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Characterization of contaminant hydrogeology, French Creek, Breckenridge, Colorado

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ABSTRACT: Most of the heavy metal loading to French Creek is from the inactive Wellington-Oro (W-O) mine and mill complex. The W-O underground workings consisted of over twelve miles of tunnels, adits, drifts, stopes and crosscuts. Over 80% of these workings are below the elevation of the groundwater table. Surface mine spoils consist of mill tailings, roaster fines, and waste rock piles. The characterization studies indicated: (1) surface mine wastes are not major contributors to metal loading; (2) local percolation and runoff of snow melt is not a significant transport mechanism for metals; (3) metal loading from W-O underground mine water is the major contributor; (4) mine water discharge is limited to a graben fault block area between the Bullhide and 11-10 faults; and (5) most metals are transported to French Creek via groundwater pathways associated with the faults, fractured shale bedrock, mine stoping/workings, and the alluvial aquifer.

1 INTRODUCTION

Acid mine drainage degrades the water quality in French Creek and the Blue River near the town of Breckenridge, Colorado. French Creek originates at the Continental Divide in Summit County and flows west for approximately six miles through the glaciated high mountain French Gulch valley to its confluence with the Blue River. Extensive placer and underground lode mining occurred in the French Gulch valley from the late 1850's to the 1960's. Lode mining was concentrated on the fairly steep valley sides where lead-zinc-silver sulfide ores and rich gold ores were extracted through an extensive network of tunnels and adits that followed mineralized veins associated with contact metamorphosed Jurassic- and Cretaceous-age sediments and Tertiary-age quartz monzonite porphyry bodies (Lovering 1934). Large floating dredge boats were used to placer mine the valley floor for gold from glacial outwash and stream gravel deposits. The historic placer dredging completely disrupted French Creek and its associated alluvial valley material resulting in large dredge tailings piles covering most of the valley floor. The disruption of French Creek caused the stream to have a significant subsurface flow component and an unnatural channel that locally disappears into the dredge piles. The interaction of surface and ground waters in the French Gulch valley with sulfide-bearing rocks, mine workings and surface mine debris produce acid solutions charged with heavy metals that are toxic to organisms. Poor water quality is a major factor contributing to reduced trout populations in the Blue River below the confluence with French Creek. Poor water quality and habitat are responsible for the lack of trout populations in French Creek.

There are several abandoned mine sites in French Gulch. Surface and ground water quality studies conducted by the Colorado Department of Public Health and Environment (CDPHE) and the U.S. Environmental Protection Agency (EPA) since 1989 demonstrated that most of the heavy metal loading to French Creek was from the inactive Wellington-Oro (W-O) mine and mill complex. The W-O was the largest mining operation in the valley. The W-O underground workings consisted of over twelve miles of tunnels, adits, drifts, stopes and crosscuts (Lovering

1934). Over 80 percent of these workings were below the elevation of the groundwater table in the French Gulch valley. The W-O mill processed ore onsite from 1908 to the 1950's. Mill tailings and roaster fines are present and exposed at the ground surface at the W-O site. An unknown quantity of mine waste also remains on site and an unknown quantity of dredge tailings remains in the valley floor.

Surface and ground water flow are potential heavy metal pathways to French Creek from the W-O site. Surface water contamination sources and pathways involve direct runoff of leachate from surface mine spoil piles during rainstorm events and spring snow melt. Groundwater contamination sources and pathways include drainage from the flooded underground mine workings and seepage of leachate from surface mine spoil piles that eventually enter French Creek by groundwater discharge.

2 CHARACTERIZATION STUDIES

During 1996 and 1997, site and regional characterization studies have been conducted by the State of Colorado Division of Minerals and Geology (DMG), U.S. Geological Survey (USGS), EPA, U.S. Bureau of Reclamation (BOR) and American Geological Services, Inc. (AGS). The characterization of contaminant hydrogeology involved surface mine waste studies, mine pool studies, surface and ground water quality studies, continuous groundwater and mine pool water level monitoring, installation of new monitoring wells, aquifer testing, subsurface flow evaluations on selected monitoring wells and the mine pool, stable isotope studies, and salt tracer studies. The objectives of the characterization were to (1) determine the relative contributions of metal loading to French Creek from the various sources, (2) identify metal contaminant pathways and fate, and (3) establish pre-remediation environmental baseline conditions.

2.1 *Water quality*

Major ion chemistry of French Creek above the W-O site has been a calcium bicarbonate type. The calculated dissolved solids concentrations in a July 1996 sampling event was 63 mg/L indicating that French Creek above the W-O mine site is a dilute headwaters stream (USGS 1997). Below the mine site, the July 1996 sampling had calculated dissolved solids that nearly doubled to 124 mg/L and a stream water type that changed to a calcium sulfate bicarbonate. The interaction of surface and ground waters with sulfide bearing rocks in the vicinity of the mine site apparently has released calcium sulfate and metals into the ground and surface waters.

Elevated concentrations of several metals and sulfate in French Creek and ground waters in the vicinity of the W-O site have been documented by studies conducted by the CDPHE (1989), EPA (1992, 1993a, 1993b, 1994, 1996a and 1996b) and the USGS (1997). The metals with the highest concentrations are cadmium (Cd), zinc (Zn), iron (Fe), and manganese (Mn). The Cd and Zn concentrations are the major contributors to fish toxicity in French Creek and the Blue River. These metals commonly exceed State water quality standards. The other metals detected in French Creek are usually below the State standards. The State of Colorado acute and chronic toxicity standards are based on the hardness of the sampled water. In general, the hardness adjusted acute and chronic standards for Zn in French Creek and the Blue River range from 50 to 120 ug/L. The hardness adjusted acute standards for Cd range from 0.7 to 1.1 ug/L while the chronic standards range from 5 to 10 ug/L (WQCC 1995). Because of the currently degraded water quality in the Blue River and French Creek, the State of Colorado Water Quality Control Commission (WQCC) has modified the Zn and Cd chronic standards. The modified French Creek Cd chronic standard is 4 ug/L and the modified Cd chronic Blue River standard is 4.3 ug/L. For zinc, the modified chronic standard for French Creek is 1,980 mg/L while the Blue River modified standard is 1,700 ug/L (WQCC 1995). Except for iron, total recoverable and dissolved metal concentrations are very similar in French Creek and the Blue River. Total recoverable Fe concentrations were usually much higher than dissolved concentrations, especially below the W-O mine site. This difference was probably due to the formation of Fe hydroxides which can be observed as the ochre color (yellowboy) that coats sediments downstream of the mine site.

Dissolved zinc concentrations in French Creek above the W-O site ranged from 10 to 109 ug/L during seven sampling events. Two out of seven sampling events slightly exceeded the State hardness adjusted chronic and acute zinc standards. Below the W-O mine site, the dissolved zinc concentrations in French Creek ranged from 2,127 ug/L to 9,300 ug/L. All of the sampling events exceeded the French Creek modified chronic standard for zinc of 1,980 ug/L and the State chronic and acute standards by orders of magnitude.

Zinc concentrations on the Blue River above the confluence with French Creek ranged from less than 4 ug/L to 60 ug/L during eight samplings events. These dissolved zinc concentrations did not exceed either the chronic or acute State standards. Below the French Creek confluence, the Blue River zinc concentrations ranged from 367 ug/L to 4,200 ug/L. Four out of eight sampling events exceeded the State modified chronic standard of 1,700 ug/L. All of the sampling events exceeded the State hardness adjusted chronic and acute toxicity standards. The lower concentrations in the sampling events were related to dilution from spring and early summer high flow conditions.

Dissolved cadmium concentrations in French Creek above the W-O site and on the Blue River above the confluence with French Creek were usually below laboratory detection limits. Below the W-O mine site, the dissolved French Creek Cd concentrations ranged from 6.3 ug/L to 11.7 ug/L during seven sampling events. All of the sampling events exceeded the French Creek modified State chronic Cd standard of 4 ug/L. The State hardness adjusted chronic standard was also exceeded by orders of magnitude in the sampling events. The State acute Cd standards were only exceeded in the two recent high flow sampling events below the W-O site.

The Blue River sampling site below the French Creek confluence had dissolved Cd concentrations that ranged from 1.1 ug/L to 6.8 ug/L. Four out of eight sampling events exceeded the Blue River modified Cd chronic standard of 4.3 ug/L. All the sampling events exceeded the State hardness adjusted chronic toxicity standards for Cd. None of these sampling events exceeded the State hardness adjusted acute toxicity Cd standards.

Ground and W-O mine pool waters in the vicinity of the mine site have metal and sulfate concentrations much higher than the stream waters. The W-O mine pool water had total recoverable and dissolved Zn concentrations that ranged from 160,000 ug/L to over 216,000 ug/L and Cd concentrations that ranged from 200 ug/L to 657 ug/L. The higher concentrations were from sampling events conducted during spring high flow conditions. The ground waters associated with the saturated portion of roaster fines were the most contaminated waters in the vicinity of the W-O site. Zinc concentrations ranged from 2,750,000 ug/L to 3,400,000 ug/L and Cd concentrations ranged from 8,500 ug/L to 14,500 ug/L.

2.2 *Ground and mine pool water level monitoring*

Water levels for the mine pool, alluvial aquifer and fractured shale bedrock at the W-O mine site were continuously monitored on an hourly basis with an automated datalogging system from July 11, 1996 to May 22, 1997. USGS discharge gage data on French Creek and climatic data from nearby weather and snow survey stations were integrated with the water level data. This characterization study evaluated the hydrologic responses to individual storm and spring snow melt events. This study also assessed the hydrologic connection between the mine pool, groundwater systems, and French Creek.

The similarity of the water level hydrographs for the mine pool, alluvium, and fractured shale bedrock implies that the bedrock and alluvial aquifer at the mine site are acting as one hydraulically connected unit that was communicating with the mine pool (Figure 1). Aquifer tests on the shale bedrock and alluvium also showed that the mine pool, alluvium, and bedrock were hydraulically connected (Morrissey 1995). The higher hydraulic head associated with the mine pool for most of the monitoring period suggests that mine pool water has been flowing into the alluvium and fractured shale bedrock at the mine site. These water level hydrographs were also very similar to the French Creek discharge hydrograph (Figure 1). The initial rise of the mine pool and ground water levels in late March of 1997 appeared to coincide with a major local snow melt event (Figure 2). A larger second rise in water levels in early May of 1997 into June of 1997 appeared to coincide with the snow melt associated with the high elevation French Creek headwaters region. This high elevation snow melt was also driving the significant increase in French Creek discharge. Individual storm events had no effect on the ground and mine pool water levels at the mine site and minor effects on the French Creek hydrograph. A comparison of water levels from an uncontaminated monitoring well that was completed in the 11-10 Fault upgradient from the W-O mine workings, with the mine pool water levels showed very similar elevations. The W-O mine workings cut and stoped along this fault (Lovering 1934). This data implies that the 11-10 Fault was a major conduit for water to the mine pool. During the spring of 1997 there was a rise of twenty feet in the mine pool water levels that was possibly driven by snow melt events.

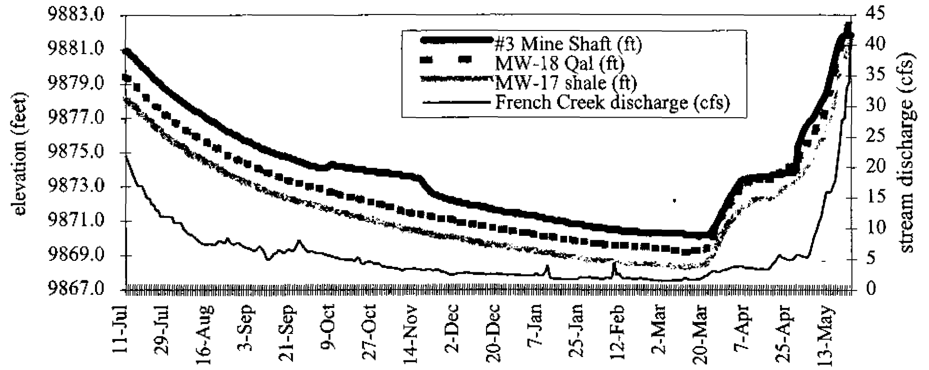

Figure 1. Stream, ground and mine pool water 1996-97 falling and rising limb hydrograph.

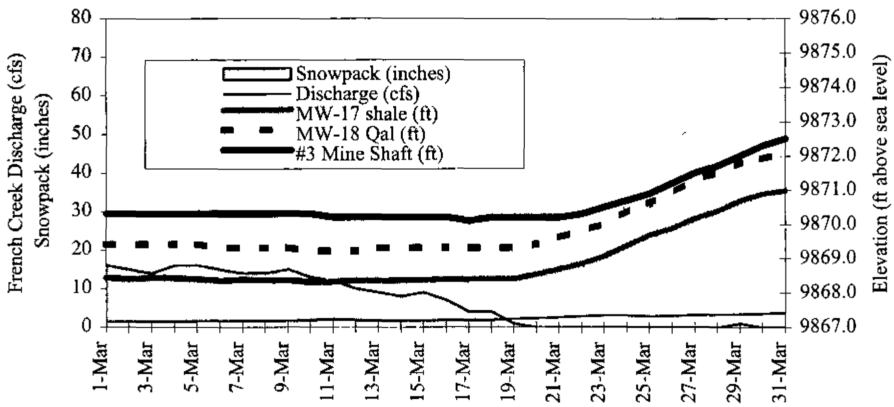

Figure 2. March 1997 hydrographs and local snowpack.

2.3 *Stable isotopes*

Oxygen and hydrogen stable isotope studies were performed in the vicinity of the W-O mine site in 1996 and 1997 for the State of Colorado Division of Minerals and Geology (RAS 1996a and 1996b, 1997b). Stable isotopes have been used as natural tracers because surface and ground waters can have distinctive stable isotopic compositions that are a function of the water molecule's structure. The studies demonstrated that the snow melt waters associated with the local mine site area and high elevation French Creek headwaters region were ^{18}O depleted compared to the mine, surface, and ground waters in French Gulch (Table 1). The oxygen isotopes for the mine, surface, and ground water samples had a limited range of compositions from -19.0‰ to -17.4‰ during both low flow and high flow sampling events (Figure 3 and 4). This limited range has been interpreted to be due to the dominance of groundwater discharge that influences the mine pool, French Creek, and the alluvial aquifer. Although all the waters in French Gulch had similar isotopic compositions, there were two statistically distinct groups; (1) mine water and (2) French Creek/groundwater (Table 1, Figures 3 and 4). The mine water was slightly ^{18}O depleted compared to French Creek and groundwater associated with the alluvial aquifer. This implies that the mine water has had a greater influence from snow melt waters over time and/or less influenced by relatively ^{18}O rich surficial waters. The lack of shifts towards the ^{18}O depleted snow melt for the mine water during the high flow sampling event suggests that the volume of water associated with the spring snow melt events are small compared to the mine pool and groundwater system. The mine pool slightly shifted towards the isotope signature of local groundwater during the high flow sampling event suggesting that groundwater was the major source of recharge water to the mine pool. The isotope signature from water associated with the 11-10 Fault showed the greatest shift in compositions (Figure 5). This is possibly due to surface snow melt waters infiltrating into the fault and also implies that the fault is a major conduit for water. The isotope data indicated that mine water discharge was apparently the major source of metal contamination in monitoring wells between the 11-10 and Bullhide faults. The isotopic signatures of a contaminated alluvial monitoring well and seep downgradient from the Bullhide Fault and the W-O mine site suggested that they were also influenced by mine water.

Table 1. Snow melt, mine pool, French Creek, and ground water oxygen isotope compositions.

Local Snow Melt (‰)	Headwaters Snow Melt (‰)	W-O Mine Pool (‰)	French Creek Groundwater (‰)
-21.6 to -27.2	-19.4 to -22.4	-18.5 to -19.0	-17.4 to -18.2

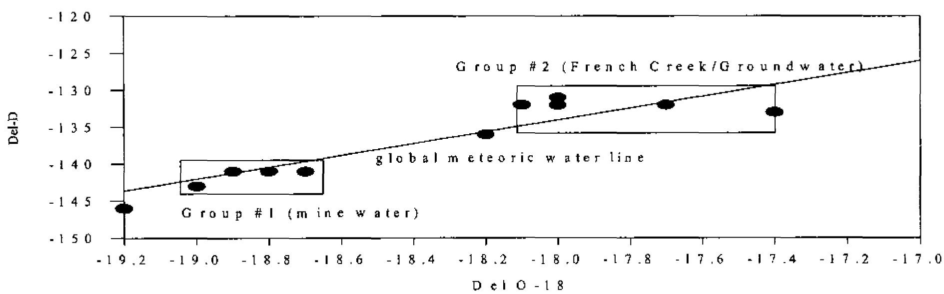

Figure 3. Low flow March 1996 and January 1997 stable isotope results.

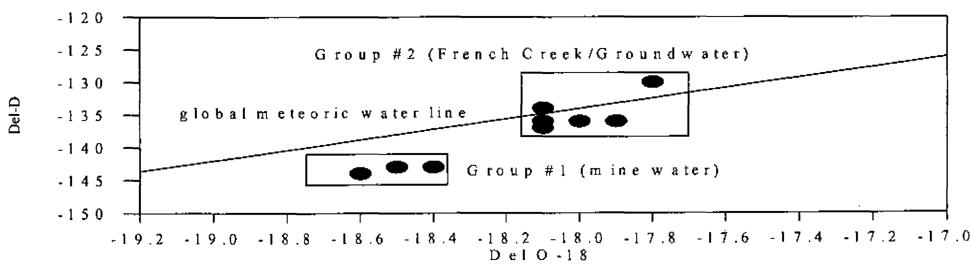

Figure 4. High flow June 1996 stable isotope results.

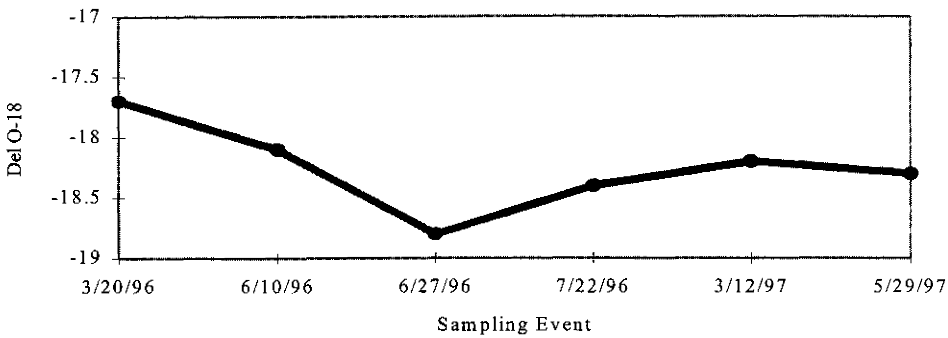

Figure 5.Oxygen stable isotope results 11-10 Fault monitoring well.

2.4 *Salt Tracers*

In July of 1996, the USGS Toxic Substances Hydrology Program conducted stream tracer-dilution, alluvial groundwater tracer, mine pool tracer, and synoptic sampling studies in the vicinity of the W-O mine site (Kimball et al. 1997). This characterization study evaluated the hydrologic flow pathways and stream hydrologic properties using three different salt tracer injections and a synoptic sampling of the stream.

A lithium chloride tracer in the upper portion of the Oro Mine shaft did not show a hydrologic connection between the #3 Mine shaft or the downgradient metal contaminated alluvium and stream. This suggests that the lower mine pool is the primary source of metals to French Creek. The sodium bromide tracer that was injected into an alluvial groundwater well was not detected in the downgradient alluvial monitoring well or in French Creek. It was assumed that the tracer was either attenuated before it reached the monitoring well and stream, or the travel time was too slow for the two month tracer sampling period.

Variations in downstream French Creek metal concentrations were quantified by applying a sodium chloride tracer to the stream. The tracer study was coordinated with a synoptic sampling event of the stream and stream inflows. The instream tracer and synoptic studies were able to identify subreaches of French Creek where the majority of metal loading occurred (Figure 6). Significant inflow of metals was attributed to the 11-10 and Bullhide faults as they crossed French Creek and metal contaminated seeps along French Gulch Road downgradient from the Bullhide Fault and W-O mine site. It was believed that the source of the metal contaminated fault water and seeps was the W-O mine pool.

2.5 *Mine Pool*

In January of 1997, geophysical logging and water sampling of the Oro Mine shaft and selected groundwater monitoring wells in the vicinity of the W-O site were performed for the EPA (RAS 1997a). Geophysical logging involved a Video Log (camera), Water Quality Log (temperature, fluid electrical conductivity, pH and oxidation-reduction potential), Discrete Point Downhole Fluid Sampler, and a Heat Pulse Flowmeter (HPF). The HPF was designed to measure vertical flow rates and direction of vertical flow (upward or downward) in boreholes. HPF flow evaluations were also conducted on selected groundwater monitoring wells.

The HPF flow evaluation on selected monitoring wells suggested that a significant amount of metal contaminated mine water has been discharging into the French Gulch valley from the Bullhide and 11-10 faults and their associated graben fault block in the vicinity of the #3 Mine shaft (Figure 7). Vertical upflow rates from monitoring wells that penetrated the Bullhide Fault were measured to be as high as 1.44 gallons per minute (gpm). Significant flow was also associated with the base of the alluvium between the 11-10 and Bullhide faults. This flow was interpreted to be due to direct mine water discharge into the base of the alluvium via

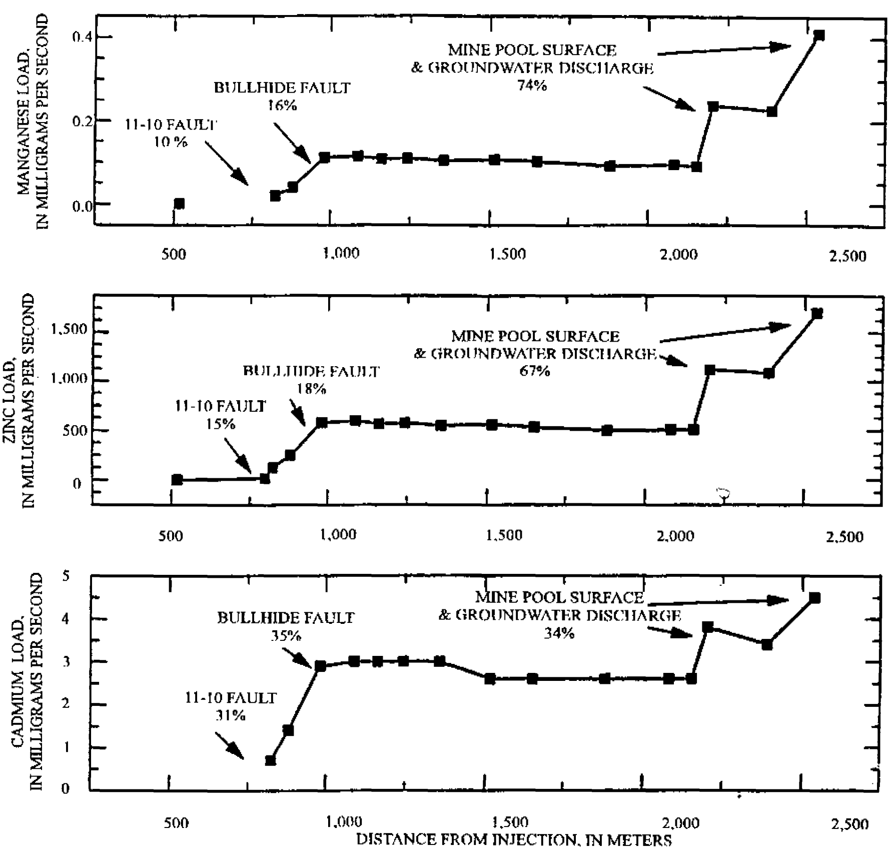

Figure 6. French Creek variation of mass loading for manganese, zinc, and cadmium with relative percentage of contributions from various contaminant pathways (after Kimball et al. 1997).

underground mine stopes. Mine stoping to the base of the alluvium in the vicinity of the #3 Mine shaft was documented by the Lovering (1934) report on the W-O mine. In contrast, minimal vertical flow was detected in alluvial monitoring wells outside the Bullhide and 11-10 fault graben (Figure 7).

The Video Log showed potential obstructions in the Oro Mine shaft at 298 feet below surface that prevented evaluation of the lower half of the mine shaft. The HPF and Video Log indicated that there was minimal water flow in the upper half of the mine shaft. The water quality and stable isotope signature of the upper Oro Mine pool were different from the mine water that was discharging in the vicinity of the #3 Mine shaft, and the Bullhide and 11-10 faults.

This characterization study supported the USGS tracer study conclusion that the upper portion of the Oro Mine shaft pool was not hydraulically connected to the #3 Mine shaft, the downgradient metal contaminated alluvium, or French Creek. This study also inferred that the lower W-O mine pool, which could not be characterized due to obstructions in the Oro Mine shaft, was the source of metal contaminated water to French Creek. It can be implied from this study that the flow pathways from the lower mine workings to French Creek are mine stopes, faults, fractures in the shale bedrock, and the shallow alluvial aquifer.

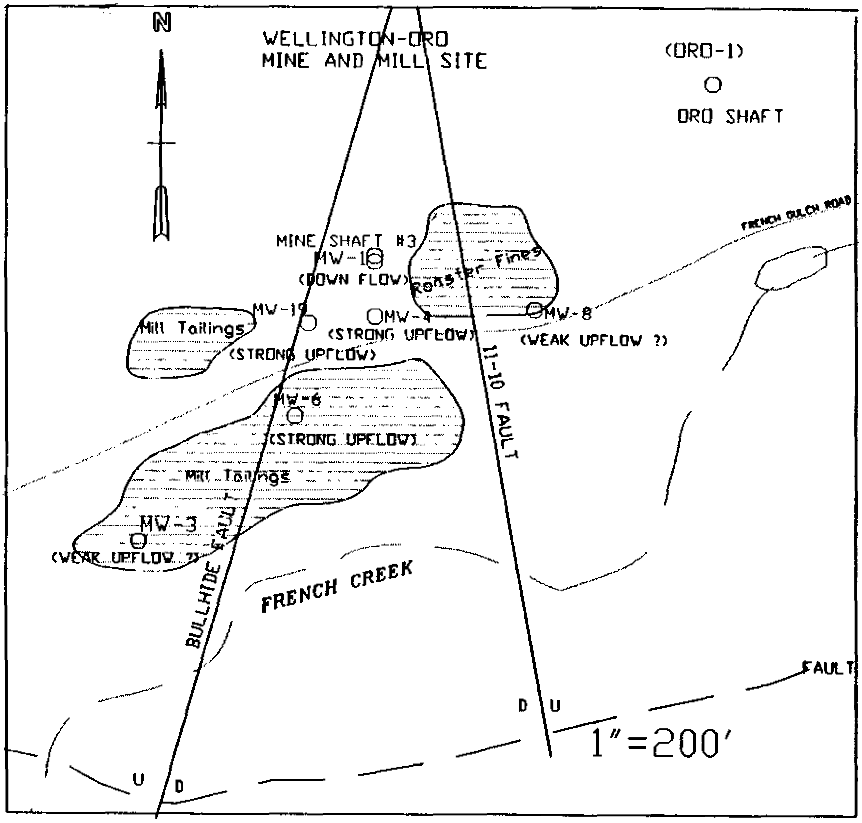

Figure 7. Site base map with flowmeter results from selected monitoring wells.

2.6 *Surface waste*

There were four investigations conducted in the vicinity of the W-O site during 1996 and 1997 that addressed surface mine waste (BOR 1997a and 1997b, URS Operating Services Inc. 1997, and Richard 1997). The surface spoils that were evaluated in these studies were the roaster fines, mill tailings and waste rock piles. Analyses of spoil materials included particle size distributions, field X-ray Fluorescence (XRF), laboratory measured total metals, X-ray Diffraction (XRD), and Total Characteristic Leaching Procedure (TCLP). Saturated paste extract results were also available from the State of Colorado Division of Minerals and Geology (DMG 1994). Material volumes were estimated by the BOR to be 43,000 cubic yards of roaster fines and 55,000 cubic yards of mill tailings (BOR 1997a). The volume of waste rock was unknown. The total metal content, particle size, mineralogy and degree of saturation varied within the different surface spoils. These factors affected the surface spoils metal leaching potential.

Mill tailings, roaster fines, and waste rock all had elevated levels of lead, zinc and other metals. In general, total iron concentrations were highest in the roaster fines and mill tailings, up to 20 percent. Total lead concentrations were highest in the waste rock and mill tailings, up to 2 percent. Zinc concentrations for the waste spoils ranged from one thousand to thousands parts per million (ppm). One roaster fines sample had up to 2% total zinc. Cadmium concentrations ranged from a few ppm to over one thousand ppm for a roaster fines sample. TCLP and saturated paste results suggest that lead was more leachable in the waste rock compared to the roaster fines and mill tailings. Zinc appeared to have greater leaching potential in the processed material than the waste rock.

Observed groundwater metal concentrations were highest in the saturated portion of the roasters fines, by orders of magnitude compared to the mill tailings. There were no groundwater monitoring wells in the waste rock. The total metal concentrations, TCLP, and saturated paste extracts showed similar magnitude of concentrations and leaching potential for the roaster fines, mill tailings, and waste rock. A possible explanation for the observed differences in groundwater quality of the surface spoils was that the roaster fines have greater leachable metals because of its acid generation potential, mineralogy, and physical characteristics.

Richard (1997) modeled potential metal loading from the W-O mine pool and surface waste. The surface waste evaluation included loading associated with groundwater flow through the spoil piles and surface runoff. The metal loading estimates associated with surface runoff were based on the assumption that most metals were transported to French Creek as metals adsorbed to sediment particles. The Universal Soil Loss Equation was used to approximate sediment yield or soil loss for the spoil piles. Metal loading associated with surface runoff were estimated by multiplying sediment yield approximations by the average metal content of the surface spoil piles.

Metal loading estimates associated with the W-O mine pool and groundwater flow through surface spoil piles were calculated by multiplying the metals content of the groundwater in the surface spoil pile or mine water by estimated discharge rates. The discharge rates for the surface spoils were approximated using Darcy's groundwater flow equation. The discharge rates for the W-O mine pool were approximated by extrapolating observed mine water discharge rates associated with the 11-10 and Bullhide faults. Fault seepage was quantified from data presented in the stream tracer and borehole flowmeter studies (Kimball et al. 1997 and RAS 1997a). The mine discharge via faults was estimated to range between two to three cubic feet per second (cfs). Mine water discharge via the mine stopes and fractured shale bedrock could not be determined because their geometry was unknown. Results of the metal loading analysis implied that nearly 90% of the Zn and Cd loading to French Gulch were from the W-O mine pool (Table II). The metal loading associated with the W-O mine pool was approximately fifteen times greater than the amount of loading observed in French Creek over one mile downgradient from the mine site. It has been suggested that this difference was due to attenuation caused by geochemical processes along the contaminates pathways and substantial subsurface flow.

Table 2 Annual Cadmium and Zinc Metal Loading Estimates from the Various Sources (after Richard 1997)

	W-O Mine Pool (kg/year)	Roaster Fines (kg/year)	Mill Tailings (kg/year)	Mine Waste Rock (kg/year)
Cadmium	1,213	40	1.1	71
Zinc	418,530	8,592	119	11,104

3 SUMMARY AND CONCLUSIONS

Characterization studies in the vicinity of the W-O mine site were able evaluate hydrologic flow pathways, hydrologic responses to storm and snow melt events, the hydrologic connection between the mine pool, groundwater systems, and French Creek, metal loading contribution from the various sources, and pre-remediation environmental baseline conditions. The results from this work suggest that the Wellington-Oro mine pool is the major source of metal contamination to French Creek and the Blue River. The faults in the area have been identified as major conduits for water into and out of the mine. Mine workings, especially stopes, are also probably major pathways for metal contaminated mine water transport out of the workings. Mine water discharge into the alluvium and French Creek seems to be limited to the 11-10 and Bullhide faults and their associated graben structure in the vicinity of the #3 Mine shaft and the faults as they crossed French Creek. Spring snow melt events appear to be driving the mine pool water level fluctuations via the fault and groundwater systems. Lovering (1934) showed that the major fault systems cut the lower mine workings. This apparently supports the mine pool characterization and tracer results which implied that the lower mine pool was the metal contaminated water source to the French Gulch valley. In addition, this work suggested that percolation of snow melt into the upper portions of the mine pool is not the major source of recharge water. Snow melt infiltration into major fault systems and the fractured bedrock as they cross the French Gulch valley are probably driving the groundwater recharge into the lower W-O mine pool. The characterization results suggested that surface spoil piles contribute a small percentage of the overall metal loading to French Creek and local infiltration of snow melt and runoff associated with the spoils are not a significant metal transport mechanism.

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