ELKHORN MINE & MILL:
SITE CHARACTERIZATION TECHNICAL MEMO

PREPARED FOR:

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1.0 INTRODUCTION

The Elkhorn Mine & Mill Restoration Project ('the project') aims to progress remediation and restoration efforts for public resources damaged by historic underground hard rock mining in the Pioneer Mountains, MT. The project is a partnership between the Big Hole Watershed Committee (BHWC), the Beaverhead Conservation District (BCD), the US Forest Service Northern Region Office (USFS), the Beaverhead-Deer Lodge National Forest (BDLNF), and Montana Fish, Wildlife, & Parks (MFWP). The Elkhorn Mine & Mill is situated along Elkhorn Creek in Beaverhead County, within the NE ¼ of Section 4, Township 4 North, Range 12 (45.49277°N, -113.04027°W).

To better understand existing conditions at the project site, the BHWC contracted **Watershed Consulting LLC** to perform site characterization assessments at the abandoned Elkhorn Mine & Mill. Site characterization efforts were funded by the MT Department of Natural Resource Conservation's (DNRC) Reclamation & Development Grant Program (RDGP) and the MT Department of Environmental Quality's (DEQ) Volunteer Monitoring Lab Analysis Support Program. This technical memorandum serves as a summary of findings related to *Objective I: Site Characterization Tasks 1.1 – 1.4* and *Objective III: Geophysical Investigation Alternatives Analysis Task 3.1* outlined in the revised RDGP Application submitted by the BCD in May 2020. Field data collection and analytical methodologies are described in the *Elkhorn Creek Water Quality Monitoring Sampling and Analysis Plan* submitted to DEQ in May 2020 and the *Elkhorn Mine & Mill: Sampling & Analysis Plan* completed in June 2020. Final methods are summarized below.

2.0 SUMMARY OF METHODS

2.1 Surface Water Quality Monitoring

Longitudinal synoptic sampling of Elkhorn Creek was performed on three occasions (June 25; July 23; August 20) to capture water quality conditions across different flow regimes. During each synoptic sampling event, field parameters [dissolved oxygen (mg/L; % saturation); temperature (°C); specific electrical conductivity (µS/cm); pH] were recorded using calibrated handheld probes. Simultaneously, unfiltered-acidified water samples were collected at each of 14 in-stream monitoring locations (Figure 1) for analysis of total recoverable metals and metalloids (As, Ca, Cu, Mg, Mn, Pb, Ag, Zn; mg/L) and water hardness. In addition, hydrologic discharge (cfs; L/sec) was measured at each monitoring location using a USGS current velocity meter. During the first sampling event, georeferenced photos were taken at each monitoring location to document upstream and downstream bankfull conditions for the stream bed, banks, and adjacent floodplain.

Following ICP-MS analysis by Energy Lab, Inc. (Helena, MT), trace metal and metalloid concentration data were coupled with hydrologic discharge to quantify material loads for each monitoring location and sampling event. This data was then used to populate a mass-balance model to estimate the magnitude of groundwater exchange and groundwater-associated loads. Changes in load between monitoring locations were calculated to illustrate proportional influence of groundwater-associated loading and highlight 'hot spots' on the landscape. Water quality data are represented as longitudinal synoptic trends to identify discrete zones of constituent loading, hydrologic dynamism, and anthropogenic influence.

2.2 AMD Water Quality Monitoring

Field parameters and constituent concentrations at acid mine drainage (AMD) sites were based on fixed-location grab samples of surface-flowing AMD originating from either the Elkhorn Mill area (AMD-01), the Elkhorn Mine (AMD-02), or a bankside spring along Elkhorn Creek near EK-27 (AMD-03)(Figure 1). Water quality and discharge data for AMD-01 were collected on two occasions (June 25, July 23) before drying up and coupled to estimate constituent loads during peak runoff. AMD-02 was outfitted with a 3" modified Parshall flume, water level logger, and barometer to collect discharge data on 15-minute intervals throughout the study period. Constituent concentrations from three sampling events were interpolated using polynomial regression and coupled with continuous discharge data to produce estimated loads for AMD-02. To characterize inputs to Elkhorn Creek, water quality data for AMD-03 was collected once at base flow from a bankside spring downgradient of the 1000'-level adit drainage settling ponds and waste rock pile.

2.3 Aerial Topographic Lidar Survey

The BHWC contracted DJ&A to provide professional land surveyor services and unmanned aircraft system (UAS) flights to collect ground and LiDAR-based topographic data. UAS flights mapped Elkhorn Mine & Mill, Elkhorn Creek, and the nearby Park Mine over approximately 1,972 acres in July 2020. DJ&A provided the final point cloud, digital elevation model (DEM), 1' contour PDF map, survey files, and closeout reports in multiple electronic file formats on August 20, 2020 via their in-house remote server access. Final survey deliverables were certified to have vertical accuracy of ±0.43 feet. Data can be accessed via *ftp://mail.djanda.com/Elkhorn_LiDAR* using Username: *Elkhorn* and Password: *Lidar@2020*. All data files were also transferred to the Montana State Library LiDAR Inventory service in October 2020 and are available for download via *http://montana.maps.arcgis.com/apps/MapSeries/index.html?appid=55cc886ec7d2416d85beca68d05686f4*. These data were used for historical map georeferencing and will inform follow-up geophysical investigations and engineering exercises for remediation and restoration planning.

2.4 Geospatial Analyses & Historical Map Georeferencing

The following analyses and exercises were performed using AutoDesk's Civil 3D 2018 computer-aided design (CAD) and ESRI's ArcGIS 10.7.1 geographic information system (GIS) software packages.

Spatiotemporal Patterns in Water Quality

To better assess the water quality monitoring data, spatial interpolations of concentration data were performed to illustrate spatiotemporal water quality dynamics in relation to the Elkhorn Mine & Mill. Monitoring location GPS data were coupled with total aqueous metal concentrations (∑[As, Cu, Pb, Mn, Ag, Zn]) in GIS, and *inverse distance weighting* interpolations were performed to illustrate contaminant patterns on the landscape. This analysis was performed independently for each sampling date to illustrate both spatial and temporal dynamics. Spatial interpolation of concentration data was performed using WGS 1984 EPSG:4326 coordinate reference system to accommodate latitude-longitude coordinates of monitoring locations.

Hydrologic Routing Analysis

Aerial LiDAR survey data was used for hydrologic analyses of the Elkhorn Mine & Mill to complement site characterization efforts. First, the LiDAR surface was exported from CAD and uploaded to GIS. From there, contour lines were converted to a raster DEM, and *hillshade* was applied to emphasize topographic features and patterns. A subset of this raster DEM encompassing the Elkhorn and Park mine complex was used for historical map georeferencing efforts. A smaller portion of the raster DEM representing only the Elkhorn Creek drainage was *clipped* and used for hydrologic analyses to identify runoff drainage patterns and flowpaths on the landscape upgradient of the Elkhorn Mine & Mill. Hydrologic analyses involved finding topographic *sinks* in the DEM, *filling* the sinks, identifying *flow direction* and *accumulation*, and delineating watershed *basins*. All hydrologic analyses were performed using the *Hydrology* tools in ArcGIS.

Historical Map Georeferencing

Historical mine survey maps were provided by the USFS Region 1 Office and sourced from the Montana Bureau of Mining & Geology library on June 18, 2020. Map PDFs were scanned at high resolution, cropped in Adobe Illustrator to exclude extraneous margins, and exported as a TIFF. From there, map TIFFs were uploaded to GIS, rotated, shifted, and transformed to approximate spatial extents based on aerial imagery and topography from the *hillshade* raster DEM. Using the *georeference* tool, points and features denoted on historical maps were georeferenced to known locations using *control point links* distributed across the entire extent of the mapped areas. *Control point links* were chosen by identifying existing ground control points, distinct topographic features, buildings, structures, bridges, and published Public Land Survey System patent claim boundary data. A network of georeferenced *control point links* distributed across an historical map results in a matrix of calculated residual errors, and individual *control point links* were added or removed to minimize this error.

Historical maps were prioritized based on their spatial extent, degree of mapped underground workings, and apparent accuracy. A total of eight historical maps were georeferenced. After georeferencing, historical maps were exported as TIFFs with associated world and auxiliary files. These map products were then imported into CAD and assessed for their functionality. Due to the temporal, spatial, and methodological variability of the historical maps, average residual error varies from <1 to ±20 horizontal feet. Those maps with higher relative accuracy and precision were typically more modern (post-1970) and encompassed much smaller survey areas. In contrast, those maps with greater residual error were older (pre-1920) and encompassed very large areas. All hydrologic analyses and georeferencing was performed using NAD 1983_2011 Montana State Plane FIPS 2500 in US International Feet, the same coordinate reference system used for the 2020 aerial LiDAR survey.

2.5 Geophysical Investigation Alternatives Analysis

Geophysical investigations are anticipated to be required to better understand the location, magnitude, and character of groundwater flowpaths and underground workings to design mitigation and management strategies for acid mine drainage. Due to the areal extent, remote location, difficult terrain, and dangerous conditions associated with the project, alternatives were limited to remotely sensed or surface-based investigations that provide 3-dimentionsal mapping and characterization results. To gauge the applicability of select geophysical investigation options for the project site, an alternatives analysis was conducted that addressed the following questions:

1. *What methods will best characterize the predominant groundwater seepage flowpaths draining from the waste rock pile into Elkhorn Creek?*
2. *What approaches are best suited to map the underground workings spanning from the Elkhorn to Park Mine?*

3. *What methods will best characterize the groundwater dynamics of the underground workings, including locating areas of groundwater mounding and approximating volumes and loading rates?*

Two consulting firms specializing in geologic and geophysical investigations were approached and asked to submit proposal for studies that would address the above questions. Proposed investigations included detailed descriptions of survey methods, constraints, limitations, deliverables, and cost estimates. Proposals were evaluated on the ability to address and answer the above questions and the anticipated cost: benefit ratio.

2.6 Fish & Wildlife

Fish population surveys were performed by MT FWP biologist Jim Olsen in September 2020. Electroshocking and species identification were conducted 1) upstream of the large culvert approximately 2 miles downstream of Elkhorn Mine & Mill, 2) within the restored stream reach near Elkhorn Mill, and 3) upstream of the Coolidge ghost town. Results from fish population surveys can be found in the MFWP report for Elkhorn Creek.

3.0 RESULTS & DISCUSSION

3.1 Site Assessment

The following sections summarize the various state factors that influence or characterize current conditions at the Elkhorn Mine & Mill, addressing relevant soil, geologic, vegetative, aquatic, biological and infrastructural resources.

3.1.1 Geology & Soils

The Pioneer Mountains – and the Elkhorn Creek drainage in particular – is primarily underlain by granitic gneiss, amphibolite, rocks of the Missoula Group, and other shelf sequences and formations (Zen 1983). While the immediate project area lies primarily within Quaternary and Tertiary-period deposits composed of talus, alluvium, colluvium, and glacial, landslide, and debris slides, the surrounding peaks and ridges are composed of Tertiary and Cretaceous intrusive rocks of the Pioneer batholith (Pearson et al. 1983). The underlying geology is exposed in many portions of the project area through talus and scree fields, bedrock outcroppings, boulder moraines, and exposed mine workings.

The valley floor was formed of glaciofluvial deposits derived from granite and similar parent materials and is characterized as a mixed composition of various soil types, ranging from Como-Lowder and frequently flooded-Lilylake families to other frequently flooded families or complex trough bottoms (NRCS 2020). They are typically characterized as having shallow O-horizons of slightly decomposed plant material overlaying gravelly sandy loams, very gravelly sandy loams, or cobbly loams. As a result, valley soils are somewhat excessively drained or excessively drained, except where frequently flooded depressions accumulate muck, later developing into peat layers.

Soils on the hillslopes above the Elkhorn Mine & Mill are primarily composed of the Como-Worock families-Rock outcrop complex on valley trough walls. The Worock soil types are dominated by stony loam and very gravelly clay loam that are well drained with moderate water holding capacity.

3.1.2 Vegetation

Excluding wet meadows, bare rock, and mining areas, the entire drainage is thickly covered by a canopy of subalpine fir (*Abies lasiocarpa*), Englemann spruce (*Picea engelmannii*), and lodgepole pine

(*Pinus contorta*) of mixed age classes. The herbaceous understory layer is comprised primarily of elk sedge (*Carex geyeri*), grouse whortleberry (*Vaccinium scoparium*), and heartleaf arnica (*Arnica cordifolia*). Wetter sites frequently host red osier dogwood (*Conus sericea*), alder (*Alnus viridis*), and several species of willow (*Salix spp.*), currant (*Ribes spp.*), sedge (*Carex spp.*), rush (*Juncus spp.*), and other hydrophytic plants.

Forest cover dominates the project site except for the areas encompassing the Elkhorn Mill, the restored stream corridor, mine shaft adits, and the waste rock piles. The entire footprint of the former Elkhorn Mill and an approximately 75-foot wide buffer is devoid of vegetation, most likely due to a combination of existing soil contamination and a lack of organic matter. On the restored reach near the Mill, 'slickens' of mine tailings are present in discrete locations on stream banks and floodplain wetlands, preventing vegetative growth and potentially acting as episodic sources of contamination to Elkhorn Creek. Otherwise, vegetative cover in the stream corridor is high and riparian forest succession is ongoing. The waste rock pile exhibited approximately 33% herbaceous cover during summer 2020 and is showing signs of continued lodgepole pine recruitment. While the waste rock pile is somewhat vegetated, the predominance of shallow-rooted grasses and weeds combined with ongoing hillslope erosion limits revegetation and slope stabilization potential. Indeed, a slough-slide measuring approximately 6ft x 25ft across has occurred within the past several years at the toe of the waste rock pile slope.

3.1.3 Streams, Springs, Seeps, and Wetlands

Only one perennial stream (Elkhorn Creek) flows through the project site, however, there exist innumerable intermittent springs, seeps, and wetlands (Figure 1). Several intermittent springs and seeps surface around the Elkhorn Mill and several converge into a drainage swale and silt-fence-generated ponded wetland before discharging directly into Elkhorn Creek near EK-18. In addition, innumerable springs and seeps discharge into Elkhorn Creek from the left (west) stream bank, particularly in proximity to the adit settling ponds and the toe of the waste rock pile. The primary source for these seeps is likely the 1000'-level adit; continuous AMD discharge from the Elkhorn Mine is routed toward several defunct settling ponds and streamside wetlands. Much of the AMD from the Elkhorn Mine likely manifest as seeps and springs between the settling ponds, the toe of the waste rock pile and Elkhorn Creek. Lastly, a particularly large spring flows from directly upgradient of the waste rock pile into a stormwater control measure located at the top of the pile. This surface runoff flows alongside the western and northern perimeter of the waste rock pile before spreading across the access road near the bridge, eventually entering Elkhorn Creek as diffuse groundwater and surface water inputs.

Wetlands are also numerous throughout the site, particularly in the restored floodplain near the Mill and on both sides of Elkhorn Creek upstream of the bridge. In general, the eastern (right) bank appears to host fewer wetland areas than the western (left) bank, possibly reflecting greater overland flow from the Elkhorn Mine and waste rock pile area. Constructed settling ponds held surface water during June and July site visits but were dry during the August site visit. It is worth noting that AMD discharge from the 1000'-level adit is disconnected from the settling ponds, instead following several overland flowpaths through the downgradient road prism and forested areas.

3.1.4 Buildings & Structures

There are numerous historical buildings and structures throughout the project site. For this memo, structures in the Coolidge Ghost Town on the right bank of Elkhorn Creek will not be addressed.

The Elkhorn Mill itself has undergone extensive reclamation and deconstruction efforts; the only remaining structures consist of the concrete frame and foundation piers. A collapsed wooden-frame building is positioned between the Elkhorn Mill and Elkhorn Creek. The former assay house is located to the southeast of the Elkhorn Mill footings and consists of a brick chimney and collapsing wooden stud walls (Figure 1). Portions of a historic trestle remain along the access road to the south of the Mill. In addition to the recognizable structures, remnants of ore processing equipment are scattered to the north, south, and east of the Elkhorn Mill.

Structures along Elkhorn Creek are both historic and contemporary in nature. Historic structures include the collapsed building (perhaps a water wheel powerhouse) residing in the middle of Elkhorn Creek near EK-26 and other collapsing wooden frame buildings on right bank. Contemporary structures include the concrete flow control structure at the head of the historic diversion ditch, the five buried culverts regulating inflow to the restored reach of Elkhorn Creek, and the bridge. During the June site visit, debris jams were removed from the five culverts to increase inflows to Elkhorn Creek, resulting in proportional decreases in diversion ditch flows. By the August site visit, base flows continued to enter Elkhorn Creek and inflow to the diversion ditch was negligible. Further research and assessments are needed to characterize the required versus actual minimum flows in the historic diversion ditch and the hydrologic suitability (e.g. flow control, fish passage) of the five buried culverts.

Buildings and structures associated with the Elkhorn Mine are separated into 1000'-level and 300'-level adit areas. At the 1000'-level adit, a tram hopper and small shed remain as the only recognizable historic structures. A contemporary portal gate prevents the public from entering the 1000'-level adit. The portal for the 300'-level adit has collapsed or was plugged, preventing access to the shaft. Wood and metal debris along the access road to the north and south of the 300'-level adit show signs of several collapsed structures – whether they were historical or contemporary is unknown. Lastly, remnants of trestles and tram structures are scattered to the east of the 300'-level adit atop a waste rock pile.

3.1.5 Fish & Wildlife

Fish and wildlife observed during field visits include several small salmonids in Elkhorn Creek upstream of the bridge, squirrels and chipmunks throughout the site, and a single cow moose in the restored floodplain downstream of Elkhorn Mill. Several bird species were present but not identified to species. See MFWP's Elkhorn Creek fish population survey report for more information.

3.2 Elkhorn Creek Water Quality

The following sections provide results of water quality monitoring and brief interpretations related to the existing conditions in Elkhorn Creek. Interpretations are to be used as summaries of overall trends and may generalize hydrologic and geochemical patterns to illustrate sub-reach-scale dynamics.

3.2.1 Hydrologic Discharge

Flows in Elkhorn Creek followed the typical hydrograph for a snowmelt-dominated watershed (Figure 2). On June 25, peak flows were 48.6 cfs at the uppermost monitoring location (EK-30). Discharge dipped slightly between EK-30 and EK-25, before declining rapidly to 27.7 cfs at EK-23 due to withdrawals to the diversion ditch (EK-24). In the restored reach, flows increased unsteadily below EK-23, reaching 30.4 cfs by the downstream monitoring location (EK-16).

This longitudinal pattern was similar but substantially muted during July and August monitoring events. On July 23, discharge at EK-30 was only 10.6 cfs – approximately 20% of peak flow. Withdrawal to the diversion ditch accounted for only 0.41 cfs, and discharge at EK-16 was 7.9 cfs. On August 20, base flow discharge at EK-30 was only 3.6 cfs and withdrawal to the diversion ditch was less than 0.1 cfs. As a result, flows at EK-16 were the same (3.6 cfs) as flows at EK-30.

The large flow reduction between June and July highlight the significance of peak runoff in the Elkhorn drainage. In early summer, flows are augmented by overland runoff of snowmelt and precipitation. In contrast, late summer flows are derived primarily from groundwater inputs. The elevated hydrologic loading during early summer suggests increased constituent transport capacity during this time of year.

3.2.2 Field Parameters

Temperature

Water temperature (Temp) followed expected patterns for seasonal and diel variation (Table 1; Figure 3). Across all monitoring locations, water temperature averaged 6.89 ± 0.16 °C on June 25; 9.91 ± 0.09 °C on July 23; and 11.47 ± 0.26 °C on August 20. While longitudinal patterns suggest a decrease in temperature with distance downstream, readings are confounded by the time of day they were taken; downstream locations were monitored in the morning and upstream locations in the afternoon. Overall, water temperatures in Elkhorn Creek are characteristic of high-alpine streams and valuable cold-water fishery habitat.

Dissolved Oxygen

Dissolved oxygen (DO) concentration and percent saturation in Elkhorn Creek followed typical seasonal trends; colder, more turbulent flows during peak discharge allowed for higher DO content (Table 1; Figures 4 and 5). During peak flow on June 25, average DO across all monitoring locations was 9.98 ± 0.05 mg/L and 106.07 ± 0.27 %. By base flow on August 20, average DO had declined slightly to 8.65 ± 0.08 mg/L and 102.88 ± 0.63 %. Longitudinal patterns indicate a slight increase in DO with distance downstream, but this is likely a relic of sampling approach limitations (time of day) mentioned above. In August, DO declined substantially in the restored reach downstream of EK-19. This is likely due to reduced passive aeration resulting from the shallower channel slope and less-turbulent flow compared to the upstream reach (EK-25 and above). While still above the 75% saturation cutoff, this decline may perpetuate further downstream and pose habitat suitability issues for salmonid and/or grayling populations during base flows.

Specific Conductivity

Seasonal and longitudinal trends in specific electrical conductance (SpC) were observed across Elkhorn Creek (Table 1; Figure 6). Specific conductivity is a measurement of the electrical conductance of water and is a proxy for dissolved ion concentration. Average reach-scale specific conductivity was lowest (28.81 ± 0.52 µS/cm) during peak flow on June 25, increased through July 23 (44.51 ± 1.07 µS/cm), and reached its maxima (59.38 ± 2.02 µS/cm) on August 30. Rapid longitudinal increases in specific conductivity between EK-30 and EK-26 were consistently observed across sampling events, ranging from 20-35% compared to background levels. The increase was most pronounced during base flow, suggesting inputs to Elkhorn Creek in this reach have disproportionately high dissolved ion concentrations. Overall, specific conductivity is relatively low in Elkhorn Creek and is characteristic of undeveloped montane drainages.

pH

The concentration of hydrogen ions (pH) also demonstrated seasonal and longitudinal patterns (Table 1; Figure 7). At peak flow on June 25, pH averaged 7.3 ± 0.1 across all monitoring stations. On July 23, pH averaged 7.4 ± 0.02. By base flow on August 20, pH averaged 7.6 ± 0.03. Changes in pH are logarithmic, so small changes in pH reflect large changes in total hydrogen ion concentration. In June and July, pH declined unsteadily between EK-30 and EK-20 before spiking near Elkhorn Mill (EK-19 or EK-18). In contrast, during base flow pH declined considerably at EK-28, increased steadily to EK-20, and declined downstream of Elkhorn Mill. While some of the longitudinal change in pH may be related to diel variation in photosynthetic activity on the stream bed, these data indicate pH in Elkhorn Creek may be influenced by seasonal hydrology and local conditions.

Hardness

Hardness – calculated as the coefficient-corrected sum of Ca and Mg – influences trace metal toxicity through concentration-dependent relationships. As a result, hardness followed the same seasonal and longitudinal trends as Ca and Mg; increasing in concentration with lower flows and distance downstream (Table 1; Figure 8). Average concentration increased from 11 ± 0.21 to 22.67 ± 0.46 mg/L between peak and base flow, indicating dilution with peak runoff. Stepwise longitudinal increases were observed on all sampling events near the settling ponds, waste rock pile, and Elkhorn Mill (in order of magnitude).

Table 1. Average field parameter readings for Elkhorn Creek taken during longitudinal synoptic sampling events. Values represent the mean ± standard error (*n* = 14) of all monitoring locations by flow regime.

	Peak Flow	Mid-summer Flow	Base Flow
Date	6/25/2020	7/23/2020	8/20/2020
Temp (°C)	6.89 ± 0.16	9.91 ± 0.09	11.47 ± 0.26
DO (mg/L)	9.98 ± 0.05	8.99 ± 0.05	8.65 ± 0.08
DO (%)	106.07 ± 0.27	103.06 ± 0.49	102.88 ± 0.63
Sp. Cond (µS/cm)	28.81 ± 0.52	44.51 ± 1.07	59.38 ± 2.02
pH	7.33 ± 0.10	7.43 ± 0.02	7.61 ± 0.03
Hardness (mg/L)	11 ± 0.21	17.13 ± 0.35	22.67 ± 0.46

3.2.3 Total Recoverable Metals, Metalloids, and Hardness Concentrations

The following subsections outlined spatial and seasonal patterns in constituent concentrations and assess acute and chronic toxicity levels based on the empirical and calculated hardness (25 mg/L) for each sampling event (DEQ 2019).

Arsenic (As)

Arsenic, a toxic metalloid, exhibited low concentrations over time and space (Table 2; Figure 9). In June, As increased from a background concentration of 0.0001 mg/L at EK-30 to 0.0003 mg/L by EK-17, increasing stepwise near the adit settling ponds and Elkhorn Mill. A more pronounced spike (0.0005 mg/L) below the waste rock pile occurred in July at EK-23, before declining back to 0.0002 mg/L near Elkhorn Mill. Finally, at base flow in August, a maximum of 0.0003 mg/L was observed downstream of Elkhorn Mill. Although spatially discrete signals were observed in proximity to the waste rock pile and Elkhorn Mill, the concentration of As in Elkhorn Creek was below toxicity thresholds for both human health (0.010 mg/L) and aquatic life (acute = 0.34 mg/L; chronic = 0.15 mg/L) standards for all samples.

Calcium (Ca)

Calcium, the third most abundant metal in earth's crust and a relatively conservative solute, demonstrated typical seasonal variation resulting from the seasonal hydrograph (Table 2). Concentrations in Elkhorn Creek doubled from a peak runoff average of 3.87 ± 0.09 mg/L to 7.73 ± 0.18 mg/L at base flow, highlighting the potential for constituent dilution during higher flows. In contrast, Ca also demonstrated consistent 20-33% concentration increases in proximity to the seeps below the settling ponds, suggesting Ca-rich inputs to Elkhorn Creek in this area.

Copper (Cu)

Copper, toxic to aquatic organisms and humans alike, exceeded both acute (0.00379 mg/L) and chronic (0.00285 mg/L) aquatic life standards in Elkhorn Creek on all sampling events (Table 2; Figure 10).

In contrast, the comparatively high human health standards of 1.3 mg/L was not exceeded in Elkhorn Creek surface waters. While background conditions upstream of EK-28 and EK-30 were either in compliance (< 0.0004 mg/L) or non-detectable at all flows, concentrations consistently spiked in proximity to the adit settling pond seeps, waste rock pile, and Elkhorn Mill. While Cu was generally more dilute during peak flows, a maximum concentration of 0.017 mg/L was observed at EK-17 on June 25 in association with greater overland runoff from the Mill area. Copper concentrations were relatively consistent across quite variable flow regimes, suggesting overland flow and groundwater inputs both act as strong – and perhaps alternating – drivers of Cu levels in Elkhorn Creek.

Lead (Pb)

Lead, a heavy metal, was typically low in Elkhorn Creek but exceeded chronic toxicity levels for aquatic life (0.00055 mg/L) on four occasions (Table 2; Figure 11). Lead concentrations in exceedance of the 0.015 mg/L human health standard were not observed. During peak runoff, Pb exceeded toxicity levels and reached 0.0007 mg/L at EK-16 just downstream of Elkhorn Mill. The elevated levels during peak runoff were likely the result of overland flow from the Elkhorn Mill area. Interestingly, the maximum Pb concentrations occurred on July 23 at EK-23 (0.012 mg/L) and EK-22 (0.011 mg/L), which reside downstream of the waste rock pile. In contrast to the July maxima, Pb was below compliance (<0.0002 mg/L) at EK-23 and EK-22 for both peak and base flows.

The spike at EK-23 on July 23 may illustrate potential hydrologic lag time for peak Pb delivery from waste rock pile runoff. During peak flow, overland runoff is diverted around the perimeter of the waste rock pile and diffusively discharge into Elkhorn Creek near EK-23. The lag time between peak runoff and peak Pb concentration at EK-23 may reflect the travel time of groundwater as it infiltrates through the waste rock pile and flows toward Elkhorn Creek, accumulating Pb along the way. Although muted, this phenomenon is also observed at EK-17 on July 23 and may reflect Elkhorn Mill groundwater entering the creek well after peak runoff has passed.

Magnesium (Mg)

Magnesium is a ubiquitous metal throughout the globe and concentrations generally followed expected seasonal and longitudinal patterns (Table 2). In Elkhorn Creek, Mg averaged 0.36 ± 0.007 mg/L on June 25 compared to 0.73 ± 0.01 mg/L on August 20, demonstrating dilution during peak runoff and concentration at base flow. Additionally, longitudinal increases were observed on all three sampling events, with the most pronounced changes occurring between EK-27 and EK-25. The increase in Mg concentration near the adit settling ponds suggest Mg-rich inputs to Elkhorn Creek from overland surface and/or groundwater flowpaths.

Manganese (Mn)

Often in combination with iron (Fe), Mn can be toxic to aquatic organisms above 0.1 mg/L (DEQ 2019). Across all monitoring locations and sampling dates, Mn was below this toxicity threshold in Elkhorn Creek (Table 1). However, Mg consistently increased from background levels of 0.001 mg/L to maxima of 0.024, 0.026, and 0.036 mg/L at peak, mid-summer, and base flows, respectively. Again, the largest absolute increases occurred in proximity to the settling pond seeps, waste rock pile, and Elkhorn Mill. While not in exceedance, Mn-associated compounds are potent contaminants and specific confined areas demonstrate considerable contributions to Elkhorn Creek.

Silver (Ag)

The concentration of Ag in Elkhorn Creek was below the detection limit for all but six samples, and only reached between 0.00004 and 0.00007 mg/L (Table 2). Detectable levels of Ag typically occurred during higher flows in proximity to Elkhorn Mill and indicate overland runoff as the culprit. For comparison, the acute aquatic life standard for Ag is 0.000374 mg/L and the human health standard is 0.1 mg/L.

Zinc (Zn)

While a common element, Zn is toxic to aquatic organisms at certain pH and hardness levels. Zinc concentrations in Elkhorn Creek were approaching or in exceedance of acute and chronic (both 0.037 mg/L) toxicity levels at nearly all monitoring locations throughout the study period (Table 2; Figure 12). The human health standard for Zn is 7.4 mg/L, far above any concentration observed in Elkhorn Creek. From background concentrations of ≤0.001 mg/L at EK-30, Zn rose to peaks of 0.044, 0.062, and 0.084 mg/L in June, July, and August, respectively. The higher end of this range is over double the Zn toxicity threshold, competing with Cu for the title as the most significant constituent of concern facing the project. Like other constituents mentioned above, the greatest increases occurred in proximity to the settling pond seeps, waste rock pile, and Elkhorn Mill, respectively. Seasonal patterns show strong correlation between hydrology and Zn, with evident dilution occurring during higher flows.

Table 2. Trace metal and metalloid concentrations for Elkhorn Creek from each longitudinal synoptic sampling event. Values represent the daily mean ± standard error (*n* = 14) of all monitoring locations by flow regime. Bold values are in exceedance of acute or chronic toxicity levels for aquatic life.

	Peak Flow	Mid-summer Flow	Base Flow
Date	6/25/2020	7/23/2020	8/20/2020
As (mg/L)	0.002 ± 0.0001	0.0002 ± 0.00001	0.0002 ± 0.00001
Ca (mg/L)	3.87 ± 0.09	5.87 ± 0.09	7.73 ± 0.18
Cu (mg/L)	**0.007 ± 0.001**	**0.009 ± 0.001**	**0.008 ± 0.001**
Pb (mg/L)	0.0002 ± 0.0001	**0.0005 ± 0.0001**	0.0001 ± 0.00001
Mg (mg/L)	0.36 ± 0.007	0.55 ± 0.01	0.73 ± 0.01
Mn (mg/L)	0.016 ± 0.002	0.02 ± 0.002	0.03 ± 0.003
Ag (mg/L)	0.00004 ± 0.00001	0.0001 ± 0.00001	-
Zn (mg/L)	0.03 ± 0.003	**0.05 ± 0.004**	**0.07 ± 0.006**

Total Aqueous Metals

This study summed the concentrations of As, Cu, Pb, Mn, Ag, and Zn to represent total aqueous metals, and grouped data by monitoring location and date. Using total metal concentration and coordinate data, spatial and temporal patterns of metal concentration in Elkhorn Creek can be summarized by its proximity to the adit settling ponds, waste rock pile, and Elkhorn Mill (Figures 13, 14, & 15). In general, total aqueous metal concentrations increase with lower flows and demonstrate discrete zones of contaminant inputs to Elkhorn Creek. On June 25, total metals increased near the adit settling pond seeps and waste rock pile but were <0.06 mg/L until approaching the Elkhorn Mill, highlighting the influences of Mill-area overland runoff (Figure 13). By July 23, the enhanced influence of waste rock pile-associated inputs – either through reduced dilution or delayed groundwater flows – begins to bring total metals in Elkhorn Creek up to 0.1 mg/L (Figure 14). On August 20, total metals exceeded 0.06 mg/L immediately following the adit pond seeps, climbed to 0.1 mg/L near the waste rock pile, and peaked at Elkhorn Mill (Figure 15). These patterns illustrate the temporal and spatial shift in the relative influence that each area has on Elkhorn Creek constituent concentrations.

3.2.4 Net Groundwater Exchange

Net Groundwater exchange was determined as the difference in discharge between each individual monitoring location and the next upstream location. This method assumes net changes of in-stream discharge are the result of *groundwater exchange* but inherently includes inputs from *overland runoff* as well. As a result, groundwater exchange rates were not available for EK-30, as that was the most upstream monitoring location. Overall, groundwater exchange became muted with decreasing flows but frequently flipped between positive (groundwater inputs to Elkhorn Creek) and negative (groundwater recharge) values in lower reaches (Figure 16). During peak runoff, groundwater inputs to Elkhorn Creek were approximately 30-40 L/sec (~1-2 cfs) near the settling pond seeps, below the diversion ditch, and near Elkhorn Mill. As flows receded, groundwater exchange at the downstream locations declined in contrast to the settling pond seeps, which exceeded 105 L/sec (~3.7 cfs) at base flow. Marked declines in groundwater exchange – to the point of groundwater recharge – occurred sporadically and did not follow clear seasonal trends with respect to monitoring locations. On average, groundwater inputs were positive at EK-26, EK-25, and EK-22, suggesting consistent inputs downstream of the settling pond seeps, waste rock pile, and diversion ditch. Detection of small changes in groundwater exchange may be confounded by differences in channel bed roughness, slope, cross-sectional area, and grain size between upstream (boulder-cobble) and downstream (sand-gravel) reaches.

3.2.5 Trace Metals Loads

Being the only constituents in exceedance of water quality standards, this study focused on assessing trace metal loads for Cu, Pb, and Zn by season and location to better understand mechanisms of constituent delivery to Elkhorn Creek. In addition, cumulative loading rates for all constituents during the study period are presented in Table 3 to illustrate the mass of contaminants originating from the Elkhorn Mine & Mill.

Copper Loads

Flow regime appeared to directly control Cu loading rates to Elkhorn Creek (Figure 17), with greater loads associated with higher flows. Loads during peak flow were nearly 15 mg/sec at EK-17 compared to virtually zero at EK-30. Similarly, mid-summer loads rose from virtually zero at EK-28 to 2.9 mg/sec at EK-16. At base flow, background Cu loads of 0.03 mg/sec (EK-30) increased longitudinally to over 1.2 mg/sec by EK-18. Overall, the greatest changes in load – totaling 8.33, 4.38, and 4.29 mg/sec – occurred during peak flow at EK-17, EK-26, EK-25, respectively. This indicates the Elkhorn Mill alone contributes as much Cu during overland runoff events as both the adit settling pond and waste rock pile areas combined. At mid-summer and base flows, the greatest load changes were associated with EK-26, suggesting that proportional inputs from the settling pond seeps and waste rock pile increase with decreasing flows. On June 25, the diversion ditch siphoned up to 30% of Cu loads from Elkhorn Creek, in contrast to the negligible influence it exerted on July 23 and August 20 resulting from low flows. On average, the total change in load was greatest at Elkhorn Mill during runoff, but not as consistent as the inputs from settling pond seeps and the waste rock pile (Figure 18).

Lead Loads

Lead dynamics appeared to be controlled by overland runoff from Elkhorn Mill and possible groundwater inputs from the waste rock pile. Elkhorn Creek Pb loads were virtually zero at EK-30 and EK-28 on all flows, but contributions from the Elkhorn Mine & Mill resulted in measurable increases on all sampling dates (Figure 19). Evidence of Pb loading to Elkhorn Creek from Elkhorn Mill and the waste rock pile was observed during peak and mid-summer flows, respectively. On June 25, Pb loads increased from 0.05 mg/sec at EK-26 to 0.6 mg/sec at EK-16, exhibiting substantial increases at EK-23, EK-19, and EK-17.

Lead loads at EK-23 were greatest on July 23, however, while Elkhorn Mill contributions were lower. The substantially higher Pb loading rates seen at EK-23 on July 23, even after considering potential diversion ditch withdrawals, may suggest hydrologic lag time in delivery of groundwater-associated contaminants from the waste rock pile. The subsequent decline in EK-23 Pb loads by August 20, in combination with the comparably low Pb loads near Elkhorn Mill on both July 23 and August 20, gives evidence to support this claim. Pb loads were low at all monitoring locations during base flow with a maximum of 0.021 mg/sec at EK-22. Generally, the greatest Pb loads originated from EK-23 and EK-17 regardless of flow regimes (Figure 20).

Zinc Loads

As with Cu, Zn loads were heavily influenced by flow regime and displayed clear seasonality as a result (Figure 21). During peak flow, the undetectable Zn loads at EK-30 rose to 38.77 mg/sec by EK-25, subsided slightly through the restored reach, and peaked once more at 38.62 mg/sec at EK-17. This pattern was repeated during mid-summer and base flows, although of lesser magnitude. On July 23, Zn loads rose considerably from below detection at EK-30 to 13.69 mg/sec at EK-25, peaked at 14.39 mg/sec at EK-21, and declined slightly through EK-16. By August 20, Zn was detectable at EK-30 (0.10 mg/sec), continued to display large increases through EK-25 (9.41 mg/sec) and EK-23 (9.84 mg/sec), and declined slightly through the restored reach (8.26 mg/sec at EK-16). The patterns clearly indicate Zn loading near the adit settling ponds, waste rock pile, and Elkhorn Mill, with differences in magnitude relating to overland runoff and groundwater inputs (Figure 22).

Total Maximum Daily Load

This study compared high (June 25) and low (August 20) flow constituent load data taken from EK-17 to Total Maximum Daily Load (TMDL) restrictions and allowances published for Elkhorn Creek and Elkhorn Mine (DEQ 2009). Overall, Elkhorn Creek is in exceedance of TMDL allowances for Cu, Pb, and Zn at various flows (Table 3). Arsenic remained in compliance at both flow regimes. Copper loads were in exceedance at both high (2.15 lb/day) and low (0.15 lb/day) flows. Lead was in exceedance at high flows (0.062 lb/day) but below the threshold at low flows. In contrast, Zn was within compliance during high flows but exceeded TMDL allowances by 0.51 lb/day at low flows.

Table 3. Trace metal and metalloid measured loads, TMDL Allowance, and TMDL Exceedance for Elkhorn Creek (EK-16) at high and low flow conditions. Exceedance is calculated as Measured Load – WLA Allowance Load (DEQ 2009). Measured loads in mg/sec were divided by 5.24991 to convert to lb/day. Bold values represent those that are in exceedance of TMDL restrictions.

Flow Conditions	As	Cu	Pb	Zn
Measured Load (lb/day)				
High Flow	0.050	2.843	0.100	7.357
Low Flow	0.004	0.221	0.002	1.527
TMDL Allowance (lb/day)				
High Flow	3.551	0.695	0.038	10.350
Low Flow	0.350	0.068	0.004	1.020
TMDL Exceedance (lb/day)				
High Flow	-3.501	**2.148**	**0.062**	-2.993
Low Flow	-0.346	**0.153**	-0.002	**0.507**

3.3 AMD Water Quality

The following sections provide water quality results and brief interpretations related to acid mine drainage (AMD) at three monitoring locations: a drainage swale located below the Elkhorn Mill (AMD-01), the 1000'-level adit at the Elkhorn Mine (AMD-02), and a bank spring/seep located just downstream of EK-27 near the settling ponds (AMD-03).

3.3.1 Elkhorn Mill: AMD-01

Acid mine drainage discharging from several intermittent seeps and springs surrounding Elkhorn Mill converge in a drainage swale and ponded silt-fence barrier prior to discharge to Elkhorn Creek (Figure 1). To better represent collective runoff and minimize the influence of physical settling or chemical and biological processes, characterization of AMD from Elkhorn Mill was performed in the drainage swale just upstream of the ponded silt-fence barrier (AMD-01). The location of AMD-01 was selected as it lies at the outflow of the drainage swale which acts to concentrate runoff from the Elkhorn Mill. It may represent some of the runoff from the historic assay building but does not capture all the runoff from both areas.

Elkhorn Mill AMD Discharge

Acid mine drainage from AMD-01 is heavily influenced by runoff from the upgradient Mill and assay house, as evidenced by visual observations and measurements of flow. Discharge at AMD-01 was measured at 2.27 L/sec (0.08 cfs) on June 25 and 1.42 L/sec (0.05 cfs) on July 23; by August 20, the swale had run dry. While these measurements reflect surface flow AMD emanating from much of the Elkhorn Mill area, the in-stream hydrologic mass-balance approach described above provides evidence for substantial AMD inputs to Elkhorn Creek via subsurface flowpaths as well (Figure 16). On June 25, groundwater inputs to Elkhorn Creek from the Mill area (EK-19) were estimated to be 48.14 L/sec (1.7 cfs) – dwarfing the surface flow inputs from AMD-01. Later in the summer, groundwater exchange in proximity to the Mill trended toward negative values, suggesting the restored reach alongside Elkhorn Mill shifts from a gaining to a losing stream as the hydrograph recedes. As a result, AMD from Elkhorn Mill is greatest during spring runoff, but may continue through mid-summer as groundwater slowly flows toward Elkhorn Creek.

Elkhorn Mill AMD Water Quality

Based on several field parameters and trace metal and metalloid analytes, water quality at AMD-01 was poor on both sampling events (Table 4 & 5). Due to the slow, shallow surface flow at AMD-01, temperatures were high (13.1 and 18.9 °C) and dissolved oxygen was low (8.43 and 7.29 mg/L) compared to Elkhorn Creek. In addition, pH was quite low (4.27 and 4.21). Specific conductivity at AMD-01 dropped by more than 50% between June 25 and July 23, from 225.3 to 110 µS/cm. High specific conductivity, coupled with low pH, suggest residual mine tailings and processing wastes in the Elkhorn Mill area continue to degrade water quality.

Table 4. Field parameter readings and hardness concentration for AMD-01 near Elkhorn Mill.

Site	Location	Date	Temp (°C)	DO (mg/L)	DO (%)	Sp. Cond (µS/cm)	pH	Hardness (mg/L)
AMD-01	Elkhorn Mill	6/25/2020	13.1	8.43	104.9	225.3	4.27	65.0
AMD-01	Elkhorn Mill	7/23/2020	18.9	7.29	102.0	110.0	4.21	64.0

Water quality at AMD-01 was most poorly affected by elevated Cu, Pb, Mn, Ag, and Zn concentrations, which remained relatively stable across sampling dates (Table 5). Copper was 1.92 and 1.99 mg/L on June 25 and July 23, respectively. These readings were over three orders of magnitude greater than the aquatic life acute (0.0073 mg/L) and chronic (0.0052) toxicity levels for the measured hardness. Copper concentrations were also in exceedance of the human health standard of 1.3 mg/L. On both occasions, Pb was in exceedance of acute (0.034 mg/L) and chronic (0.0013 mg/L) toxicity thresholds for aquatic life and greatly exceed the human health standard of 0.015 mg/L. Lead increased from 0.096 mg/L on June 25 to 0.12 mg/L on July 23. Manganese concentrations at AMD-01 were relatively similar between June (0.58 mg/L) and July sampling events (0.64 mg/L), but were over five-times higher than the recommended toxicity threshold of 0.1 mg/L. Silver was detected on both June 25 (0.0003 mg/L) and July 23 (0.0005 mg/L), but did not exceed the acute toxicity threshold (0.00132 mg/L) due to the high hardness (64-65 mg/L) of AMD discharge. Zinc at AMD-01 was the highest detected in the entire study: concentrations of 2.25 mg/L (June 25) and 2.32 mg/L (July 23) were two orders of magnitude greater than the acute and chronic toxicity threshold (0.067 mg/L). Zinc concentrations did not exceed the human health standard of 7.4 mg/L.

Table 5. Trace metal and metalloid concentrations for AMD-01 near Elkhorn Mill.

Site	Location	Date	As (mg/L)	Ca (mg/L)	Cu (mg/L)	Pb (mg/L)	Mg (mg/L)	Mn (mg/L)	Ag (mg/L)	Zn (mg/L)
AMD-01	Elkhorn Mill	6/25/2020	0.001	22.0	1.92	0.0959	2.0	0.578	0.0003	2.25
AMD-01	Elkhorn Mill	7/23/2020	0.002	22.0	1.99	0.121	2.0	0.642	0.0005	2.32

Instantaneous trace metal and metalloid loads at AMD-01 for June 25 and July 23 were integrated to estimate the total material load delivered between the two sampling dates (Table 6). Over the course of 28 days following spring runoff, this approach determined AMD-01 delivered 0.0062 kg of As, 8.66 kg of Cu, 0.47 kg of Pb, 2.68 kg of Mn, 0.0017 kg of Ag, and 10.13 kg of Zn to Elkhorn Creek.

Table 6. Estimations of total material load for select constituents delivered from the Elkhorn Mill (AMD-02) between June 25 and July 23. Total load calculations are based on integrations of empirical measurements of instantaneous constituent loads taken during the study period.

Total Load	As	Cu	Pb	Mn	Ag	Zn
kg	0.0062	8.66	0.47	2.68	0.002	10.13
lb	0.014	19.09	1.04	5.91	0.004	22.33

3.3.2 Elkhorn Mine: AMD-02

Acid mine drainage discharging from the 1000'-level adit at Elkhorn Mine (AMD-02) was conveyed through a flume and monitored with a water level logger to track continuous discharge during the study period. To represent AMD as it exited the adit portal and prior to flowing over the landscape, field parameter measurements and water samples for AMD-02 were taken immediately upstream of the flume. The location of AMD-02 was chosen because it sits approximately 25' outside the adit portal gate where flows are relatively channelized.

Elkhorn Mine Continuous Discharge

Acid mine drainage from AMD-02 is driven by groundwater infiltration to and discharge from the underground mine workings. Between June 24 and August 20, discharge at AMD-02 ranged from 6.48 to 11.59 L/sec (0.23 to 0.41 cfs; 102.64 to 183.72 gpm), demonstrated measurable diel swings, and generally decreased slightly over time (Figure 23). Daily minimum and maximum flows typically occurred in the late afternoon (15:00 – 18:00) and early morning (04:00 – 07:00), respectively. While time-series analyses might elaborate on the character of diel variation, overall, the flows were relatively consistent over time and closely matched measurements from USFS and Montana Tech researchers taken in 1998, 1999, and 2009. Consistent flows at AMD-02 across 20+ years of study suggest AMD discharge is at dynamic equilibrium with slight variations driven in part by snowmelt and peak runoff.

Elkhorn Mine Water Quality

Water quality at AMD-02 was fair with respect to field parameter readings, but poor overall due to high trace metal and metalloid concentrations. Field parameters were relatively stable during the study period: water temperature averaged 5.6 ± 0.12°C; dissolved oxygen averaged 9.61 ± 0.12 mg/L and 99.47 ± 1.28 %; specific conductivity averaged 216.5 ± 17.3 µS/cm; pH averaged 6.5 ± 0.13 (Table 7). Stable temperatures were anticipated due to the thermal regulation of groundwater in underground mine workings. High specific conductivity was also expected due to greater solubility of ions present in mine workings than Elkhorn Creek substrates. The relatively neutral pH and oxygen-saturated conditions were unexpected and may reflect rapid oxygenation of AMD as it exits the portal and equilibrates to atmospheric conditions. Evidence of this can be found in the thick Fe precipitates and redoximorphic features carpeting the adit floor.

Table 7. Field parameter readings and hardness concentrations for AMD-02 at Elkhorn Mine.

Site	Location	Date	Temp (°C)	DO (mg/L)	DO (%)	Sp. Cond (µS/cm)	pH	Hardness (mg/L)
AMD-02	Elkhorn Mine	6/25/2020	5.4	9.35	96.4	258.3	6.34	94.0
AMD-02	Elkhorn Mine	7/23/2020	5.5	9.84	101.6	201.6	6.35	76.0
AMD-02	Elkhorn Mine	8/20/2020	5.9	9.65	100.4	189.6	6.82	81.0

Like AMD-01, water quality at AMD-02 was poorly affected by elevated Cu, Pb, Mn, and Zn concentrations. Unlike AMD-01, AMD-02 demonstrated clear temporal patterns with respect to trace metal and metalloid concentrations (Table 8). All constituents were found in greater concentration during peak flow and declined substantially over the course of the study. Arsenic remained below acute (0.34 mg/L) and chronic (0.15 mg/L) aquatic life standards but was in exceedance of human health standards (0.01 mg/L) on all dates. Arsenic declined from 0.065 to 0.014 mg/L between June 25 and August 20. Copper concentrations halved over time from 0.31 to 0.14 mg/L, was in exceedance of acute (0.014 mg/L) and chronic (0.0093 mg/L) aquatic life standards on all sampling dates, but did not exceed human health standards (1.3 mg/L). Lead exceeded acute (0.082 mg/L) and chronic (0.0032 mg/L) aquatic life standards on two and three occasions, respectively, and was consistently above human health standards (0.015 mg/) Lead concentrations decreased from 0.18 mg/L on June 25 to 0.023 mg/L on August 20. Maximum Mn concentrations were up to three-times greater at AMD-02 than AMD-01 and were twenty-times higher than the recommended toxicity threshold (0.1 mg/L). Manganese also showed seasonal declines from 2.46 mg/L on June 25 to 1.74 mg/L on August 20. The maximum Zn concentration at AMD-02 (2.24 mg/L) on June 25 was very similar to those measured at AMD-01, although Zn declined to 1.74 mg/L by August 20. Zinc concentrations exceeded aquatic life standards (0.037 mg/L) but remained below human health standards (7.4 mg/L) on all sampling dates. The consistent decline in trace metal and metalloid concentrations following peak discharge in June suggests seasonal hydrologic 'flushing' may be a primary driver of AMD dynamics at Elkhorn Mine.

Table 8. Trace metal and metalloid concentrations for AMD-02 near Elkhorn Mine.

Site	Location	Date	As (mg/L)	Ca (mg/L)	Cu (mg/L)	Pb (mg/L)	Mg (mg/L)	Mn (mg/L)	Ag (mg/L)	Zn (mg/L)
AMD-02	Elkhorn Mine	6/25/2020	0.065	33	0.309	0.178	3	2.46	-	2.24
AMD-02	Elkhorn Mine	7/23/2020	0.036	27	0.245	0.139	2	1.67	-	1.98
AMD-02	Elkhorn Mine	8/20/2020	0.014	29	0.136	0.0226	2	1.74	-	1.66

Instantaneous trace metal and metalloid loads at AMD-02 for June 25, July 23, and August 20 were integrated to estimate the total material load delivered during the study period (Figure 24, 25, 26, & 27). Over the course of 28 days following spring runoff, this approach determined AMD-01 delivered 0.0062 kg of As, 8.66 kg of Cu, 0.47 kg of Pb, 2.68 kg of Mn, 0.0017 kg of Ag, and 10.13 kg of Zn to Elkhorn Creek (Table 9).

Table 9. Estimations of total load for select constituents delivered from the Elkhorn Mine (AMD-02) during the study period. Total load calculations are based on integrations of empirical measurements of instantaneous constituent loads taken during the study period.

Total Load	As	Cu	Pb	Mn	Ag	Zn
kg	1.7	10.8	5.8	79.4	-	88.2
lb	3.7	23.7	12.7	175.2	-	194.6

3.3.3 Bank Seeps: AMD-03

Due to the drying up of AMD-01 by August 20, a replacement monitoring location was included to attempt to characterize shallow groundwater inputs to Elkhorn Creek downgradient of Elkhorn Mine (AMD-02). This additional AMD monitoring location (AMD-03) was positioned 500 feet downgradient of AMD-02, in the vicinity of EK-27 (no coordinate data available), to represent left bank seep/spring inputs to Elkhorn Creek from the nearby adit settling ponds and waste rock pile. This opportunistic monitoring location was ungaugable, thus, AMD discharge rates are not available. However, field parameter and constituent concentration data help to characterize AMD after it has flowed from the Elkhorn Mine, through forest and wetland features, and into Elkhorn Creek. It is worth noting that the selection the seep for AMD-03 was arbitrarily chosen, as there were numerous visible seeps and springs along this section of Elkhorn Creek.

AMD-03 Water Quality

Field parameter data showed signals of groundwater influences for temperature, dissolved oxygen, and specific conductivity (Table 10). On August 20, water temperature at AMD-03 was only slightly higher than AMD-02 but substantially lower than Elkhorn Creek, suggesting thermal regulation in groundwater flowpaths. Dissolved oxygen concentration (7.0 mg/L) and percent saturation (77.0%) were also low compared to surface waters and other AMD sources, illustrating oxygen depletion in groundwater flowpaths. However, dissolved oxygen levels were not characteristic of pure groundwater, perhaps due to aeration of AMD-03 prior to discharge to Elkhorn Creek. Specific conductivity (229.0 µS/cm) at AMD-03 was elevated compared to readings taken from AMD-02 on the same day (189.6 µS/cm). The accumulation of dissolved ions along groundwater flowpaths between AMD-02 and AMD-03 indicate an abundance of soluble minerals residing in the vicinity of the adit settling ponds and waste rock pile. In addition, there was a measurable decline in pH between AMD-02 (6.82) and AMD-03 (6.61).

Table 10. Field parameter readings for AMD-03 near Elkhorn Creek.

Site	Location	Date	Temp (°C)	DO (mg/L)	DO (%)	Sp. Cond (µS/cm)	pH	Hardness (mg/L)
AMD-03	Bank seep	8/20/2020	7.0	7.2	77.0	229.0	6.61	86.0

Constituent concentrations at AMD-03 were elevated compared to Elkhorn Creek levels, but not as high as other AMD sources (Table 11). Arsenic concentration at AMD-03 (0.0002 mg/L) was 70-times lower than AMD-02 and comparable to levels found in Elkhorn Creek. Calcium at AMD-03 was identical to AMD-02, suggesting conservative transport of this ion through surface and groundwater flowpaths. Copper concentration at AMD-03 (0.034 mg/L) was one-quarter of the level measured at AMD-02 (0.14 mg/L). Less than 1% of the Pb concentration measured at AMD-02 (0.023 mg/L) was detected at AMD-03 (0.0002 mg/L). Zinc was found to be have more than halved between the two monitoring stations, from 1.66 mg/L at AMD-02 to 0.695 at AMD-03. Concentrations of As, Cu, Pb, and Zn at AMD-03 were below the human health standards for surface waters. However, aquatic life standards were exceeded for Cu (acute & chronic) and Zn.

Table 11. Trace metal, metalloid, and hardness concentrations for AMD-03 near Elkhorn Creek.

Site	Location	Date	As (mg/L)	Ca (mg/L)	Cu (mg/L)	Pb (mg/L)	Mg (mg/L)	Mn (mg/L)	Ag (mg/L)	Zn (mg/L)
AMD-03	Bank seep	2020-08-20	0.0002	29.0	0.034	0.00017	3.0	0.014	-	0.695

While these data are limited in their ability to accurately quantify changes in water quality as AMD flows from Elkhorn Mine to Elkhorn Creek, they suggest potential explanations for the observed differences. First, uncontaminated groundwater may be mixing with AMD prior to discharge to Elkhorn Creek, resulting in a dilution effect. While this phenomenon is most certainly occurring to some degree, it is unlikely to play a major role since the concentration of the most conservative solute, Ca, did not change between AMD-02 and AMD-03. Since groundwater dominates base flow, and the background base flow concentration of Ca in Elkhorn Creek is only 6 mg/L, a significant change in Ca concentration would be expected at AMD-03 if uncontaminated groundwater were causing a dilution effect.

Another explanation for the large decrease in constituent concentrations between AMD-02 and AMD-03 may be related to physical, chemical, and biological retention along various surface and groundwater flow paths. Sorption, precipitation, and biological sequestration are known retention mechanisms at AMD sites. Discharge from AMD-02 flows diffusely through a mature forest and wetland complex prior to reaching Elkhorn Creek, and thus, may be subject to a range of conditions that promote contaminant retention. Further research is needed to determine the validity of these claims and evaluate the potential to incorporate in-line treatment strategies to mitigate contaminant loading from Elkhorn Mine to Elkhorn Creek.

3.4 Hydrologic Routing

Field assessments in June 2020 identified a large spring draining onto the waste rock pile that originates far upgradient along a geomorphic feature resembling a lateral moraine. The hydrologic routing analysis conducted for the Elkhorn Creek drainage in the vicinity of Elkhorn Mine & Mill identified clear drainage patterns and runoff flowpaths, many of which converge along this lateral moraine feature (Figure 28). This analysis confirmed field observations and identified this phenomenon as a potentially significant driver of runoff and groundwater dynamics in the vicinity of the waste rock pile. In effect, this feature acts to collect large quantities of runoff from vast upgradient areas and conveys it directly to the waste rock pile. Most of this runoff is channeled into the stormwater control measure (see Figures 1, 13-15), but portions of this runoff may slowly percolate through the waste rock pile. This delayed infiltration might explain the observed lag time for peak As and Pb concentrations in Elkhorn Creek below the waste rock pile, which occurred several weeks after peak runoff. In addition, this analysis identified several important flow paths upgradient of the Elkhorn Mill and the Elkhorn Mine that can be targeted for management to reduce runoff and groundwater infiltration in those areas.

3.5 Map Georeferencing

PDF copies of the georeferenced historical maps illustrate the type of information and extent of mine surveys preformed in the Elkhorn – Park Mine Complex between 1914 and 1973. A map of the Park Mine area from 1973 accurately captures many topographic and planimetric features visible on the raster DEM and also includes several patented claim boundaries (Figure 29; 33801-1973.tif). This survey map was one of the most modern and detailed but appears to capture only surficial mine workings. Due to this map’s comparability to the raster DEM and extremely low average residual error (<1 horizontal foot), the older maps were often georeferenced to the 1973 map when other options were unavailable. Two combined topographic survey maps ca. 1970 captured surface features, tailings piles, and infrastructure across the Elkhorn Mine & Mill and Elkhorn Creek areas (Figure 30; 02813_09257.tif). A map lacking a date stamp and composed of several individual maps combined showed many patented claim boundaries across the Elkhorn – Park Mine Complex (Figure 31; Elkhorn_nodate.tif). Two planimetric survey maps from 1916 captured underground workings from the 1,000’-level adit and select patented mine claims in the vicinity of Elkhorn Mine (Figure 32, 09260-1916.tif & 16388-1916.tif). One map without a date stamp captures select veins as well as many patented mine claims across both the Elkhorn and Park mines (Figure 33; 16606.tif). A map from 1914 illustrates the patented claims owned or controlled by the Boston Montana Co but provides little additional information or reliable georeferencing points (Figure 34; BostonMontanaCo-1914.tif). The above georeferenced maps are ready to be digitized and coupled with the LiDAR DEM to develop a 3D model of above- and belowground workings, veins, and other geologic features.

3.6 Analysis of Geophysical Alternatives

This alternatives analysis identified several potential investigations to address the questions provided in Section 2.5. Two geophysical consulting firms were approached, virtually oriented to the project, offered data and information on current conditions, and solicited for a proposal. Ultimately, only one firm submitted a complete scope of work and fee estimation. However, the second firm provided helpful information through several virtual discussions that allowed this analysis to consider and reject potential investigative approaches due to methodological constraints.

Alternative 1 – No Action

This option concludes that geophysical investigations are neither economically nor practically feasible and therefore will not be undertaken. The *No Action* option does not preclude additional georeferencing of historical mine survey maps or the development of a 3D model to better characterize underground workings. This option does not provide needed data or information on groundwater dynamics, geologic faults, the current state of underground workings, or the interaction between the

Elkhorn and Park mine drainages. It imparts no adverse effects to human health, environmental quality, cultural resources, or public safety.

Alternative 2 – Electromagnetic, Seismic, & Resistivity Surveys

This option focuses on using magnetic and seismic surveys to map infrastructure, geologic features, underground voids, and groundwater presence. According to *GeoLex Inc* of Helena, MT, "electromagnetics are quick and useful for near surface exploration [while] resistivity and seismic surveys can provide profiles and 3D data to several hundred meters" (GeoLex, 2019). An electromagnetic approach requires a magnetic total field survey and artificially charging the earth to create a temporary magnetic field that can be remeasured as the charge decays. In contrast, seismic surveys use primary wave velocities to determine depth to bedrock and density characteristics of the subsurface. This is done by generating seismic signals and measuring the resulting waves with geophones. Similarly, resistivity surveys introduce a signal to the earth – in the form of an electrical current – and the voltage of the current is measured at different distances to provide local resistivity readings. All methods impart no adverse effects to human health, environmental quality, cultural resources, or public safety.

These methods are widely used and often coupled to map underground voids, utilities, unexploded ordinances, groundwater presence, depth to bedrock, and various geologic faults and features. However, after consultation with geologists and geophysicists at *GeoLex Inc.*, it was determined these methodologies are limited in their applicability to this project due to several important constraints. The greatest constraint is the average depth to underground workings (> 1,000 ft) and their presence in bedrock, which greatly reduces the efficacy of electromagnetic, seismic, and resistivity surveys at this scale. Additional constraints include the large extent of the area of interest (> 1,000 acres), the likely presence of large iron deposits, rough terrain, limited access, and cost. As a result, confidence with the approach was low and deliverables were not guaranteed to provide useful data or information if applied to the waste rock pile or underground workings. Instead, these methods could be used to characterize shallow groundwater, buried infrastructure/cultural resources, and depth to bedrock in the vicinity of the Elkhorn Mill at an estimated cost of $30,000.

Alternative 3 – Willowstick™ Survey

This option was developed as a site-specific investigation for the 1,000' adit and the waste rock pile at the entrance to the Elkhorn Mine. The Willowstick LLC methodology is built upon several scientific principles. First, subsurface water migrating through earthen materials increases the electrical conductance of the earthen materials by many orders of magnitude. Second, any artificial electrical circuit establishes a magnetic field that emanates from the electric current. Third, the electric current flows preferentially through groundwater flowpaths or the path of least resistance to complete a circuit between strategically placed electrodes. Fourth, magnetic field intensity can be measured to determine zones of highest conductivity or transport porosity of groundwater. Using these guiding principles, *Willowstick™* surveys introduce electric currents to groundwater systems and measure the resulting magnetic fields, which are most intense along groundwater flowpaths (Figure 35). This approach then uses 3D inversion modeling and compares the measured magnetic fields with expected electrically homogeneous magnetic fields of the subsurface environment (Willowstick, 2021). Through this approach, deliverables would include 2D and 3D maps of groundwater mounding, flowpaths, and estimation of volumes for the water rock pile (Figure 35). Due to the low-voltage electrical circuits and the ground-based survey methods, this option imparts no adverse effects to human health, environmental quality, cultural resources, or public safety.

Advantages of this investigation alternative is its history of successful employment in many similar groundwater studies and reliable characterization of groundwater flowpaths, mounding, and volumes in settings like those found at the waste rock pile. *Willowstick LLC* estimated the cost of this alternative at

$40,000, including direct costs, project management/administration, 5-7 days of field work, and 2 weeks of office work. An additional site visit task item of $20,000 was estimated to provide field reconnaissance and historical research in preparation of field surveys. This alternative is best suited to site-specific issues relating to shallow groundwater dynamics over similar areas and at similar depths to the waste rock pile. Disadvantages of this approach include its high cost-per-acre and the limited footprint of the survey due to logistical constraints. Limitations to this approach center on the difficulty of laying out the electrical cable over the required length, the resolution of survey data points (max. 5-10m) and isolating the waste rock pile groundwater dynamics from those of the 1,000’ adit and underground workings.

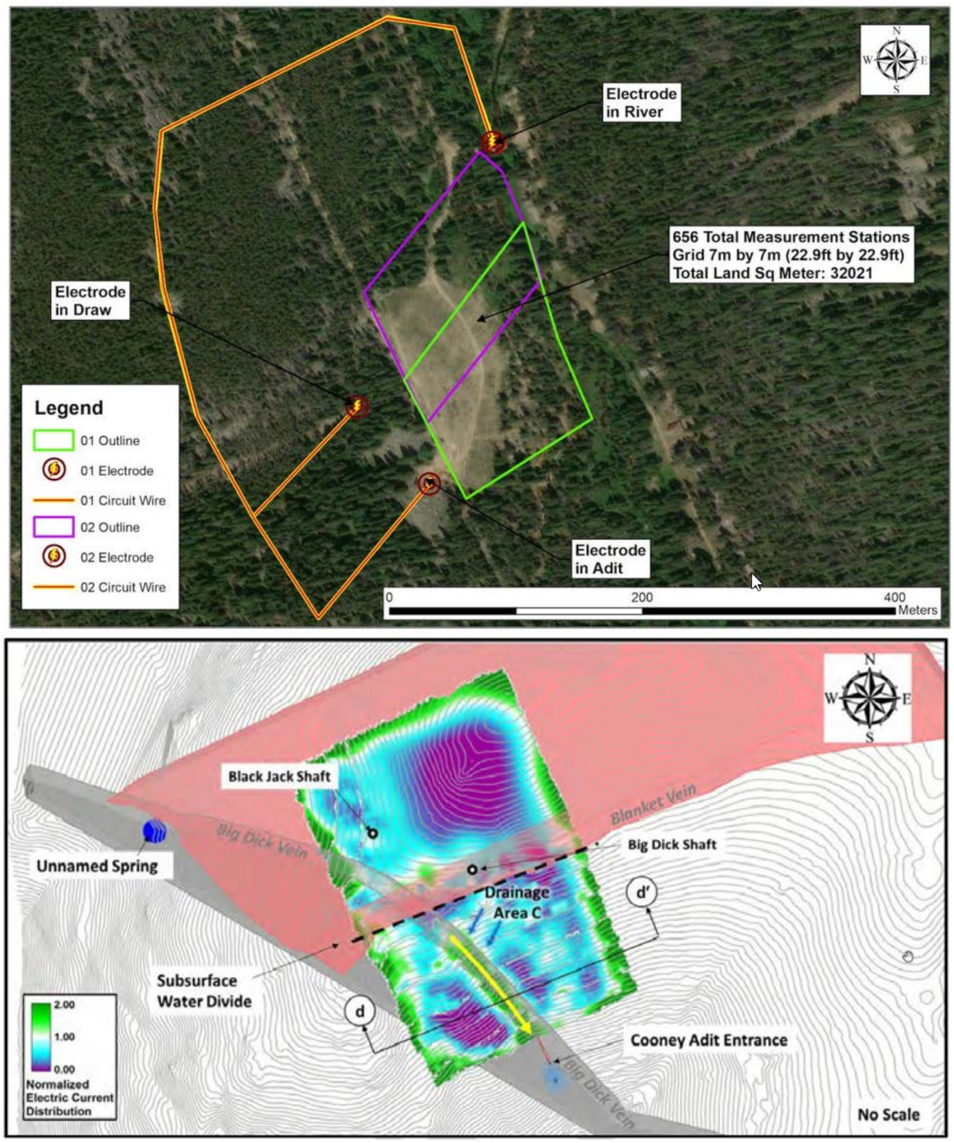

Figure 35. Proposed Elkhorn waste rock pile Willowstick™ survey layout and circuit wire configuration (top) and the model results showing groundwater dynamics (bottom).

Alternative 4 – Rapid Acoustic Profiling Passive Seismic Surveys & Radiometric Gamma Ray Scintillation Counting

This alternative builds on the willowstick™ survey of the waste rock pile by investigating the underground workings and groundwater dynamics of the Elkhorn and Park mines. This method includes both rapid acoustic profiling (RAP) and radiometric gamma ray scintillation counting to characterize geologic features and groundwater. The RAP surveys detect structural weakness in the subsurface and can locate fault and fracture zones with high accuracy to depths of ~2000 feet. With this method, resonances from the natural flexing of earth's crust are measured and interpreted to identify structural weakness in rocks that allow for the location of fracture zones where groundwater is likely most concentrated and where groundwater preferentially flows through the subsurface. In contrast, radiometric gamma ray surveys measure gamma emissions from subsurface rocks and soils. With this method, gamma signals are attenuated where groundwater occurs in permeable zones beneath the sensor, making it well suited for use in conjunction with the RAP system to locate highly permeable fracture zones with high water content. In practice, this option employs phased ground surveys to map underground features one area at a time, allowing field adjustments to accommodate new information. Together, these techniques produce 2D acoustic profiles showing strengths or weaknesses of the underlying stratigraphy and are used to develop detailed 3D models of underground workings and groundwater (Figure 36). Due to the passive

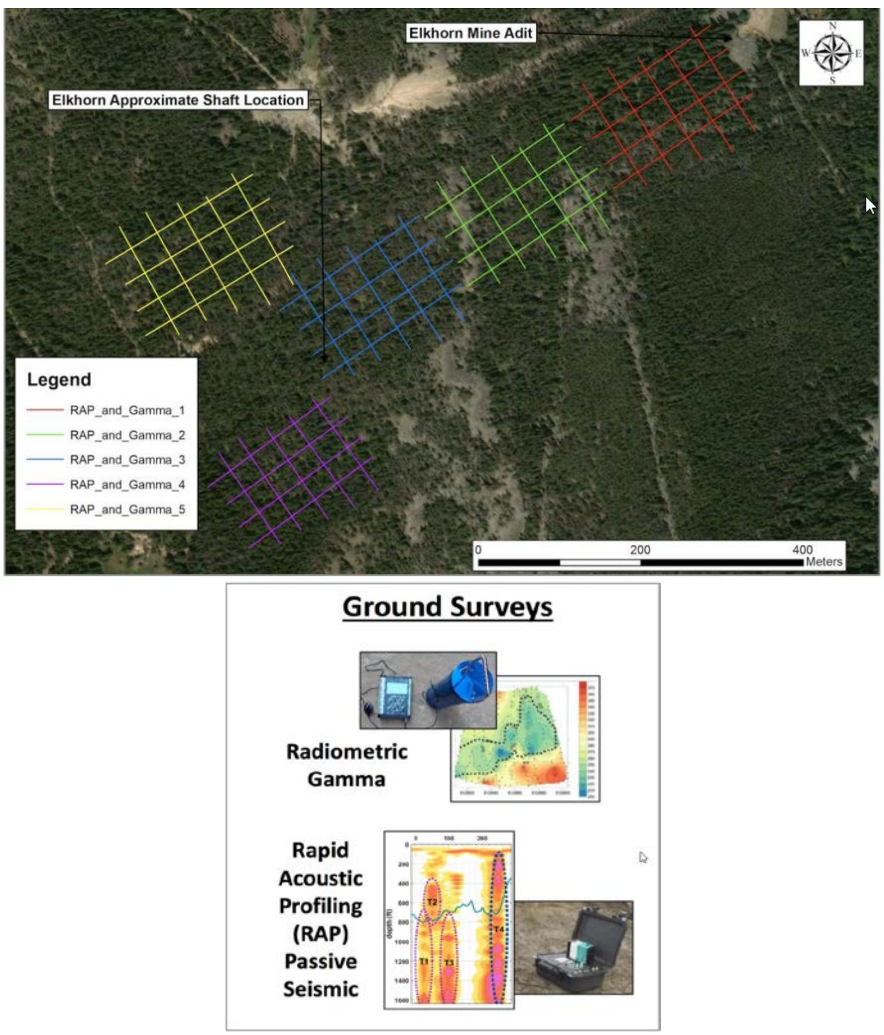

Figure 36. Proposed phased radiometric gamma and rapid acoustic profiling survey areas (top) and example results identifying highly permeable fracture zones and groundwater mounding (bottom).

instrumentation and ground-based survey methods, this option imparts no adverse effects to human health, environmental quality, cultural resources, or public safety.

These coupled surveys were designed and estimated through a phased approach. The first phase would cost $15,000 and would cover the area immediately upgradient of the 1,000' adit to refine field methods and provide preliminary results from which adjustments can be made. A second phase would survey the remaining four areas at a cost of $50,000. Advantages associated with this alternative include its ability to survey the vast expanse of underground workings from the surface in relatively short timeframes and its flexibility for adjusting survey areas and transects in real time. In addition, this approach is the most cost-effective per-acre. Disadvantages of this approach are the coarse resolution of data to characterize the underground workings and groundwater dynamics compared to the Willowstick™ survey.

Alternative 5 – 3D Model to Inform Geophysical Investigation Alternative Selection

This option addresses the information and data gap presently confounding the selection of a suitable geophysical investigation alternative. While eight historical mine survey maps have been georeferenced, there likely exist more that have not been fully assessed and interpreted, particularly relating to the location and condition of underground workings. To select the most suitable geophysical investigation, there must be a foundational understanding of the locations, dimensions, slopes, and geologic character of the underground workings in order to design a survey that will capture the necessary information. This information can be extracted from historical reports and survey maps to generate a 3D model of underground workings as they were constructed. The location and character of the 24,000 feet of workings are poorly understood and may greatly influence the geophysical investigation selection. Thus, this option focuses on continuing the historical research and map georeferencing to develop a 3D model to inform geophysical investigation selection, support field efforts, and provide usable data for analyses. In addition, this alternative can provide useful information regarding drainage patterns that may influence groundwater dynamics in the workings. Due to the office-based exercises and passive field reconnaissance work, this option imparts no adverse effects to human health, environmental quality, cultural resources, or public safety.

Watershed Consulting LLC estimated historical research, map georeferencing, and 3D model development to cost $10,000. Advantages of this alternative include comprehensive collation of available historical reports, maps, and relevant information, development of a usable 3D model for investigation design and analysis, assessment of likely groundwater drainage patterns, and low costs. Disadvantages include the inability of this approach to locate or evaluate actual groundwater dynamics.

Table 12. Summary of geophysical investigation alternatives, their scope, advantages, disadvantages, and costs.

Alternative	Scope	Advantages	Disadvantages	Cost
1. No Action	-	No cost	Does not address issues	$0
2. Electromagnetic, Seismic, & Resistivity Surveys	Elkhorn Mill	Locate shallow groundwater, buried materials & depths to bedrock	Limited to <10m depth	$30,000
3. Willowstick™ Survey	Waste rock pile	Detailed groundwater flowpaths through waste rock pile	Highest cost per acre	$60,000
4. RAP & Gamma Survey	Elkhorn & Park Mines	Comprehensive mapping of underground workings & groundwater	Lowest cost per acre; coarse resolution	$75,000
5. 3D Model	Elkhorn & Park Mines	Build 3D model of underground workings	Does not address groundwater	$10,000

4.0 CONCLUSIONS

The above efforts effectively utilized water quality monitoring and hydrologic modeling to characterize and quantify AMD dynamics, identify discrete zones of contaminant loading, assess acute and chronic toxicity exceedances, measure TMDL performance, and evaluate additional barriers to remediation and restoration of the project area. In addition, it provided georeferenced historical mine survey maps to better understand underground workings and offers several alternatives for geophysical investigation to continue characterizing groundwater and acid mine drainage. This study offers several launching points for more specific investigations to progress planning and design, identifies low-hanging fruit with respect to immediate remediation and restoration solutions, and provides crucial baseline data that will be invaluable for monitoring in years to come.

This study identified three primary areas of concern with respect to contaminant loading to Elkhorn Creek. Depending on flow conditions, the primary contributor of trace metals and metalloids shifted from the Elkhorn Mill, to the waste rock pile, to the seeps downgradient of the 1,000'-level adit settling ponds. At all flows, Cu and Zn loading is greatest near the settling pond seeps, but both constituent loads also spike near Elkhorn Mill during peak runoff. Similarly, Pb loading is greatest at Elkhorn Mill during peak runoff. In contrast to Cu and Zn, Pb and As loads spike immediately downstream of the waste rock pile in the middle of the summer, suggesting potential lag time between groundwater infiltration of the waste rock pile during peak runoff, and eventual discharge during midsummer.

Of the discrete AMD monitoring locations, the poorest water quality was found to originate from the Elkhorn Mill area (AMD-01), although the proportional contributions were greatest at the Elkhorn Mine (AMD-02) due to higher flows. This study also found evidence of substantial reduction of constituent concentration along the flowpaths between AMD-02 and AMD-03, suggesting opportunities for in-line AMD mitigation and treatment. In addition, groundwater-associated AMD appears to play an important role between the adit settling pond seeps and the waste rock pile. While the 1,000'-level adit (AMD-02) discharged approximately 0.3 cfs, hydrologic mass-balance models estimate up to 3.7 cfs of groundwater entered the stream near AMD-03 at base flow. This discrepancy suggests that far more AMD enters Elkhorn Creek via groundwater flowpaths than can be accounted for at the portal of the 1,000'-level adit (AMD-02).

Site characterization efforts also provided useful information for follow-up investigations and restoration planning. For instance, hydrologic routing analyses identified geomorphic features that actively work to collect and convey uncontaminated water through contaminated zones, highlighting potential restoration actions to reduce surface- and groundwater contamination. In addition, the geophysical alternatives analysis was a useful exercise in identifying potential investigations, ruling out unsuitable methods, and identifying data gaps.

Based on the results of this site characterization, a portion of the TMDL exceedances for Cu, Pb, and Zn demonstrate the potential to be mitigated via 'low-hanging fruit' while investigations are still ongoing. In this case, low-hanging fruit are AMD mitigation and treatment solutions that are surficial, low-tech, and provide measurable runoff or constituent load reductions. The following solutions are considered low-hanging fruit:

- Characterize, excavate, and remove residual tailings and contaminated soils from the Elkhorn Mill, assay house, and nearby restored floodplain
- Remediate, regrade, and restore Elkhorn Mill and surrounding area to discourage overland runoff and discharge to Elkhorn Creek

- Regrade hillslope topography to re-direct hydrologic routing and overland flowpaths upgradient of Elkhorn mine, mill, and the waste rock pile to reduce groundwater infiltration and overland runoff through contaminated areas
- Modify and enhance existing stormwater control measure to minimize infiltration and redirect runoff to forested areas further downgradient of the waste rock pile and Elkhorn Creek
- Construct a drainage swale or French drain to capture and direct overland and subsurface runoff from waste rock pile
- Modify and enhance 1,000'-level adit drain system to redirect flows into existing, disconnected settling ponds
- Increase residence time, flow path length, and retention capacity of 1,000'-level adit drain system by constructing additional in-line wetland treatment cells

To aid in the development and execution of low-hanging fruit as well as more technically complex and long-term solutions, further research should be done to better characterize soil contamination, groundwater influences, and in-line wetland treatment systems:

- Utilize low-cost, portable X-ray fluorescence spectroscopy (XRF) to characterize residual tailings and contaminated soils for informed excavation and removal
- Conduct discrete soil sampling across various depth profiles to characterize vertical extent of soil contamination for informed excavation and removal
- Install shallow groundwater wells along Elkhorn Creek near Elkhorn Mill, the waste rock pile, and the adit settling ponds to characterize shallow groundwater conditions, hydraulic conductivity, and flow rates
- Perform a pilot study to evaluate the performance of in-line constructed treatment wetlands for AMD under site-specific conditions

6.0 ACKNOWLEDGEMENTS

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