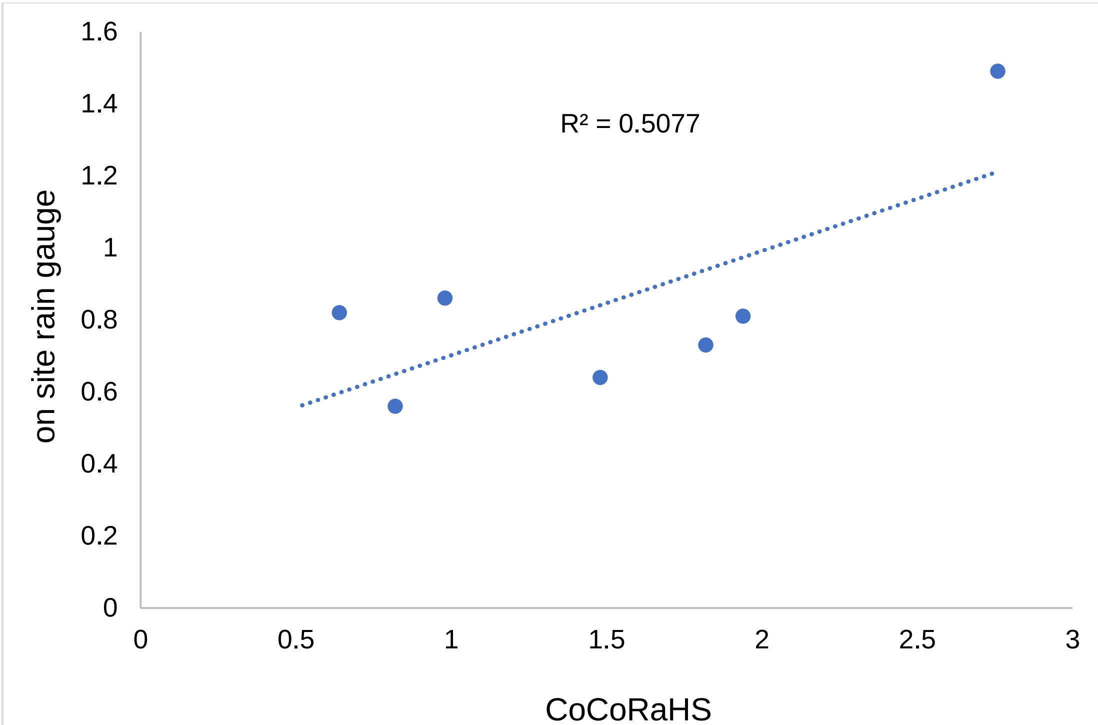


Figure 20: CoCoRaHS and on-site rain gauge regression curve with seven data points.

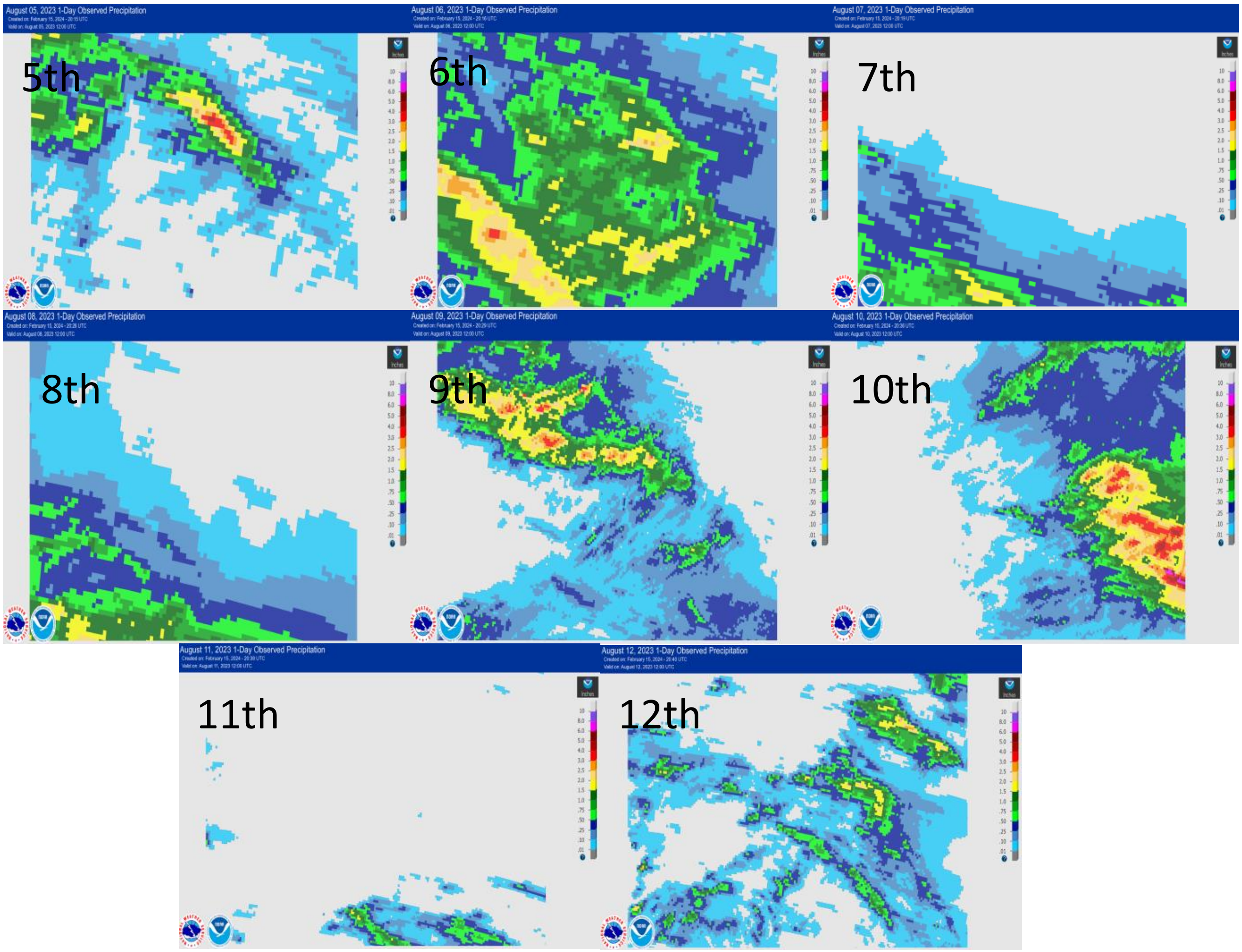


Figure 21: Storm #1 Daily Rainfall Maps.

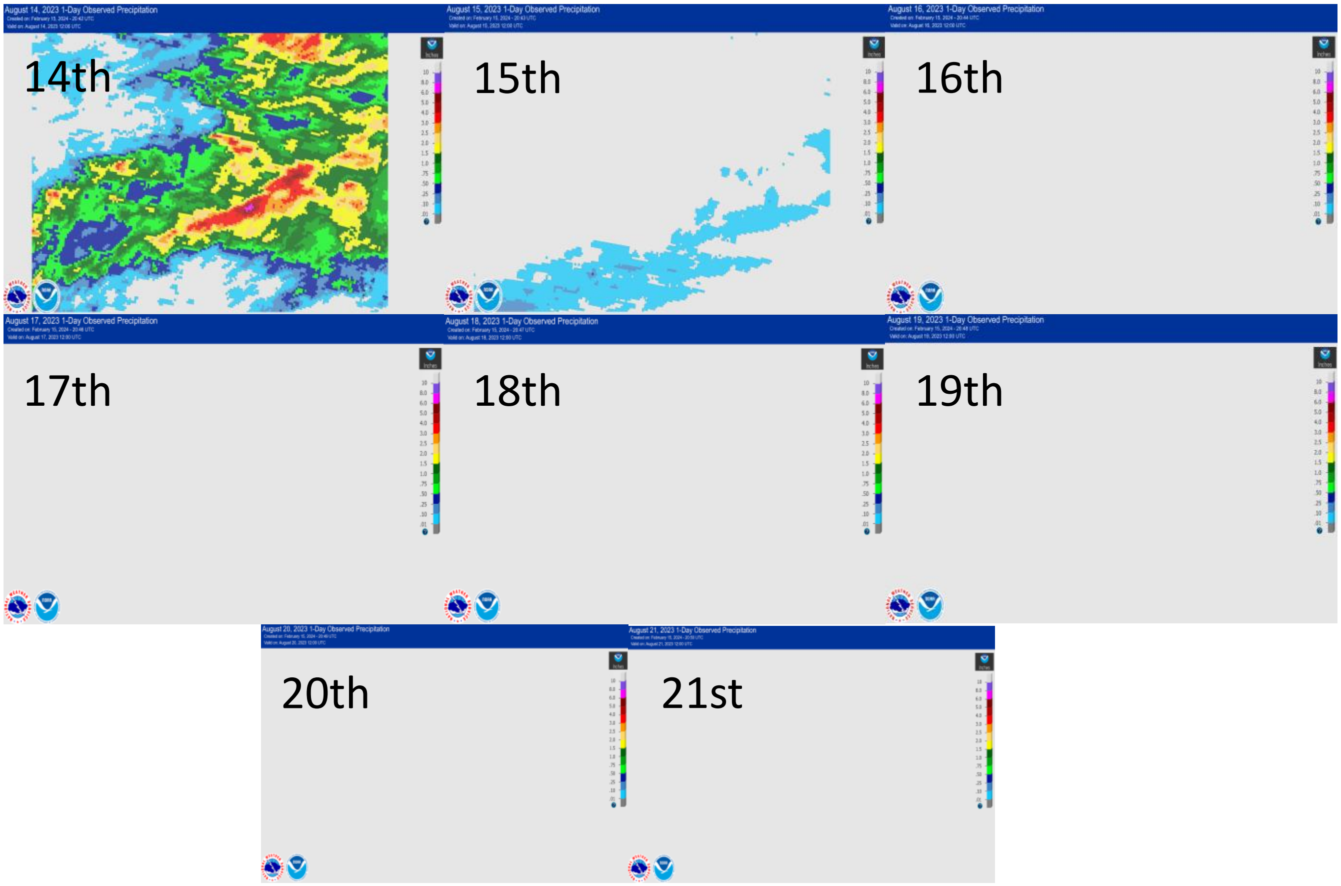


Figure 22: Storm #2 Daily Rainfall Maps.

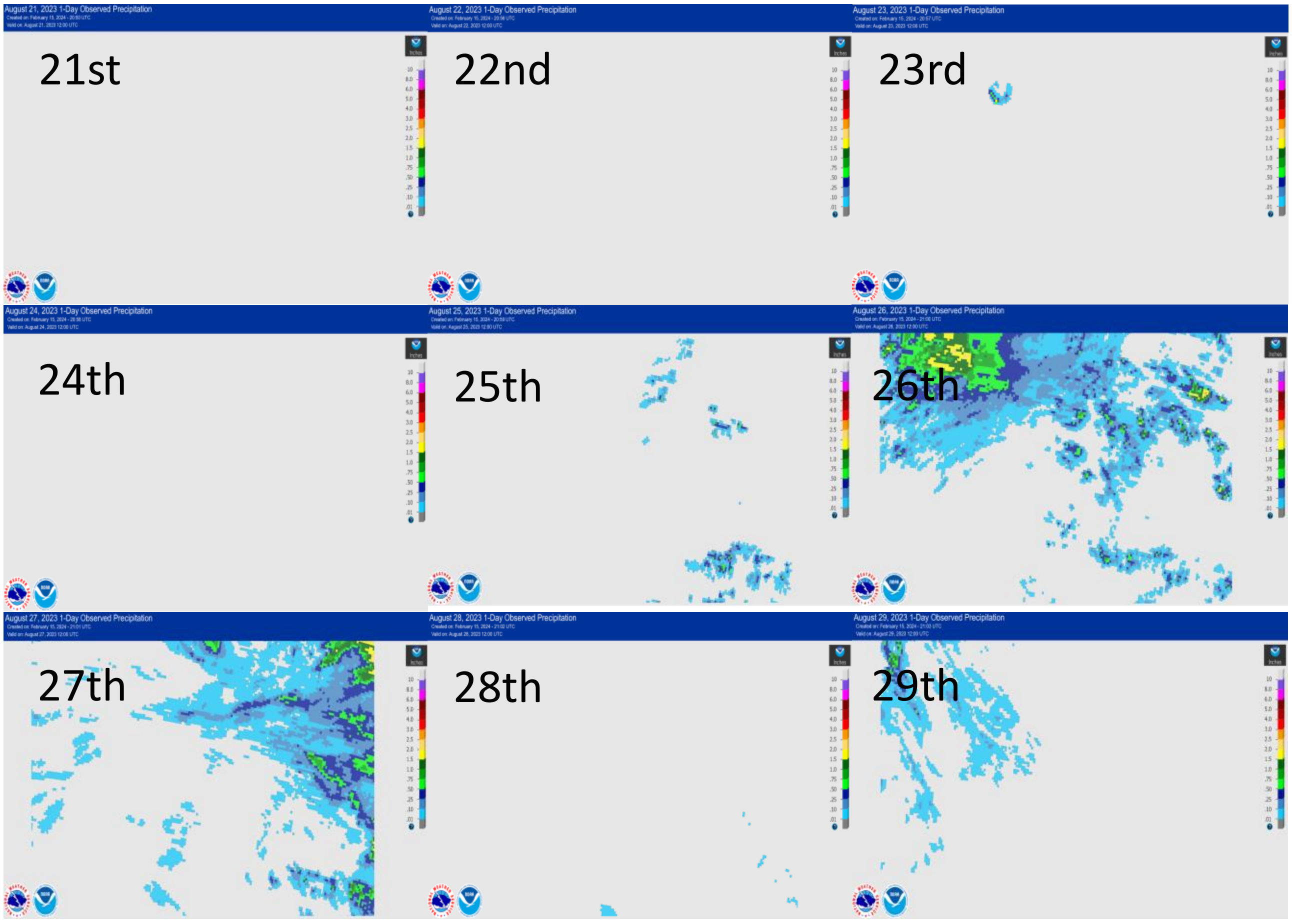


Figure 23: Storm #3 Daily Rainfall Maps.

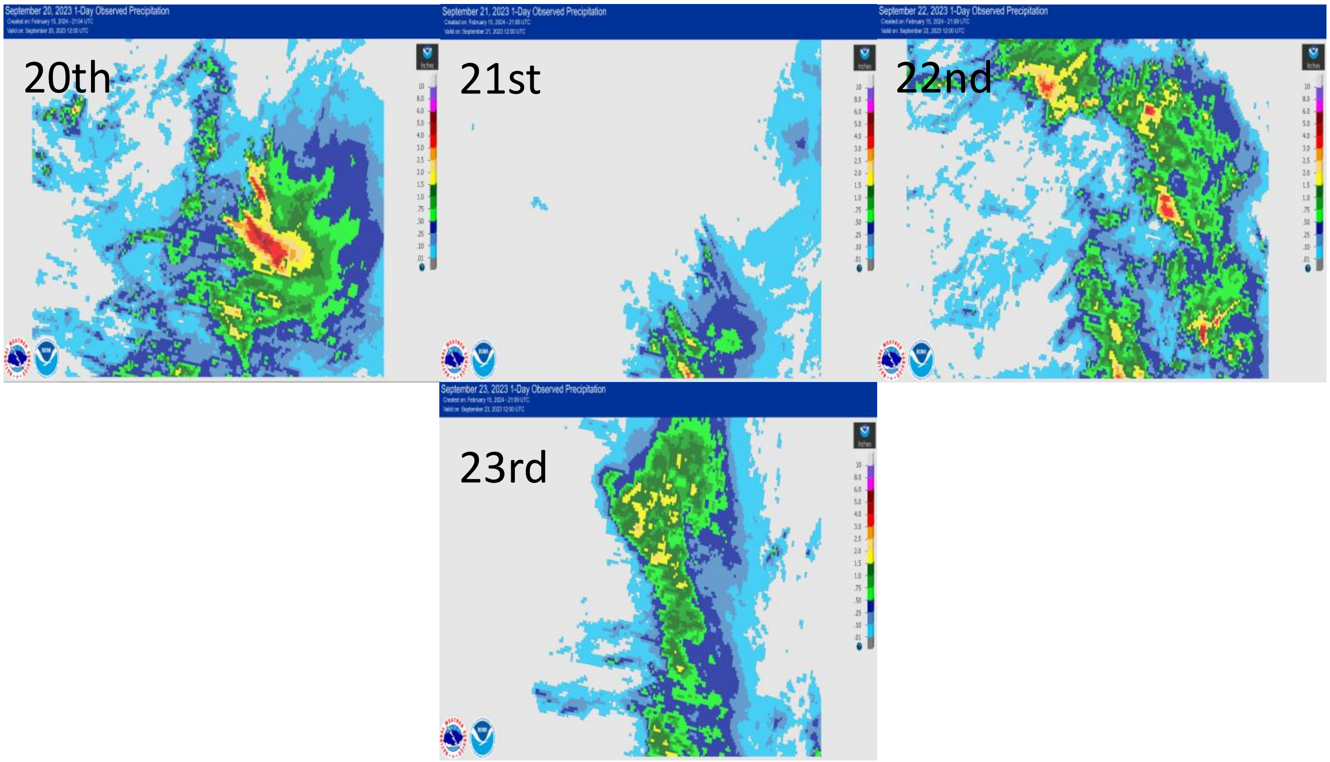


Figure 24: Storm #4 Daily Rainfall Maps.

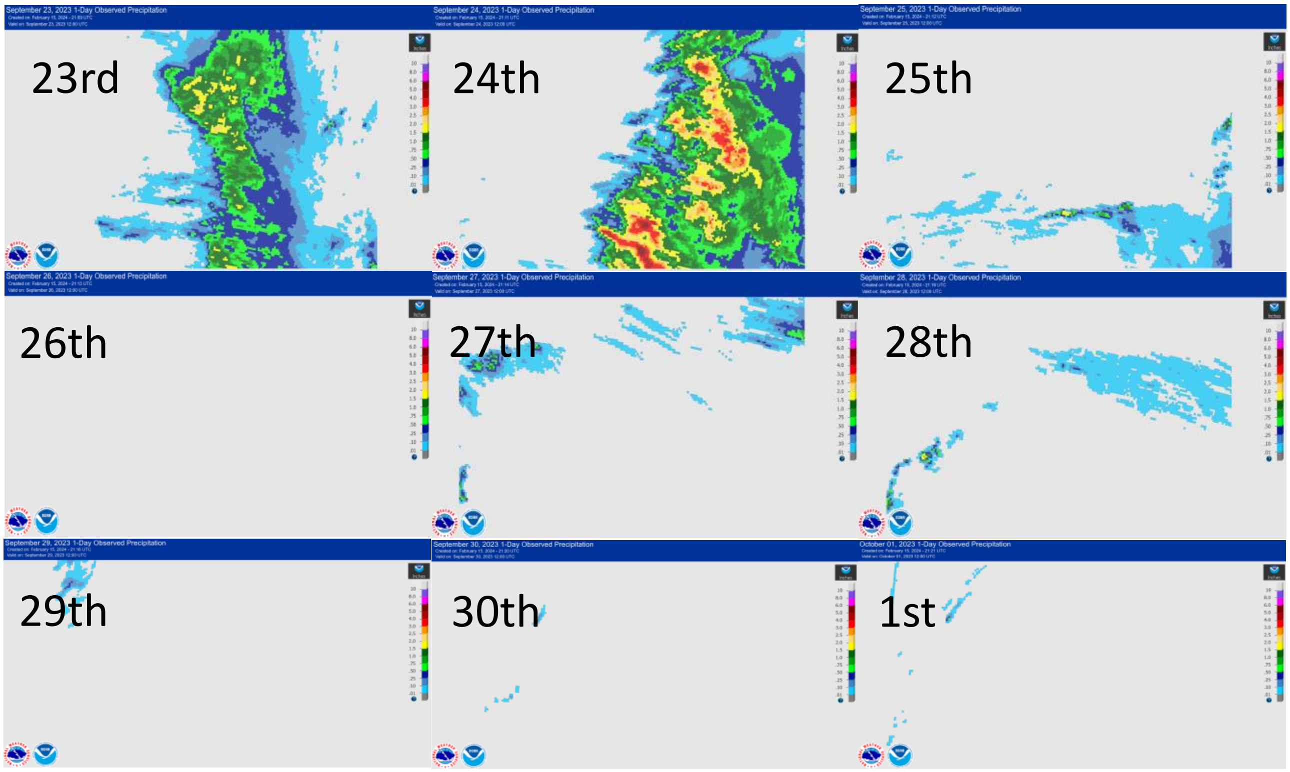


Figure 25: Storm #5 Daily Rainfall Maps.

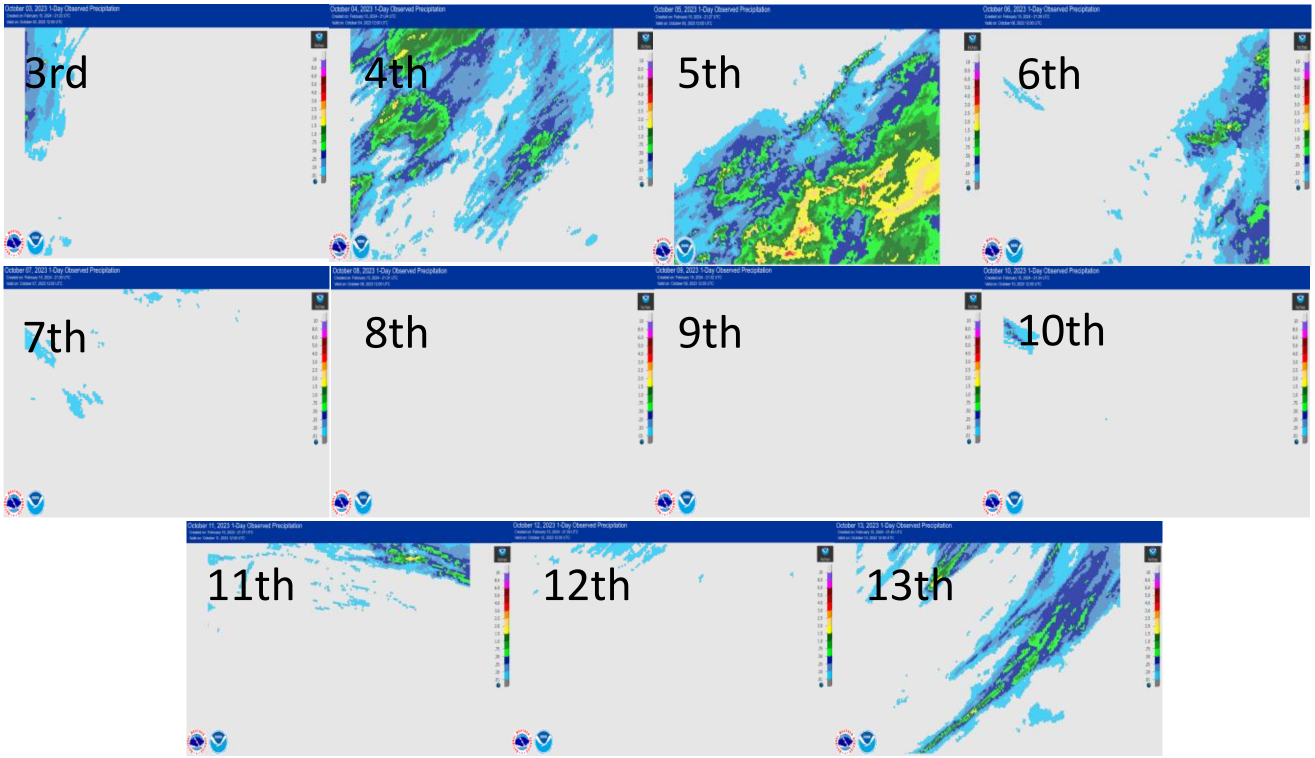


Figure 26: Storm #6 Daily Rainfall Maps.

Figure 27: Storm #7 Daily Rainfall Maps.

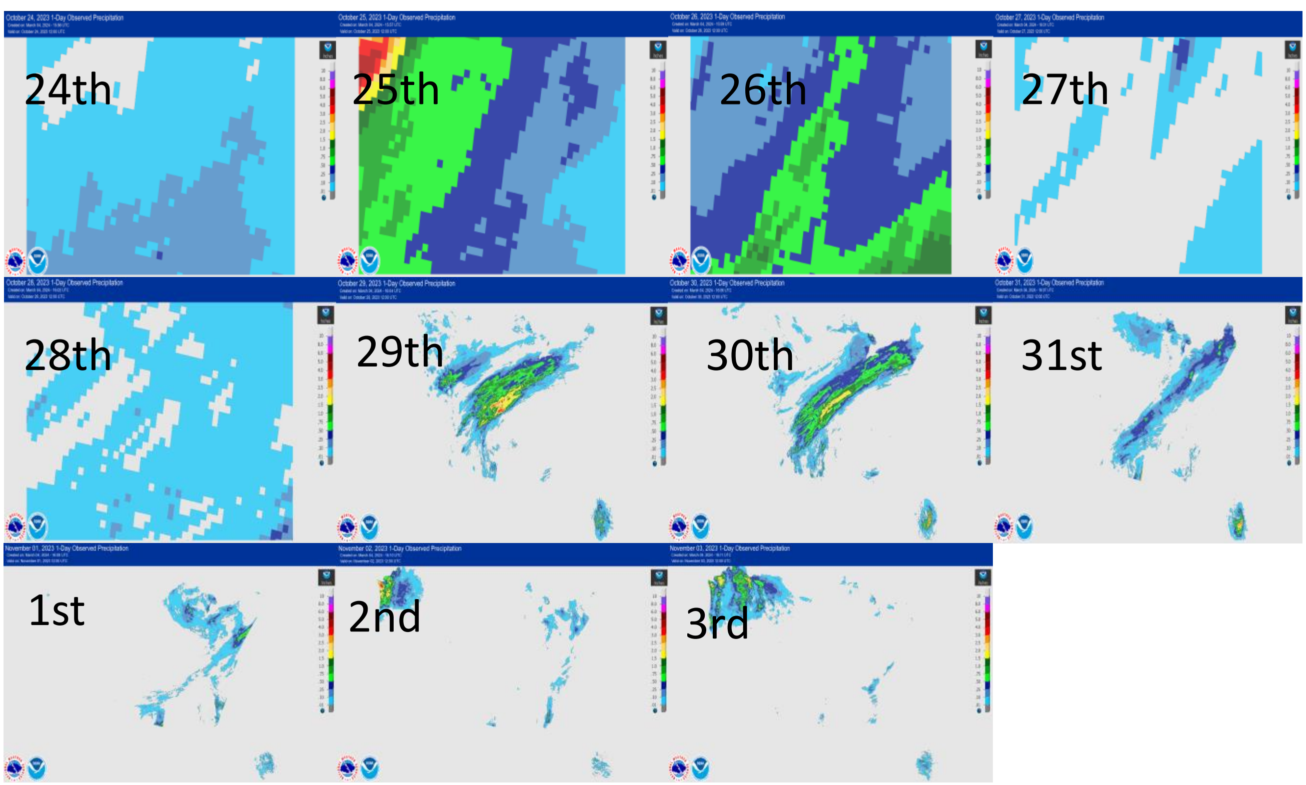


Figure 28: Storm #8 Daily Rainfall Maps.

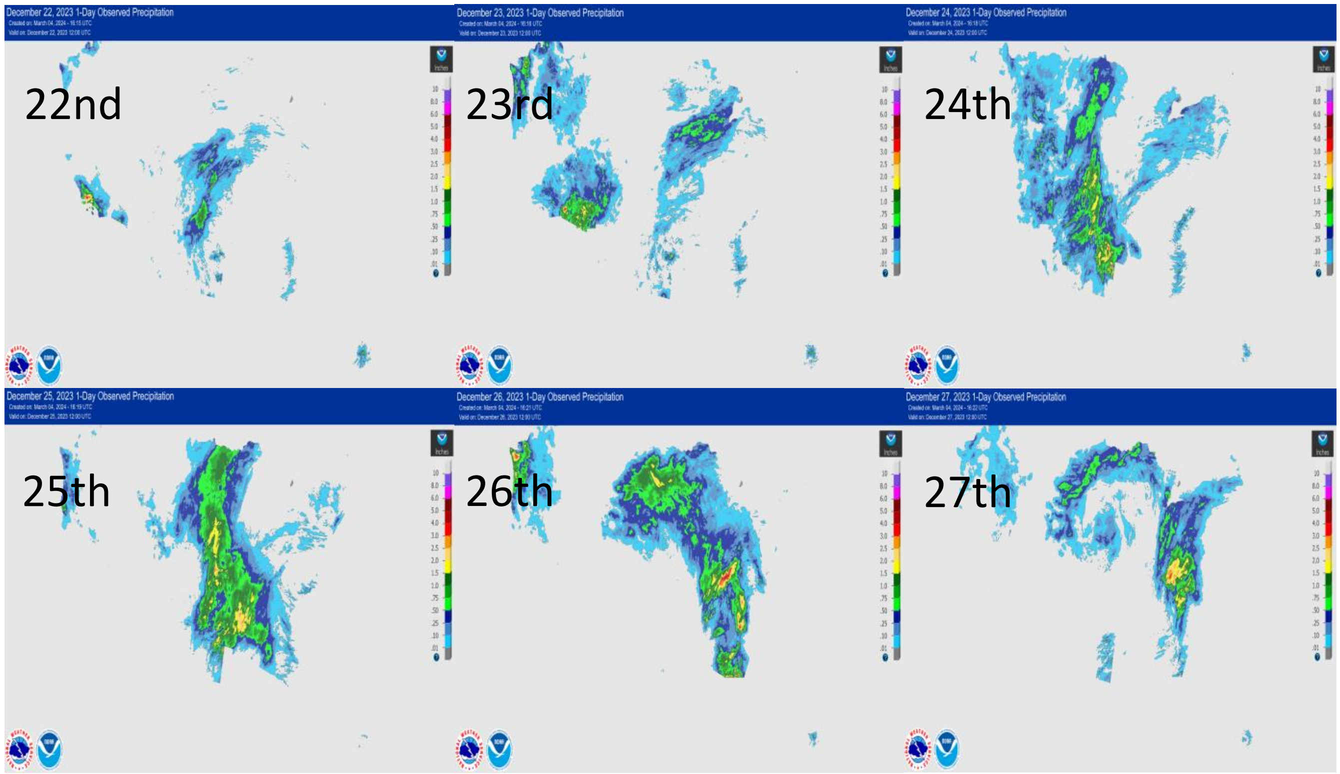


Figure 29: Storm #9 Daily Rainfall Maps.

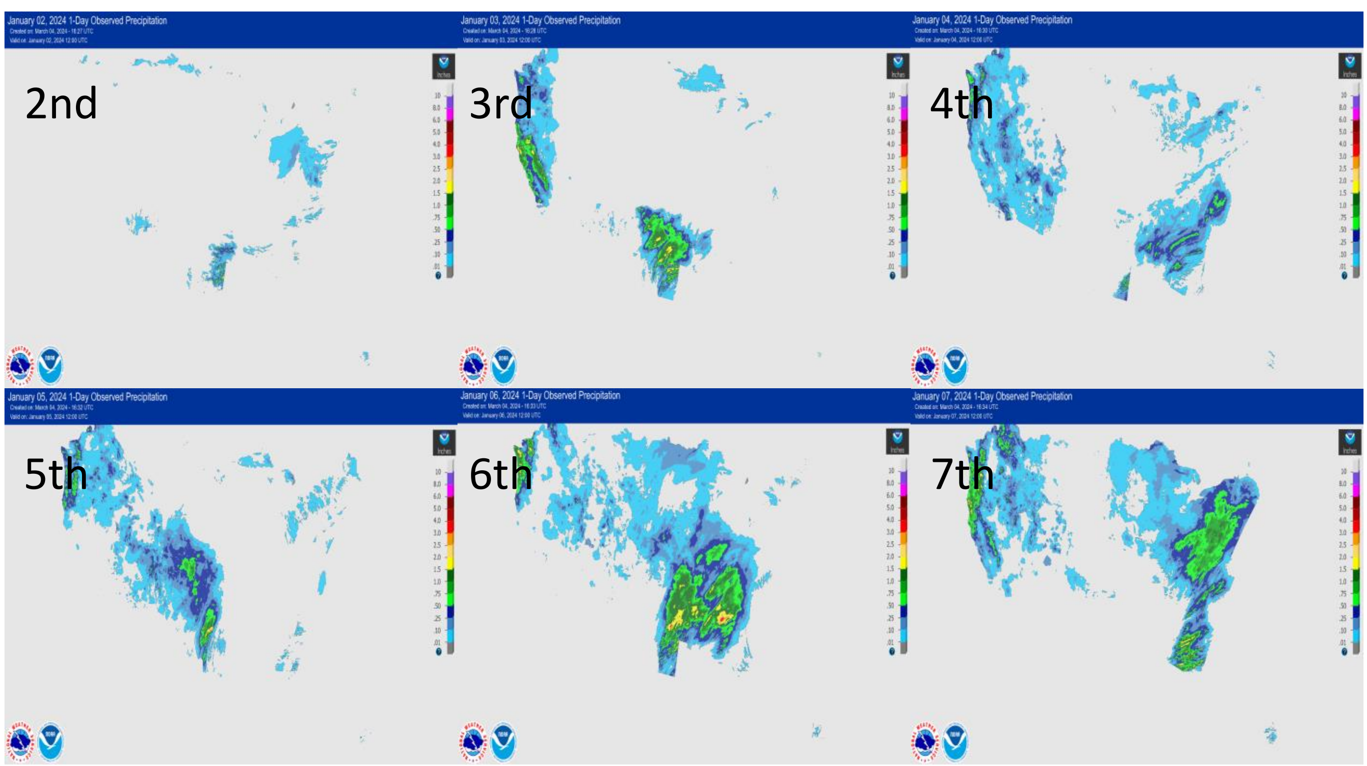


Figure 30: Storm #10 Daily Rainfall Maps.

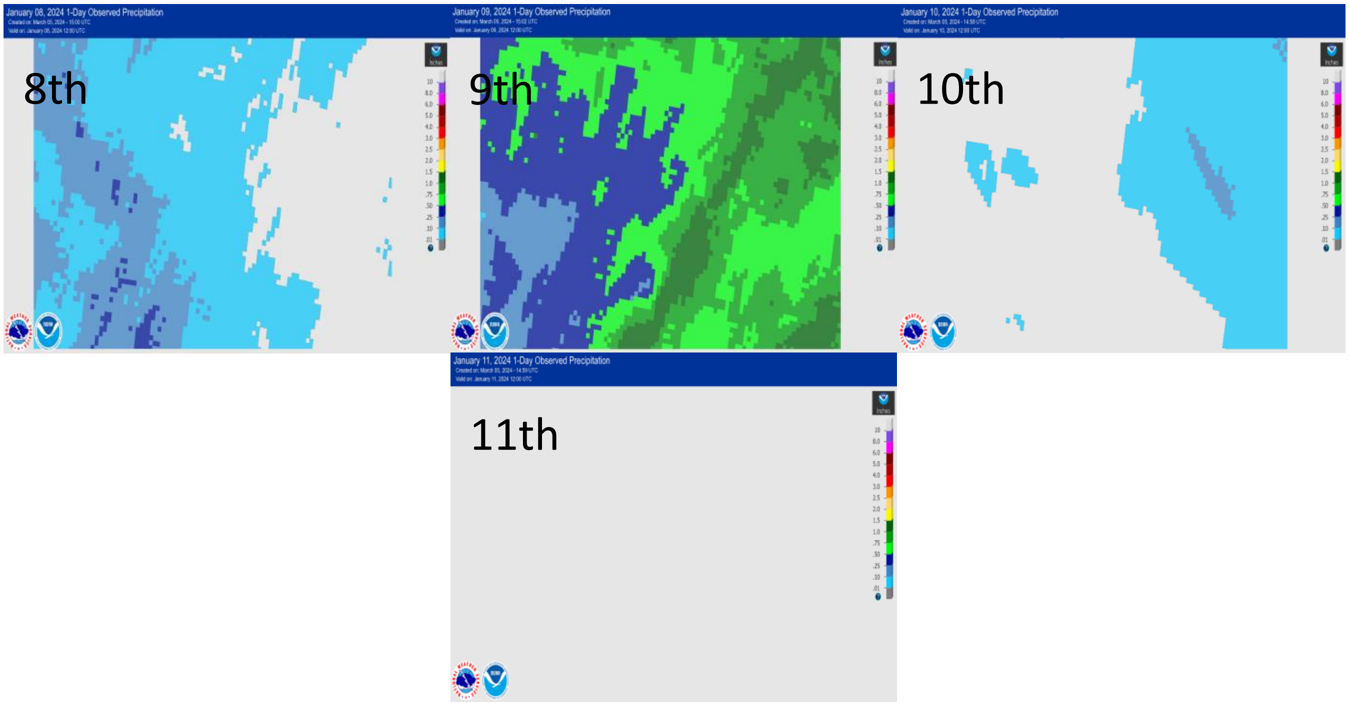


Figure 31: Storm #11 Daily Rainfall Maps.

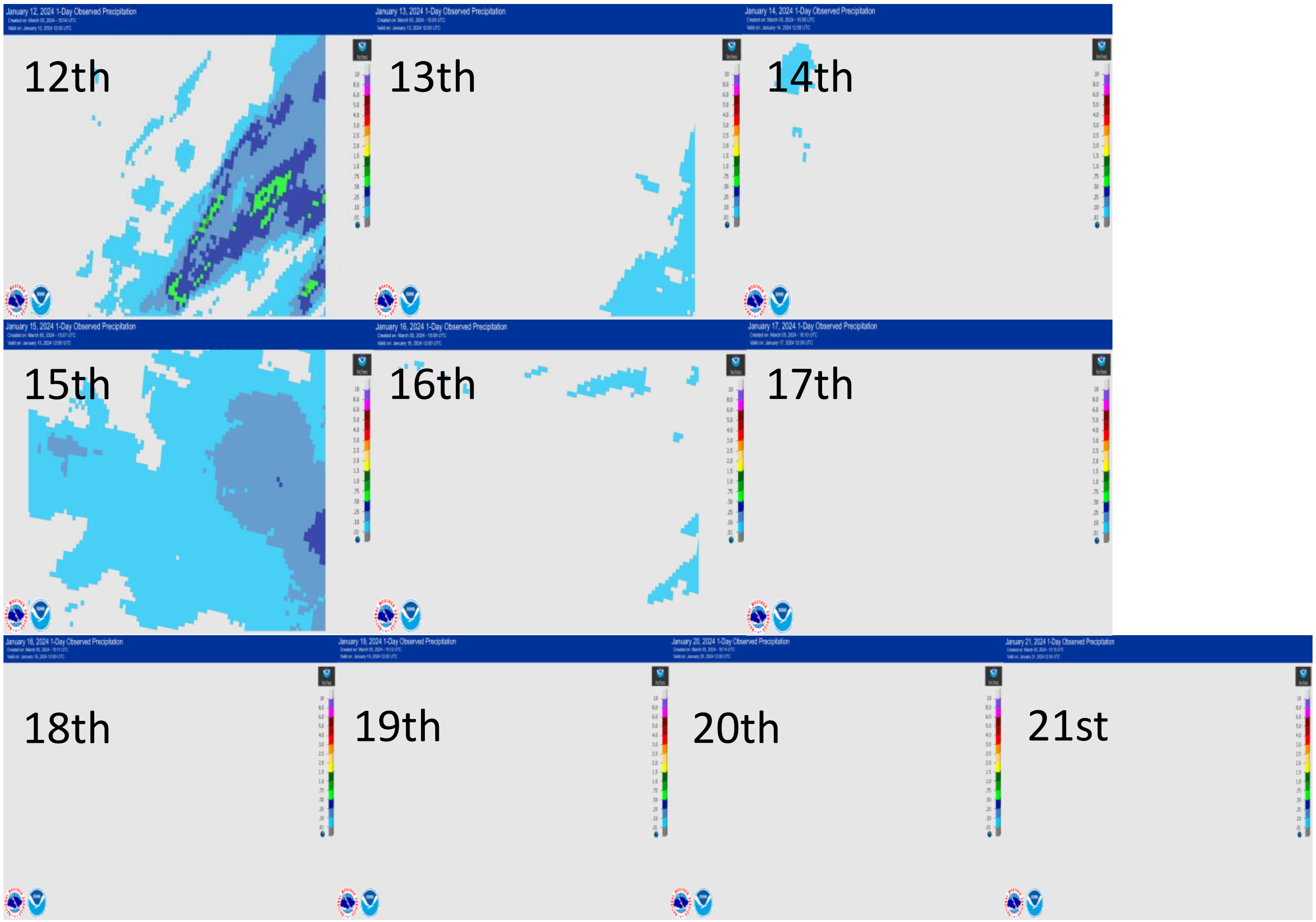


Figure 32: Storm #12 Daily Rainfall Maps.

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VITA

Colin Michael Dixon is from Keller, Texas. A 2019 graduate of Keller High School, Keller, Texas, he went on to receive a Bachelor of Science degree with a major in Biology from Centenary College of Louisianna, Shreveport in 2022.

In August 2022, he enrolled in graduate study at Texas Christian University, where his research focused on metals analysis and hydrology at the Tar Creek Superfund site located in northeastern Oklahoma. He is currently a candidate for a Master of Science in Environmental Science.

ABSTRACT

AN EVALUATION OF WATER AND SEDIMENT QUALITY IN A MINE-IMPACTED WATERSHED: CASE STUDY OF ELM CREEK, PICHER, OKLAHOMA

By Colin Dixon

Department of Environmental and Sustainability Sciences

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Thesis Advisor: Michael Slattery, Professor, Department Chair and Director of the Institute for Environmental and Sustainability Studies

Across the U.S. there are 1335 superfund sites that range from abandoned mines to old military bases that pose serious risk to the public if not remediated properly. The Tar Creek Superfund site, located in Picher, OK, is one example which could contaminate downstream water supplies via contaminated water and sediment due to the heavy metals, such as Cd and Pb, left behind from the mining activities. This study seeks to determine if the ongoing remediation is effective at Tar Creek which is located within the Tar Creek Superfund site, and whether contaminated sediment is migrating downstream through the watershed.

Contamination within local sediment did not appear to traverse downstream in large concentrations from the primary remediation site of Bird Dog South.

Contamination levels, however, slowly increased in the latter part of this research indicating finer-grained sediments are making their way through the sediment delivery system. Contamination within the water column was elevated compared to the sediment samples suggesting greater flushing of contaminants downstream. Elm Creek is characterized as hydrologically sluggish and likely dominated by subsurface storm processes. The low rate of instantaneous sediment flux from Distal West suggests that sediment storage is the dominant process within this fluvial system.