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AMERICAN GEOLOGICAL SERVICES, INC.
Environmental, Geological, and Natural Resource Consultants

Final Hydrogeologic Report

Wellington-Oro Mine and Mill Site

French Gulch

Near Breckenridge, Colorado

May 1999

Volume 1
Report, Selected Figures, and Plates

Prepared for:

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1.0 Executive Summary

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. Lead-zinc-silver sulfide and gold lode mining was concentrated on the fairly steep valley sides. Ore deposits 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. The dredging commonly involved the disruption of alluvial material to the top of the bedrock, over fifty feet in depth. This resulted in large dredge tailing piles covering most of the valley floor. The disruption of French Creek also caused the stream to have a significant subsurface flow component and an unnatural channel. The present day stream channel can be observed to locally disappear into the dredge piles, have multiple diversions from its original course, and contain significant gaining and losing reaches. Mapping of alluvial ground-water levels in the vicinity of the mine site has shown that the alluvial ground-water is not discharging in the stream, but tends to flow parallel to the stream in the approximate location of the original stream channel prior to dredging.

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 and habitat are responsible for the lack of trout populations in French Creek. Poor water quality is also a major factor contributing to limit trout populations in the Blue River below the confluence with French Creek.

There are several abandoned mine sites in French Gulch. Surface and ground water quality studies have been conducted by the Colorado Department of Public Health and Environment (CDPHE), the U.S. Environmental Protection Agency (EPA), and the U. S. Geological Survey National Water-Quality Assessment (NAWQA) program since 1989. These studies have demonstrated that most of the heavy metal loading to French Creek is from the inactive Wellington-Oro (W-O) mine and mill complex. The W-O was the largest mining operation in the valley. The underground workings consisted of over twelve miles of tunnels, adits, drifts, stopes and crosscuts (Lovering, 1934) with a significant portion being below the elevation of the ground-water table and French Creek (Figure 1-1). The W-O mill processed ore onsite from 1908 to the 1960's. Prior to the

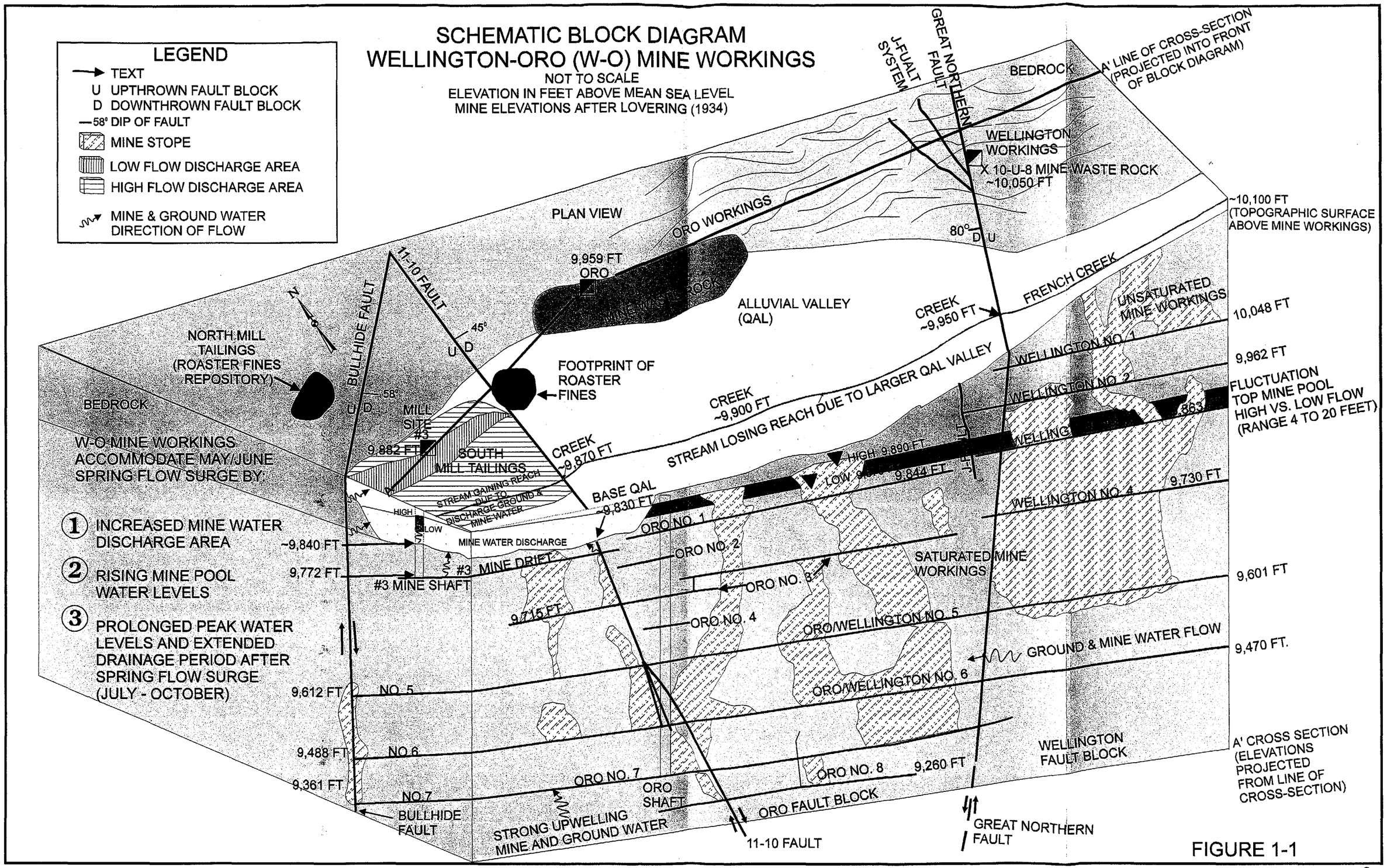

SCHEMATIC BLOCK DIAGRAM
WELLINGTON-ORO (W-O) MINE WORKINGS
NOT TO SCALE
ELEVATION IN FEET ABOVE MEAN SEA LEVEL
MINE ELEVATIONS AFTER LOVERING (1934)
LEGEND
TEXT
U UPTHROWN FAULT BLOCK
D DOWNTHROWN FAULT BLOCK
58° DIP OF FAULT
MINE STOPE
LOW FLOW DISCHARGE AREA
HIGH FLOW DISCHARGE AREA
MINE & GROUND WATER DIRECTION OF FLOW
PLAN VIEW
J-FUALT SYSTEM
GREAT NORTHERN FAULT
BEDROCK
A' LINE OF CROSS-SECTION (PROJECTED INTO FRONT OF BLOCK DIAGRAM)
WELLINGTON WORKINGS
X 10-U-8 MINE WASTE ROCK ~10,050 FT
~10,100 FT (TOPOGRAPHIC SURFACE ABOVE MINE WORKINGS)
ORO WORKINGS
80° D U
9,959 FT ORO
ALLUVIAL VALLEY (QAL)
FRENCH CREEK
CREEK ~9,950 FT
UNSATURATED MINE WORKINGS
10,048 FT
9,962 FT
FLUCTUATION TOP MINE POOL HIGH VS. LOW FLOW (RANGE 4 TO 20 FEET)
11-10 FAULT
45°
U D
BULLHIDE FAULT
N
NORTH MILL TAILINGS (ROASTER FINES REPOSITORY)
FOOTPRINT OF ROASTER FINES
BEDROCK
58°
U D
MILL SITE #3
9,882 FT
SOUTH MILL TAILINGS
CREEK ~9,900 FT
STREAM LOSING REACH DUE TO LARGER QAL VALLEY
CREEK ~9,870 FT
W-O MINE WORKINGS ACCOMMODATE MAY/JUNE SPRING FLOW SURGE BY:
1 INCREASED MINE WATER DISCHARGE AREA
2 RISING MINE POOL WATER LEVELS
3 PROLONGED PEAK WATER LEVELS AND EXTENDED DRAINAGE PERIOD AFTER SPRING FLOW SURGE (JULY - OCTOBER)
STREAM GAINING REACH DUE TO DISCHARGE GROUND & MINE WATER
HIGH
LOW
MINE WATER DISCHARGE
BASE QAL ~9,830 FT
HIGH 9,890 FT
LOW 9,844 FT
WELLINGTON NO. 1
WELLINGTON NO. 2
WELLINGTON NO. 4
9,730 FT
~9,840 FT
9,772 FT
#3 MINE SHAFT
#3 MINE DRIFT
ORO NO. 1
ORO NO. 2
ORO NO. 3
ORO NO. 4
SATURATED MINE WORKINGS
9,601 FT
9,715 FT
ORO/WELLINGTON NO. 5
GROUND & MINE WATER FLOW
9,470 FT.
9,612 FT
NO. 5
ORO/WELLINGTON NO. 6
9,488 FT
NO. 6
9,361 FT
NO. 7
ORO NO. 7
ORO SHAFT
ORO NO. 8
9,260 FT
WELLINGTON FAULT BLOCK
A' CROSS SECTION (ELEVATIONS PROJECTED FROM LINE OF CROSS-SECTION)
BULLHIDE FAULT
STRONG UPWELLING MINE AND GROUND WATER
ORO FAULT BLOCK
11-10 FAULT
GREAT NORTHERN FAULT

FIGURE 1-1

surface waste cleanup in the fall of 1998, the mill tailings and roaster fines were present at the ground surface. Unknown quantities of mine waste rock remains on site and unknown quantities of dredge tailings remain in the valley floor.

Surface and ground water pathways leading off the site are potential heavy metal avenues to French Creek. Surface water contamination pathways involve direct runoff of leachate from surface mine spoil piles (waste rock, mill tailings, and roaster fines) during rainstorm events and spring snowmelt. Ground-water contamination pathways include discharge of mine water from the flooded underground mine workings into the alluvium and fractured bedrock and seepage of leachate from surface mine spoil piles that eventually enter French Creek by ground-water discharge.

During 1996 and 1997, site and regional characterization studies were conducted by the State of Colorado Division of Minerals and Geology (DMG), CDPHE, 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 ground-water 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 tracer 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.

Section 3 of this report reviews the water quality studies in French Creek and the Blue River. The metals with the highest concentrations or greatest impacts to water quality in French Creek and the Blue River are zinc (Zn), iron (Fe), manganese (Mn), and cadmium (Cd). Cd and Zn are the major contributors to fish toxicity. These metals commonly exceed State water quality table standards by orders of magnitude. 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 ground waters associated with the saturated portion of the roaster fines were the most contaminated waters at the W-O site. The water chemistry of the alluvial ground-water and seeps were similar to the W-O mine pool suggesting that mine water was discharging directly into the alluvium. The

occurrence of numerous contaminated seeps downgradient of the W-O site implies that ground-water flow is a major pathway for metals.

Section 6 of this report summarizes the mine pool and ground-water level monitoring studies. This section also discusses continuous temperature monitoring at various levels in the Oro mineshaft. Water levels for the mine pool, alluvial aquifer, and fractured shale bedrock at the W-O site were continuously monitored with an automated datalogging system from July 11, 1996 to May 22, 1997. The mine pool and alluvial aquifer were also continuously monitored from late March 1998 to September 2, 1998. USGS discharge gage data on French Creek and climatic data from nearby weather and snow survey stations were integrated with the water level data.

The monitored water levels suggest that the fractured shale bedrock and the alluvial aquifer at the downgradient western portion of the mine site are acting as one hydraulically connected unit that is communicating with the mine pool. The hydraulic properties of the fractured bedrock and faults appear to control the rate of mine inflow and outflow. The water levels indicate that the downgradient western portion of the mine pool was flowing at a relatively constant rate into the alluvium and fractured shale throughout the monitoring period. The W-O mine accommodates the spring high flow surge through (Figure 1-1):

- Increased discharge area,
- Rising mine pool levels (increased mine water storage), and
- Prolonged peak mine pool water levels with extended drainage periods after the spring surge.

An initial rise in the mine pool and ground-water levels observed in late March and April of 1997 and 1998 coincided with local site snowmelt. The rise in May and June of 1997 and 1998 was driven by the snowmelt associated with the high elevation French Gulch headwater region and the more protected areas above the Wellington mine workings. Because the mine workings geometry and associated water volumes for mine water elevations are unknown, it is difficult to assess the volume contribution of the various recharge sources.

French Creek peak discharges are due to headwater snowmelt (P. Brooks, 1998). The mine pool peak elevations coincide with peak French Creek discharge from late May into June. This suggests that the waters that recharge the peak mine pool water levels and stream flows have similar origins.

The poor correlation between individual peaks on the French Creek hydrograph and the relatively smooth mine pool hydrographs indicate that there is a limited hydraulic connection between the mine pool and French Creek. Based on this limited hydraulic connection, it can be concluded that French Creek is not a major source of inflow to the mine. The broad and smooth character of the mine

pool hydrographs suggests that regional groundwater is the major source of inflow to the W-O mine and/or there is significant water storage in the underground mine workings.

The W-O mine pool, ground-water monitoring wells, and French Creek responded within a day of major snowmelt events. The nearly immediate responses are probably due the release of ground-water from storage in the fractured bedrock. This release is driven by pressure loading associated with snowmelt events. This implies that the water that recharges the mine pool and French Creek is not snowmelt, but older ground-water that was released from storage during snowmelt events.

Individual storm events had no effect on the ground and mine pool water levels at the W-O site and minor effects on French Creek discharge. The minimal effects of storm events on French Creek discharge suggest that infiltration of precipitation is much greater than runoff. The mine pool and ground-water lack of response to storm events implies that there are minimal direct flow pathways for precipitation to enter the mine pool and the volume of water associated with the storm events is very small compared to the ground-water system and mine pool.

A comparison of water levels from an uncontaminated 11-10 Fault monitoring well (MW-14) that was completed 277 feet below ground surface in the vicinity of the W-O site with 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 deeper portion of the 11-10 Fault is a major conduit for ground-water to enter the mine pool. The continuous temperature monitoring of the Oro mineshaft, which is intersected by the 11-10 Fault, showed the mine pool to increase in temperature, especially in the vicinity of the 11-10 Fault, during the spring flow surge. These temperature data also supports a regional ground-water recharge source to the mine pool. The predominant source of this ground-water is believed to be from the upgradient headwater region of French Creek (Figure 1-2). The pathway to the W-O underground mine workings would be regional ground-water flow in the fracture bedrock. The W-O mine workings intercept this regional ground-water flow and enhance its discharge into the French Gulch alluvial valley and stream.

Section 5 and 7 of this report discusses stable isotope studies on the mine, surface, and ground waters in French Gulch. Oxygen and hydrogen stable isotope studies were performed in the vicinity of the W-O site in 1996 and 1997 (RAS, 1996a, 1996b, and 1997b). Stable isotopes have been used as natural tracers because surface and ground waters can have distinctive isotope compositions that are a function of the water molecule's structure. The isotope studies demonstrated that snow melt waters associated with the local mine site area and the high elevation French Creek headwaters region were ^{18}O depleted compared to the mine, surface, and ground waters in French Gulch. The

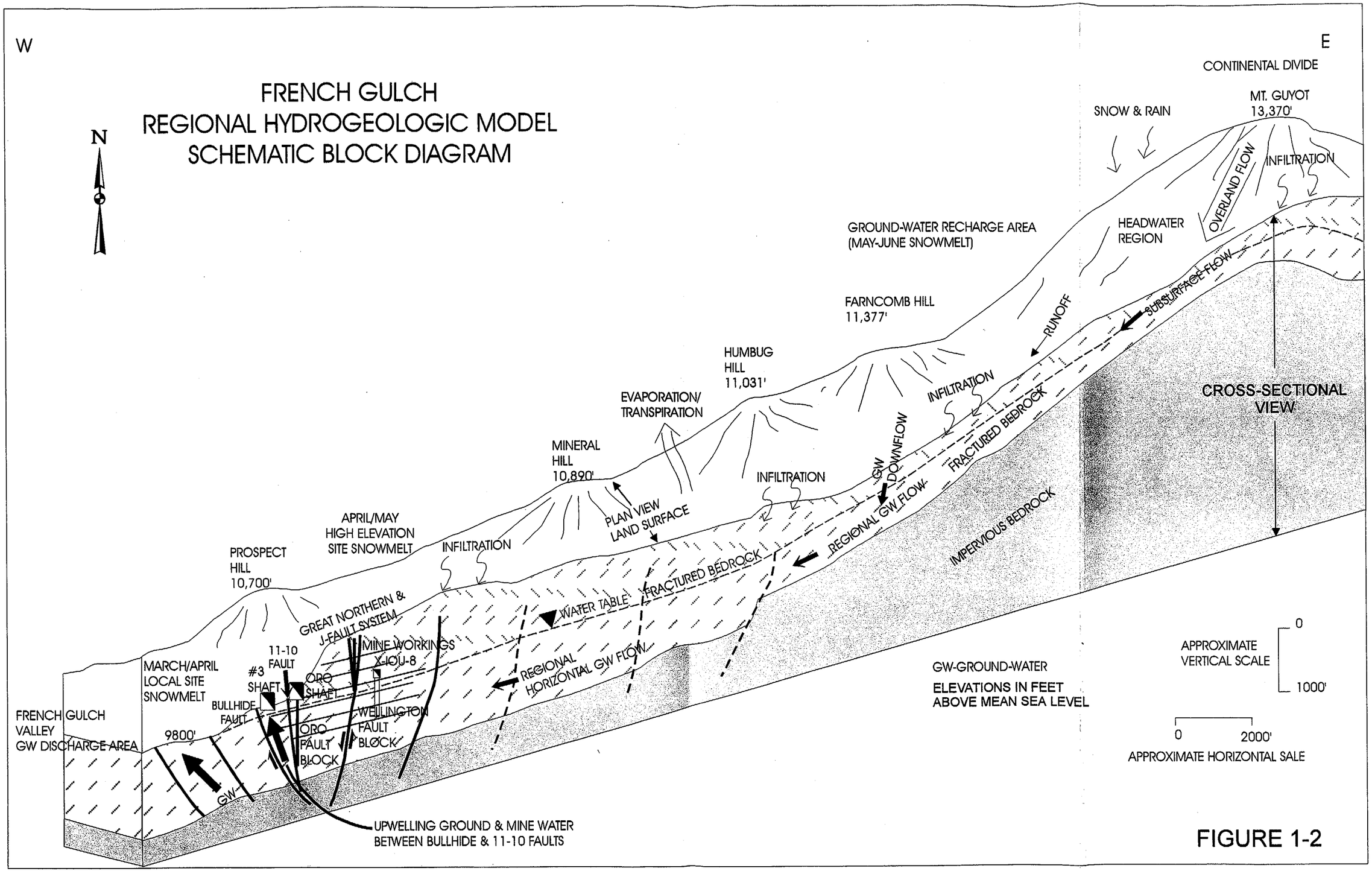

W
E
FRENCH GULCH
REGIONAL HYDROGEOLOGIC MODEL
SCHEMATIC BLOCK DIAGRAM
N
CONTINENTAL DIVIDE
MT. GUYOT
13,370'
SNOW & RAIN
INFILTRATION
OVERLAND FLOW
HEADWATER
REGION
GROUND-WATER RECHARGE AREA
(MAY-JUNE SNOWMELT)
SUBSURFACE FLOW
RUNOFF
FARNCOMB HILL
11,377'
HUMBUG
HILL
11,031'
INFILTRATION
FRACTURED BEDROCK
CROSS-SECTIONAL
VIEW
EVAPORATION/
TRANSPIRATION
MINERAL
HILL
10,890'
GW
DOWNFLOW
INFILTRATION
PLAN VIEW
LAND SURFACE
REGIONAL GW FLOW
IMPERVIOUS BEDROCK
APRIL/MAY
HIGH ELEVATION
SITE SNOWMELT
PROSPECT
HILL
10,700'
INFILTRATION
FRACTURED BEDROCK
WATER TABLE
GREAT NORTHERN &
J-FAULT SYSTEM
MINE WORKINGS
X-IOU-8
11-10
FAULT
#3
SHAFT
ORO
SHAFT
MARCH/APRIL
LOCAL SITE
SNOWMELT
BULLHIDE
FAULT
WELLINGTON
FAULT
BLOCK
ORO
FAULT
BLOCK
REGIONAL
HORIZONTAL GW FLOW
FRENCH GULCH
VALLEY
GW DISCHARGE AREA
9800'
GW
UPWELLING GROUND & MINE WATER
BETWEEN BULLHIDE & 11-10 FAULTS
GW-GROUND-WATER
ELEVATIONS IN FEET
ABOVE MEAN SEA LEVEL
APPROXIMATE
VERTICAL SCALE
0
1000'
0
2000'
APPROXIMATE HORIZONTAL SALE

FIGURE 1-2

snowmelt oxygen isotopes ranged from -19.4‰ to -27.2‰. The oxygen isotopes for the mine, stream, 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. This limited range has been interpreted to be due to the dominance of regional bedrock ground-water 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/ground-water. The mine water was slightly ^{18}O depleted compared to French Creek and local ground-water associated with the alluvial aquifer. The lack of shifts towards the ^{18}O depleted snowmelt for the mine water during high flow sampling events suggests minimal direct snowmelt recharge. The mine pool oxygen isotope composition slightly shifted towards the signature of local ground-water during the high flow sampling events suggesting that regional ground-water was the major source of recharge water to the mine pool. The isotope signature of water from the 11-10 Fault well MW-14 showed significant shifts in compositions. These shifts imply that the fault was a major conduit for water that was influenced by snowmelt and/or regional ground-water in the spring. The isotope data also indicated that mine water discharge was the major source of metal contamination in ground-water monitoring wells between the 11-10 and Bullhide Faults. The isotope signature of a contaminated alluvial monitoring well and seeps downgradient from the Bullhide Fault and the W-O site suggested that they were also influenced by mine water.

Section 4 of this report summarizes the salt tracer studies. In July of 1996, the USGS Toxic Substances Hydrology Program conducted stream tracer-dilution, alluvial ground-water tracer, mine pool tracer and synoptic sampling studies in the vicinity of the W-O site (Kimball et. al., 1997). These characterization studies 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 was injected at the top of the mine pool in the Oro shaft. The top of the mine pool had elevated levels of tracer for months after injection. The tracer was not detected at any downgradient monitoring sites. The lack of tracer dilution and downgradient tracer detection indicated that there was minimal hydrologic connection between the upper levels of the Oro shaft and the #3 Mine shaft, the downgradient metal contaminated alluvium, and the downgradient stream. This suggested that the deeper portion of the shaft is the primary source of metals to French Creek or significant mine flow is bypassing the upper levels of the Oro shaft. Characterization of the deeper portion of the Oro shaft in June of 1998 suggested that significant mine water flow could be bypassing both the upper and lower portions of the Oro shaft and discharging in the area of the #3 Mine shaft (Figure 1-1).

The sodium bromide tracer that was injected into an alluvial ground-water well was observed to be diluted within a few days. The tracer was not detected in the downgradient alluvial monitoring well or in French Creek. It was assumed that the tracer was either (1) attenuated or diluted before it reached the monitoring well and stream, (2) the travel time was too slow for the two-month tracer-sampling period, or (3) preferential pathways in the alluvium may of bypassed the monitoring stations. Direct measurements of alluvial groundwater velocity with a colloidal borescope in June of 1998 indicated significant preferential flow pathways with velocities as high as 460 feet per day. This suggests that there are significant volumes of water flowing within the alluvium that could have diluted the tracer below detection limits. Mapping of alluvial ground-water levels also suggested that the tracer flow pathway could have paralleled the stream and bypassed the monitoring well.

Variations in downstream French Creek metal concentrations and stream discharge 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 dilution of the stream salt tracer below the 11-10 Fault was interpreted to be due to a significant increase of ground-water discharge to the stream. The increase in stream discharge below the 11-10 Fault was quantified by applying spot tracer injections above and below the 11-10 Fault. These spot injections also showed that a significant flow component of the stream, up to 30%, was occurring within the stream gravels and cobbles. This type of flow is referred to as transient storage and can not be measured with traditional stream flow meter methods. The instream tracer and synoptic studies were able to identify subreaches of French Creek where the majority of metal loading occurred. 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.

Section 7 in this report reviews the characterization studies performed on the W-O mine pool. During low flow conditions in January of 1997, geophysical logging and water sampling of the Oro Mine shaft and selected ground-water monitoring wells in the vicinity of the W-O site were performed for the EPA (RAS, 1997a). American Geological Services, Inc. in June of 1998 complemented this study with a high flow evaluation. 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 flow evaluations (Heat Pulse Flowmeter, Colloidal Borescope, and Hydrophysical Logging techniques). Flow evaluations were also conducted on selected ground-water monitoring wells in January of 1997 and May of 1996.

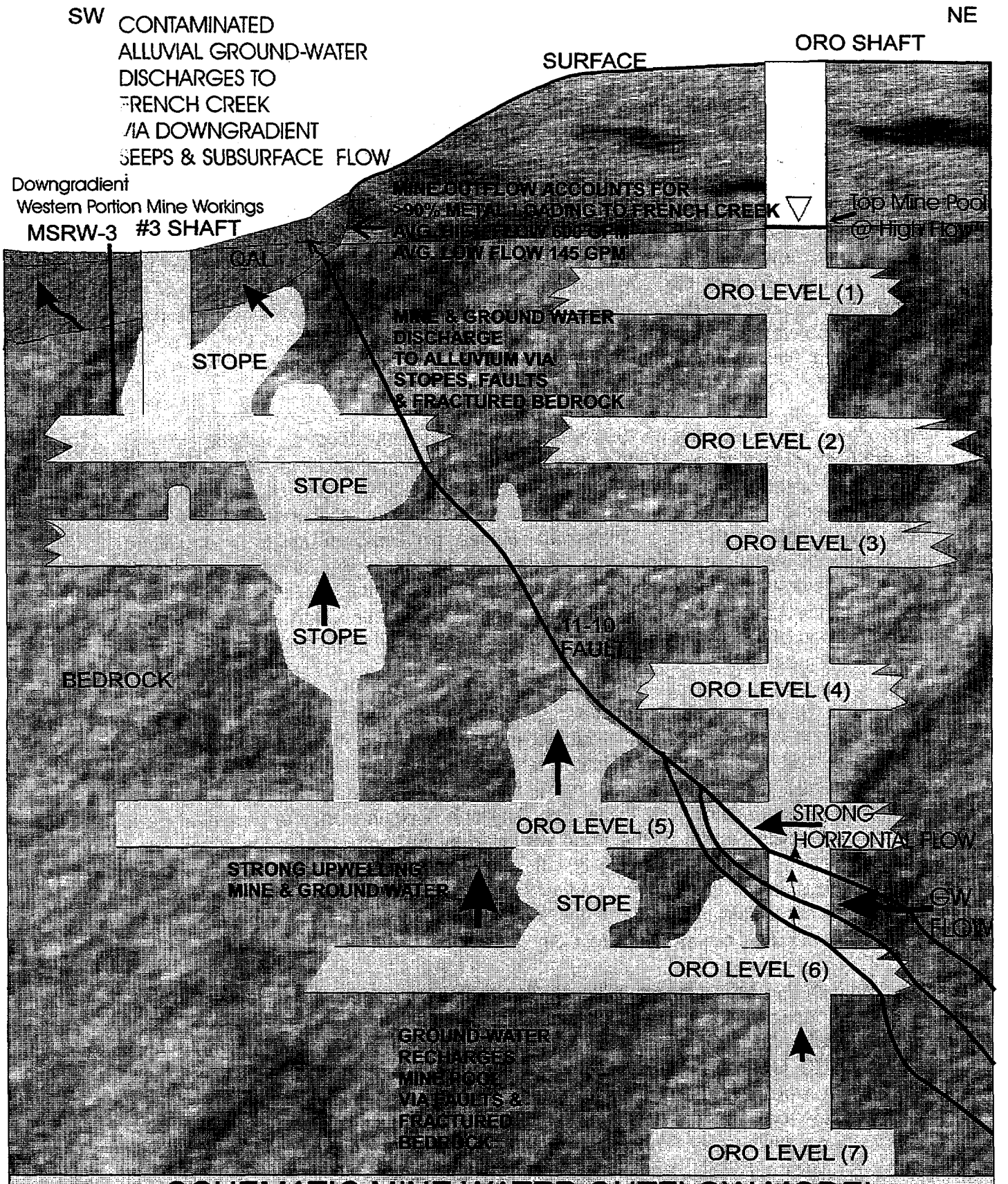
The Heat Pulse Flowmeter (HPF) evaluation on selected monitoring wells suggested that a significant amount of metal contaminated mine and ground

water has been upwelling from the Bullhide and 11-10 faults and their associated fault block in the vicinity of the #3 mineshaft (Figures 1-1 and 1-3). This area represents the downgradient western portion of the W-O mine workings. Vertical upflow rates from a monitoring well 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 from direct mine water discharge into the base of the alluvium via underground mine stoping and fault seepage. Mine stoping to the base of the alluvium in the vicinity of the #3 Mine shaft and stoping along faults were 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 block.

The video log in January of 1997 showed potential obstructions (conduit cable?) in the Oro mineshaft at 298 feet below surface that prevented evaluation of the lower half of the mineshaft. Further evaluation in the June 1998 study resulted in the assessment that these obstructions would not impact the characterization of the lower half of the Oro mineshaft. Based on temperature logs and flow evaluations, significant mine flow appears to be occurring below the 2nd drift level. A review of mine maps and comparison of mine water chemistry between the mine discharge areas, the #3 Mine, and the Oro mineshaft suggests that a large portion of this mine pool flow could be bypassing the upper and lower levels of the Oro mineshaft.

The mine waters appear to be young, less than 25 years old. The mine pool waters are in a predominantly reducing environment. The mine pool chemistry is very unstable, highly reactive, and chemical processes are poorly understood. Consequently, the actual source, metal fate, and pathway of mine water to the discharge areas are difficult to assess. Any conclusions from the chemical data and bench scale testing of the mine waters may be suspect because they may not represent in-situ conditions. It can be implied from these mine characterization studies that the flow pathways from the mine workings to French Creek are mine stopes and workings, faults, fractures in the shale bedrock, and the shallow alluvial aquifer (Figure 1-3).

Section 8 of this report reviews the studies that were conducted on surface mine wastes. 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



SCHEMATIC MINE WATER OUTFLOW MODEL
WELLINGTON-ORO

DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

NOT TO SCALE

FIGURE 1-3

mill tailings (BOR, 1997a). Subsequent evaluations and surface cleanup work indicated that the roaster fines volume was overestimated and could be closer to 6,000 cubic yards (L.F. Brown, 1998). L.F. Brown (1998) believed that the volume of mill tailings was also overestimated. AGS interpretation of historic air photos implied that additional mine wastes, possibly related to the roaster fines, may be buried below the main waste rock pile. The volume of waste rock is 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 (Pb), Zn and other metals. In general, total Fe concentrations were highest in the roaster fines and mill tailings, up to 20 percent. Total Pb concentrations were highest in the waste rock and mill tailings, up to 2%. Zn concentrations for the waste spoils ranged from one to several thousand parts per million (ppm). One roaster fines sample had up to 2% total Zn. Cd concentrations ranged from a few ppm to over one thousand ppm for a roaster fines sample. TCLP and saturated paste results suggest that Pb was more leachable in the waste rock compared to the roaster fines and mill tailings. Zn appeared to have greater leaching potential in the processed material than the waste rock (URS, 1997).

Observed ground-water metal concentrations were highest in the saturated portion of the roaster fines, by orders of magnitude compared to the mill tailings. There were no ground-water monitoring wells in the waste rock. The total metal concentrations and TCLP showed similar magnitude of concentrations and leaching potential for the roaster fines, mill tailings, and waste rock. The saturated paste extracts indicated that the leachate concentrations of the roaster fines were orders of magnitude greater than the mill tailings and waste rock. A possible explanation for the observed differences in ground-water quality of the surface spoils was that the roaster fines have greater leachable metals because of their 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 ground-water flow through the spoil piles and surface runoff. The metal loading estimates associated with surface runoff was based on the assumption that most metals were transported to French Creek as metals adsorbed to sediment particles. The Universal Soil Loss Equation (USLE) was used to approximate sediment yield or soil loss for the spoil piles. Metal loading associated with surface runoff was estimated by multiplying sediment yield approximations by the average metal content of the surface spoil piles. Estimating the dissolved phase concentrations in surface runoff from saturated paste results and using approximations of runoff from climatic data resulted in similar metal loading calculations to the USLE method.

Metal loading estimates associated with the W-O mine pool and ground-water flow through surface spoil piles were calculated by multiplying the metals content of the ground-water in the surface spoil pile or mine water by estimated discharge rates. The discharge rates for the surface spoils were approximated using Darcy's ground-water flow equation. The original estimates of discharge rates for the W-O mine pool were approximated by extrapolating observed mine water discharge associated with the 11-10 and Bullhide faults and the alluvial aquifer in the vicinity of the #3 Mine site. Fault seepage was quantified from data presented in the stream tracer and borehole flowmeter studies (Kimball et. al., 1997 and RAS, 1997a). Mine discharge into the alluvium was estimated from the observed alluvial head elevation differences and Darcey flow calculations in the vicinity of the #3 Mine. These mine discharge estimates range between 0.9 to 3.2 cubic feet per second (cfs) or 400 to 1430 gallons per minute (gpm). The stream tracer and flowmeter studies were conducted during two consecutive above average snow seasons. Ground-water baseflow and fault seepage may have been significantly influenced by the above average snow seasons. Consequently, these original mine discharge estimates may represent conditions for above normal (150% - 200%) snow seasons.

A sulfate mass balance model was used to evaluate historic mine discharge rates that may be more representative of average snow seasons. French Creek sulfate concentrations and flow measurements since 1989 were integrated into the sulfate mass balance model. A sulfate flux associated with alluvial ground-water and transient flow was also incorporated into the model. It was assumed that approximately 90% of the total French Creek and associated ground-water sulfate production were due to the W-O mine pool discharge. This evaluation resulted in a calculated peak mine flow in June of 600 gpm and a low mine flow in February of 145 gpm.

The mine and surface spoil discharge and loading analysis suggested that surface spoil piles contribute a small percentage of the overall metal loading to French Creek. Local infiltration of snow melt and runoff associated with the spoils are not a significant metal transport mechanism. It is estimated that the W-O mine pool contributes over 90% of the Zn and Cd loading to French Creek. A comparison of mine Zn production with French Creek surface and ground-water zinc production suggest that Zn is being attenuated 40% to 60% by geochemical processes along the contaminate pathways to French Creek.

Characterization studies in the vicinity of the W-O mine site were able to evaluate hydrologic flow pathways, hydrologic responses to storm and snow melt events, the hydrologic connection between the mine pool, ground-water 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 and fractured bedrock in the area have been identified as major conduits for water into and out

of the mine (Figure 1-2). Mine workings, especially stopes, are also probably major pathways for metal contaminated mine water transport out of the workings (Figure 1-3). There is not a point source of mine discharge to the alluvium and French Creek. As a result, the mine outflow rates are buffered by the hydrologic properties of the collapsed(?) stopes, fractured bedrock, and faults. Hydraulic head difference between the mine pool and the alluvial valley is the driving mechanism for flow out of the mine. The interception of regional ground-water flow by the mine workings results in the contamination of the bedrock ground-water. This contaminated ground-water discharges to the alluvial valley and is diluted by clean alluvial ground-water. Geochemical processes within the alluvium and possibly in fractured bedrock flow downgradient of the mine appears to attenuate metals. Mine water discharge into the alluvium and French Creek seems to be confined to the 11-10 and Bullhide faults and their associated fault block in the vicinity of the #3 Mine shaft (Figures 1-1 and 1-2). The inflow rates during the spring flow surge can range from 550 gpm to 1,400 gpm depending on the available moisture in the winter snow pack. Inflow rates of 550 gpm would be typical for average snow years while the upper flow rates probably represent 150-200% above average snow years. French Creek headwater region snowmelt and the higher elevation site snowmelt recharge the faulted and fractured bedrock system that results in a nearly instantaneous rise in the regional bedrock ground-water table. The rising ground-water table recharges the mine pool. Significant rises of water levels in the mine pool are the result of inflow rates exceeding outflow rates. The mine inflow is driven by large hydraulic head differences between the upgradient regional ground-water table and the downgradient western discharge portion of the mine workings. Since mine outflow is buffered by the hydrologic properties of the faults, fractured bedrock, and possibly collapsed stopes, the spring flow surge is accommodated by an increase in the mine water discharge area, rising mine pool levels, and a prolonged peak and drainage period after the spring surge (Figure 1-1). The large fluctuations in mine pool levels are the major mechanism for the generation of acid rock drainage and the formation of metal-bearing solutions. Based on the data compiled during the characterization studies, it has been concluded that percolation of local site snowmelt into the upper portions of the mine pool is not a major source of recharge water to the W-O mine pool.

2.0 Introduction

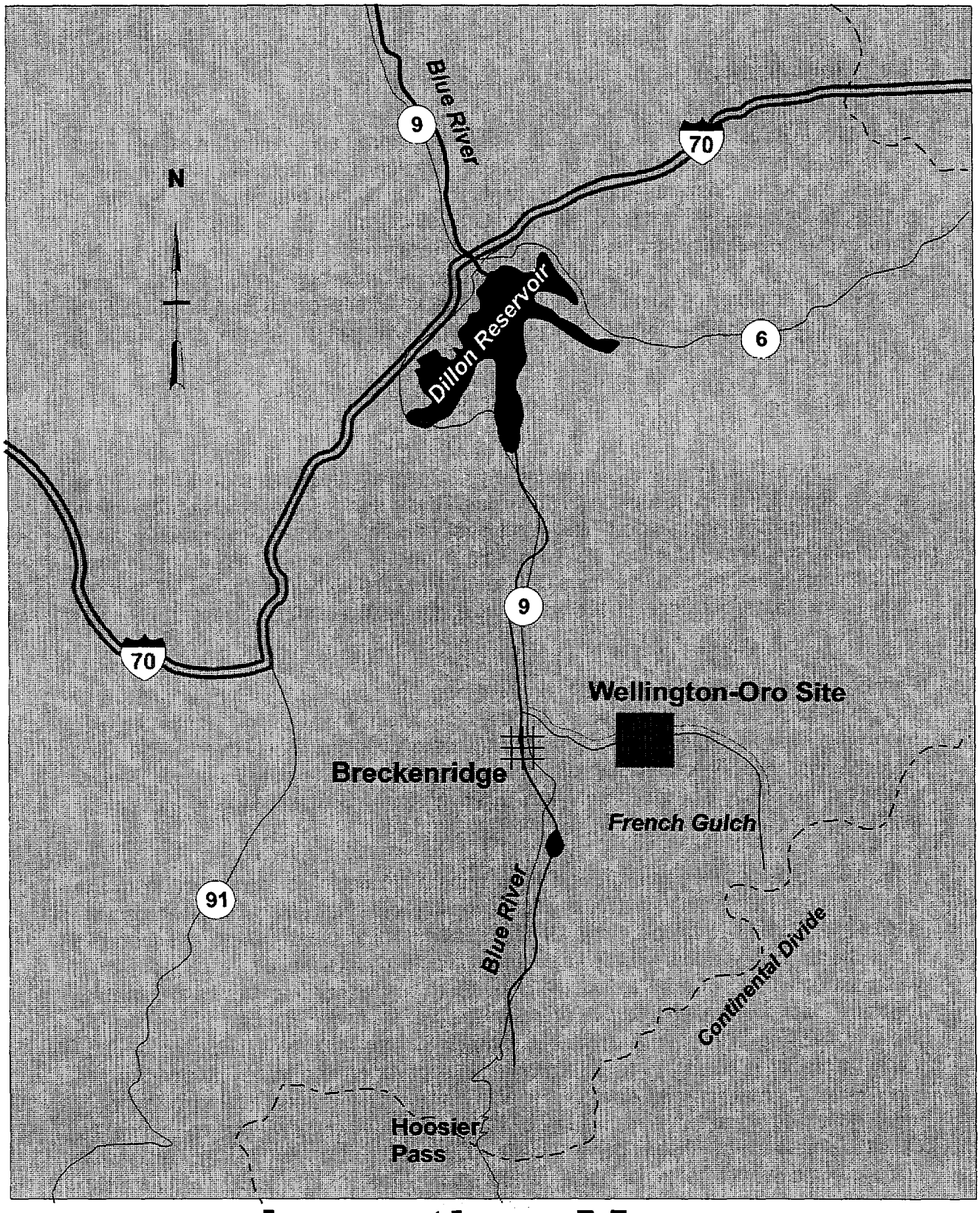
The U.S. Bureau of Reclamation (BOR) contracted American Geological Services, Inc. (AGS) in November of 1996. This contract included preparation of a report on site characterization studies and the development of a conceptual hydrogeologic model for the Wellington-Oro (W-O) mine and mill site. The U.S. Environmental Protection Agency (EPA) Region 8 through an interagency agreement with the BOR requested this work. A large portion of the funding for the characterization studies conducted at the W-O site originated from an EPA Region 8 Headwaters Grant to the Colorado Division of Mines and Geology (DMG).

2.1 Setting

The W-O site is located approximately 2.2 miles upstream or east of the confluence of French Creek with the Blue River near Breckenridge, Colorado. The site is on the north side of the west east trending French Gulch valley in the southeast quarter of Section 32, Township 6 South, Range 77 West. The local site ground elevation range from 9,800 to 10,100 feet above sea level. The ridge above the eastern extent of the mine workings is over 10,500 feet above sea level.

French Creek originates east of the site along the Continental Divide in Summit County and flows north and west for over six miles through the glaciated high mountain French Gulch valley to its confluence with the Blue River. The Blue River flows into Dillon Reservoir, a municipal water supply for the Denver Metropolitan area, approximately ten miles north of Breckenridge (Figures 2-1 and 2-2).

Extensive placer and underground lode mining occurred in the valley from the late 1850's to the 1960's. There was some mine dewatering and underground exploration activities in the early 1970'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. Large floating dredge boats were used to placer mine the valley floor for gold. The historic placer dredging completely disrupted French Creek and its associated alluvial valley material resulting in large dredge piles covering the valley floor from the Blue River to over a mile east of the W-O site. The placer mining commonly involved dredging to the bedrock, over 50 feet below the valley surface. The W-O site consists of three mine shafts (Oro, #3, and X-10-U-8), extensive underground workings, a mill site, waste rock piles, mill tailings piles, roaster fines pile, and dredge tailings. Portions of the mill and dredge tailings are within the French Creek drainage (Figure 2-2). DMG surface maps showed the buried Monahan shaft located north of French Gulch road and immediately east of the

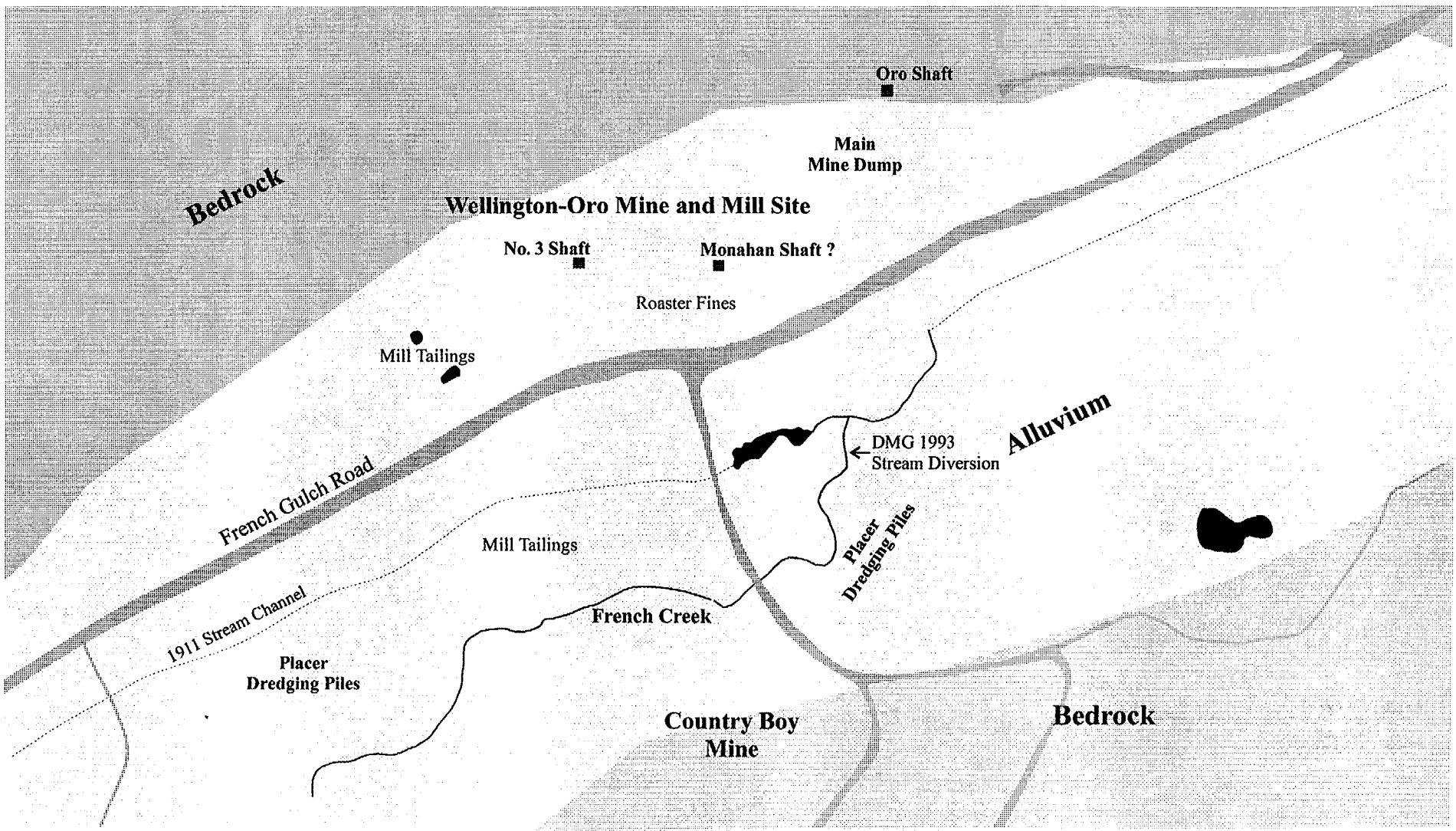


Location Map

0 Kilometers 8

0 Miles 5

Figure 2-1



Scale in Feet

0 100 500

N

French Gulch

Base Map Study Area

Figure 2-2

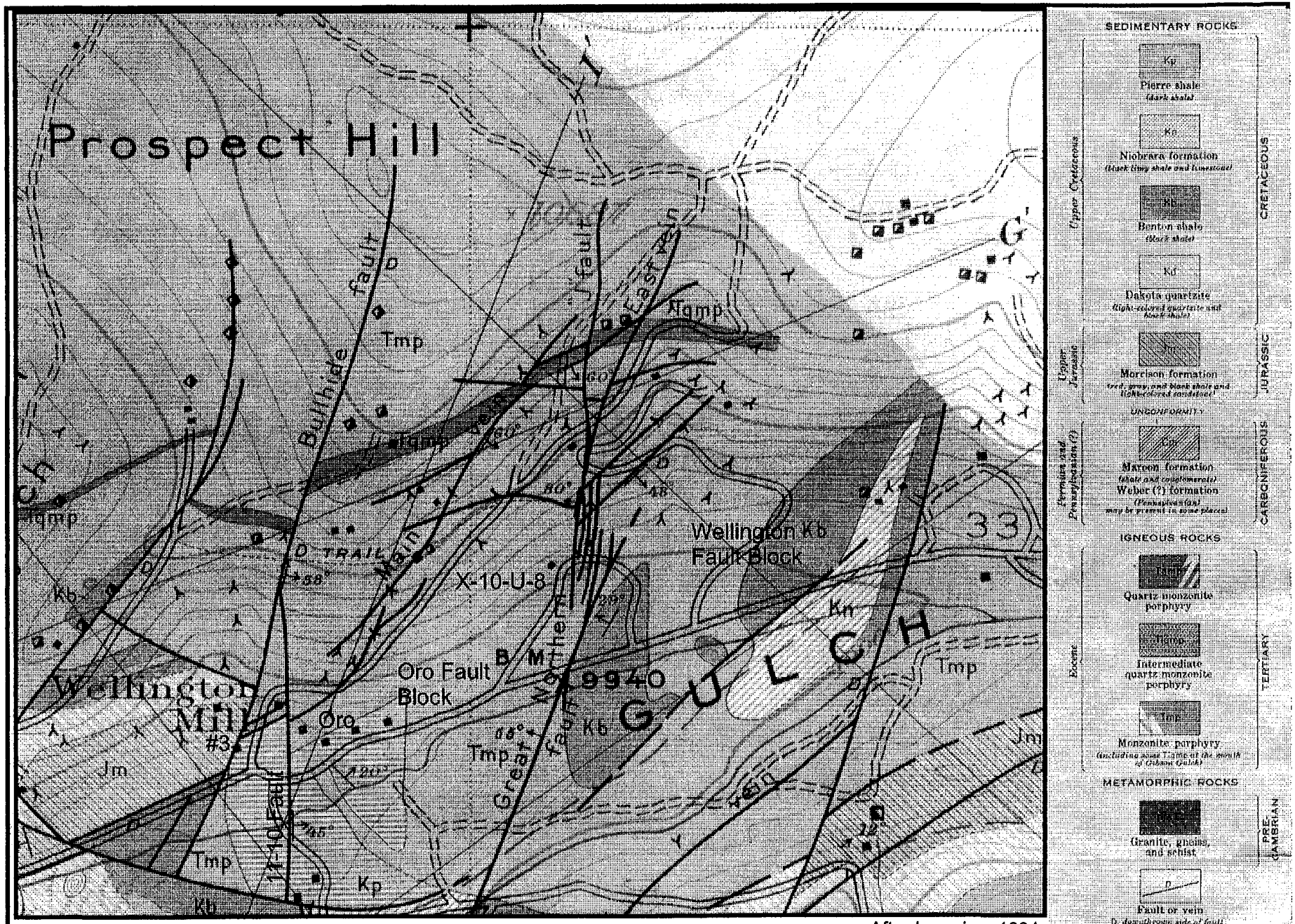
roaster fines. Published USGS mine maps and report in 1934 made no reference to this shaft (Lovering, 1934).

2.2 Geology

T.S. Lovering (1934) described the geology of the Wellington-Oro Mine and surrounding area in the U.S. Geological Survey Professional Paper 176. Figure 2-3 is a portion of Lovering's geologic map in the area of the W-O site. The bedrock in the W-O area consists of Cretaceous shale, limestone and quartzite (Pierre shale, Niobrara formation, Benton shale, and Dakota quartzite); Jurassic shale and sandstone (Morrison formation); Permian and Pennsylvanian (?) shale and conglomerate (Maroon and Weber? formations); and Tertiary monzonite porphyry and quartz monzonite porphyry. Lode mining occurred along mineralized veins and metamorphic replacement deposits associated with contact metamorphized Jurassic- and Cretaceous-age sediments and the Tertiary-age porphyry bodies (Lovering, 1934). The valley floor is draped with Quaternary glacial material that consists of alluvium and colluvium. The alluvium valley material is commonly 50 feet in thickness and ranges in width from 700 feet to over 1/4 of a mile. Placer dredging has disrupted a large portion of this material.

The sedimentary rocks and igneous intrusions are cut by a series of north to northeast trending faults (Figure 2-3). The sedimentary strata are faulted and folded into a large graben (down-dropped fault block) and syncline structural feature. Within the graben fault block, named the Oro fault block, the synclinal axis trends along the Oro underground mine workings in a northeastward direction from the W-O site. The Oro fault block is bounded to the west by the Bullhide Fault and to the east by the Great Northern and "J" fault zones (Figure 2-3). The 11-10 Fault is a splay from the Bullhide Fault. The Oro and #3 Mine shafts and their workings were developed in this graben and syncline structural feature. The Wellington Mine workings were associated with both the downthrown Oro Fault block and the upthrown Wellington Fault block east of the Great Northern and "J" Faults. The original Wellington Mine workings were opened by several adits, the largest was the inclined X-10-U-8 (Extenuate) shaft that was located approximately 1,400 feet east of the Oro Mine shaft. The Oro and Wellington workings were joined in 1902 by their fifth and sixth levels. The upper Wellington-Oro workings were mostly in the Tertiary monzonite porphyry while the lower levels exposed the Pierre, Niobrara, Benton, Dakota, and Morrison sedimentary units (Lovering, 1934).

Lovering (1934) calculated the vertical displacement on the Bullhide Fault to be 800 feet with a dip slip movement of approximately 900 feet. The Great Northern and "J" faults have similar displacement as the Bullhide Fault. Lovering (1934) calculated the net slip for the 11-10 Fault to be 110 feet. The vertical



After Lovering, 1934

0 1/2 mile

Geologic Map of the Wellington-Oro Mine Area

Figure 2-3

displacement on the 11-10 Fault was estimated to be as much as 50 feet. The 11-10 Fault also has a significant strike slip (horizontal) component of approximately 45 to 50 feet. Lovering (1934) also indicated that there was evidence for horizontal movement on the Bullhide, Great Northern, and "J" faults. Ore veins were commonly associated with the fault zones and it was not unusual for mine stopes to follow the faults. Lovering (1934) suggested that the Great Northern and "J" fault zones were the major conduit for hypogene mineralization (formed by ascending waters) originating from the Tertiary intrusions in the area.

2.3 Mining History

Placer mining in French Creek began in 1859 with small gravity separation operations. With the subsequent consolidation of mining claims, surface water diversions were installed for hydraulic mining and booming (SAIC, 1994). Nine dredges were operating in the area during the early 1900's. Dredging operations continued until the 1940's. These operations resulted in 40 to 50 foot high piles and ridges of cobbles and gravel size placer tailings.

There are several abandoned underground lode mining sites in French Gulch. Numerous shafts, adits, and waste rock piles are located on the slopes of Gibson, Prospect, Mineral, Humbug, and Farncomb hills. The Country Boy mine is located due south of the W-O site (Figure 2-2). This mine began operations in 1889 and produced high-grade zinc-lead-silver ore with some gold (SAIC, 1994). The Country Boy is presently operated as an underground mine tourist attraction. The Mineral Hill McLeod Tunnel and Farncomb Hill (Wire Patch) gold mine were located upstream of the W-O site. The Detroit Mine was located downstream of the W-O on the eastside of Gibson Hill and above Gibson Gulch. This mine began operations in the 1890's and produced gold, lead and silver (SAIC, 1994). The Union City Mine and Mill was located one mile downstream from the W-O site. An unknown quantity of mill tailings appears to be underlying the placer dredge piles in this area. There are presently no active mining operations in the French Gulch valley.

The Wellington-Oro mine and mill complex was the largest mining operation in the valley. Most of the lead-zinc-copper-silver sulfide ores and gold ores were extracted from the W-O between the 1880's to the 1930's. According to Lovering (1934) over 1 million tons of ore was mined in this time period. By the end of the 1920's the underground W-O mine workings consisted of over twelve miles of tunnels, adits, drifts, stopes and crosscuts (Lovering, 1934). Significant portions of these workings were below the elevation of the ground-water table and French Creek.

W-O mine ore was removed at two main locations: the mill site through several tunnels and the Oro Shaft, and from the X-10-U-8. Large waste rock piles remain at the Oro Shaft and X-10-U-8. In 1928, the deepest level of the mine,

the eighth Oro level, was developed. Ore removal at the W-O ceased in 1960's when mine water management became unfeasible (SAIC, 1994).

A pump station was located on the sixth level near the X-10-U-8 or Wellington inclined shaft (Lovering, 1934). According to the U.S. Bureau of Mines inspection records in 1919 and 1921, the station consisted of two pumps with a total capacity of 1,000 gallons per minute (gpm). At the time of inspection, these pumps were operating at a rate between 300 and 350 gpm.

A 100-ton gravity mill was constructed at the W-O site in 1908. Lead, zinc and pyrite concentrates were produced from this mill until 1929. In 1912, a 50-ton roaster and magnetic separation plant was built to remove iron and sulfur from the zinc byproducts. The roaster and magnetic separation plant operated until 1927, when it was replaced by a more economical flotation mill (Lovering, 1934). The byproducts of these plants resulted in roaster fines and mill tailings being discarded at the site.

The roaster fines were exposed at the ground surface until the fall of 1998 (Figure 2-2). B&B Mines performed cleanup work on the roaster fines in the fall of 1998 under an EPA administration order. The roaster fines were moved to a nearby repository above the ground-water table and capped.

Based on AGS review of historic air photos it is believed that some of the gravity and flotation mill tailings, and possibly roaster fines, were buried by waste rock and tailings generated by operations in the 1950's and 1960's. Some of the tailings were also discarded into French Creek and washed downstream during the early operations. Tailings possibly associated with this time period can be observed along the lower reaches of the French Gulch valley.

Minimal mining occurred at the W-O site from the late 1930's and 1940's. In the 1940's the present owners (B&B Mines and several affiliated companies) acquired the W-O properties. Sporadic mining and mill operations occurred at the W-O from the late 1940's to the early 1970's. Lessees of B&B Mines conducted these operations. Mining and mill operations of these lessees are poorly documented in B&B Mines files and public records. Consequently, the extent of operations during this period is poorly understood.

From the late 1940's into the early 1950's, a Mr. Davenport leased and conducted mining operations at the W-O site. Former partners of Mr. Davenport, Horn and Burger, acquired the lease and mining operations in the mid-1950's. Consolidated Parnett/Wellington Mining Association leased and mined the W-O during the early 1960's. Gilmore/Wellington Mining Company leased and mined the W-O from the late 1960's into the early 1970's.

The Davenport operations included ore removal from the 300 feet level possibly via the Main Tunnel or Wellington Portal immediately west of the Oro shaft. This

mining level would have required dewatering of the W-O mine pool by over 250 feet. The dewatering was probably accomplished by pumping the Oro shaft. The mining operation during the mid to late 1950's apparently was limited to the 80 feet level which was above the static water level of mine pool.

A fire destroyed the W-O mill in 1962. Consolidated Parnett/Wellington Mine Association rebuilt the mill by early 1963. Consolidated Parnett/Wellington Mine Association conducted extensive mining and mill operations at the W-O in the early 1960's. The new mill was planned to handle up to 150 tons of ore per day. It is believed that the north and south mill tailing ponds and a significant portion of the main waste rock pile were developed at this time. Ore extraction was associated with stoping from the 80 feet and 230 feet drift levels that were accessed by the Wellington Portal or Main Tunnel. The 230 feet level was a new drift developed by Consolidated Parnett/Wellington Mine Association. During the mining operations the 4th Level of the old Wellington workings was intersected by an inclined winze from the 230 feet level. A mine blowout and flood occurred in 1962 when the old 4th level was intersected. To develop the new 230 feet level in 1961 the mine was dewatered by over 200 feet by pumping the Oro shaft. To maintain the water levels below the 230 feet level the Oro shaft was pumped at a rate of 350 gpm.

The Gilmore operations began in 1968 from the shallow 80 feet level off the Main Tunnel. The U.S. Bureau of Mines reported a production rate of 500 tons per month at this time. Ore production apparently ceased by 1970. In the early 1970's Gilmore developed a new 176 feet drift level off the Main Tunnel and drifts and crossuts from the Oro shaft's 5th level. Dewatering of the Oro shaft for these operations required a steady pumping rate of 600 to 1,000 gpm for approximately 1-1/2 years to lower the mine pool level to the 6th Oro level, around 85% of the original saturated thickness of the mine. A pumping rate of 500 to 600 gpm was required to maintain this water level (Woodward-Clyde, 1975). The Woodward-Clyde (1975) report also indicated that major water entry occurred at or below the 5th Oro level. Gilmore had planned to extract ore from these new workings but went bankrupt due to a Security and Exchange Commission (S.E.C.) investigation (Brunton, 1980). The Gilmore operation was the last active underground mining and exploration that occurred at the W-O site. In the 1980's, B&B Mines had only issued exploration leases for the W-O properties.

2.4 Review of Previous Characterization Work

In 1989, the Colorado Department of Public Health and Environment (CDPHE) and the Colorado Division of Minerals and Geology (DMG) proposed a Non-Point Source (NPS) 319 project in French Gulch after observing trout fingerling kills in the Blue River below French Creek. According to SAIC (1994), Moran and Wentz (1974) and McConnell (1979) had previously documented elevated levels of Zn, Fe, Mn, Pb, and other metals in French Creek below the W-O site and the

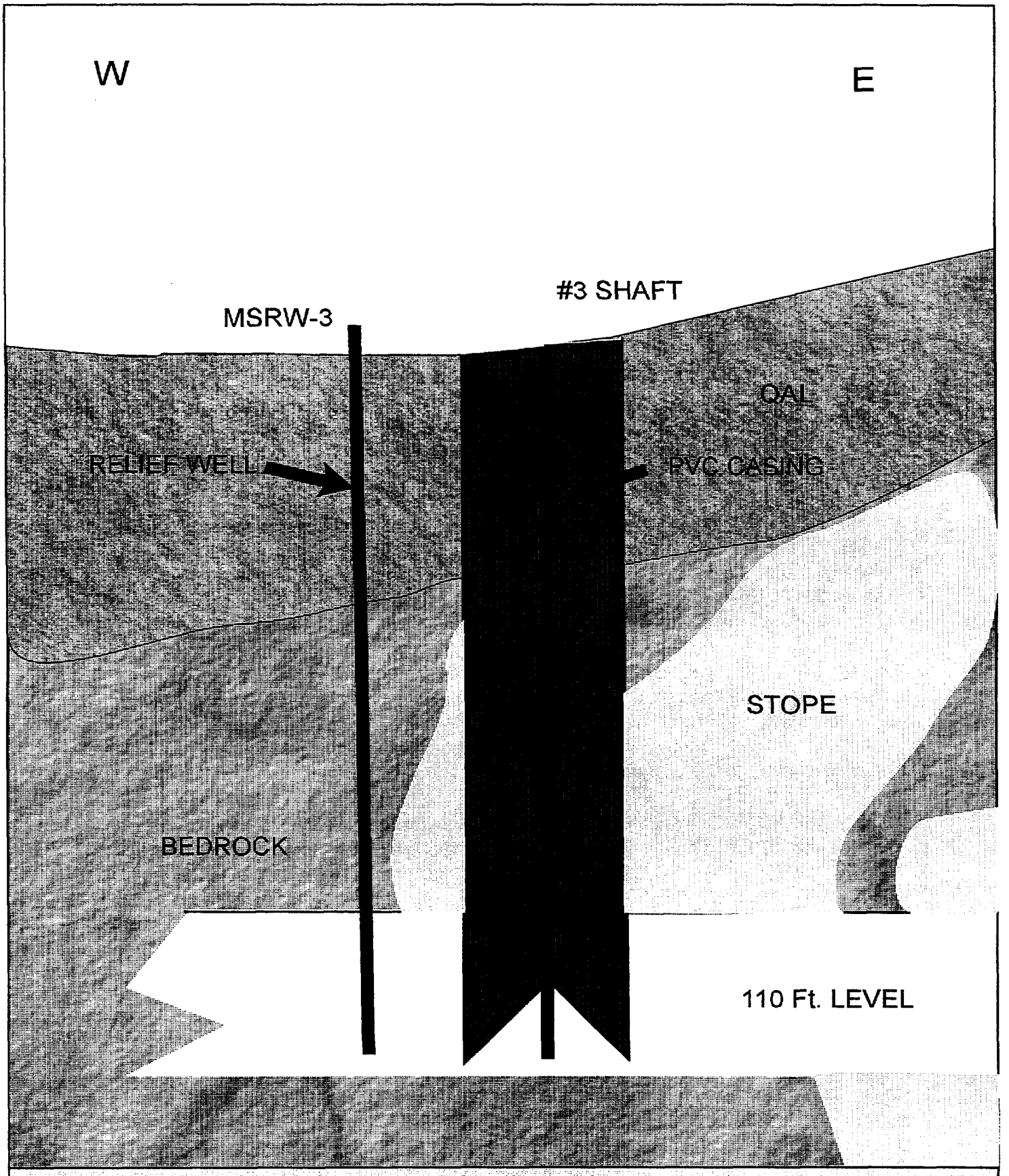
Blue River below French Creek. During the mid-1980's, the City of Breckenridge reclaimed and improved the Blue River from south of town to a couple of miles below French Creek. This reclamation involved dredging and removing the old placer tailings, reconstructing the stream channel, and revegetating the stream banks (SAIC, 1994). Subsequent to the reclamation of the Blue River, the Colorado Division of Wildlife (CDOW) initiated a stocking program to re-establish a trout population in the Blue River. As a result of this stocking, the acute toxic conditions associated with French Creek were first noticed.

In 1989 and 1990, the CDPHE performed surface water sampling and toxicity testing (CDPHE, 1989 and 1990). These studies identified the W-O site as the major metals source in French Gulch. It was observed that the trout population had been eliminated in French Creek between the W-O site and the Blue River. A small native cutthroat trout population was detected in French Creek upstream of the W-O. The Blue River was impacted below French Creek with a significant reduction in trout populations (SAIC, 1994).

In 1991, DMG began drilling ground-water monitoring wells in the vicinity of the #3 Mine shaft and the mill tailings. In March of 1992, DMG grout sealed the #3 Mine shaft and set PVC casing from the ground surface to the #3 Mine drift level (Figure 2-4). This project was based on the premise that the #3 Mine shaft was a point source of mine water discharge to the alluvium. The purpose of the grout sealing was to isolate the shaft from the alluvial aquifer. In conjunction with this sealing, a relief well (MSRW-3) was drilled to measure mine flows and characterize mine water quality. The mine pool did not rise above water levels prior to grout sealing. This suggests that there were other ground-water pathways, possibly faults and fractures in the bedrock, and mine stopes, for mine water discharge to the alluvium (Stover, 1997).

In May of 1993, the DMG diverted French Creek around the mill tailings south of French Gulch road (Figure 2-2). The objective of this diversion project was to allow spring high flow to bypass the mill tailings and reduce ponding and the level of the ground-water table in the south mill tailings area. The diversion eliminated most of the ponding, but did not significantly lower the ground-water table. There were no noticeable improvements in downgradient stream and ground-water quality as a result of this project (SAIC, 1994).

In the summer of 1993, the U.S. Bureau of Mines (USBOM) conducted geophysicial surveys using conductivity methods to identify the subsurface location of the 11-10 fault zone in the W-O site area. The 11-10 Fault appeared as a high conductivity anomaly. In the fall of 1993, DMG drilled additional ground-water monitoring wells including the 278 feet deep 11-10 Fault well (MW-14). The ground-water associated with the deep fault well was uncontaminated. Surface wastes were also sampled and characterized with auger holes in the fall of 1993.



1992 GROUT SEAL
#3 MINE SHAFT

NOT TO SCALE

FIGURE 2-4

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AFTER LOVERING (1934)

In the fall of 1994, a series of new ground-water wells were drilled for the purpose of conducting aquifer tests on the alluvial aquifer and fracture shale bedrock at the W-O site in the vicinity of the #3 Mine shaft. These tests indicated that the shale bedrock and alluvium are in hydraulic communication with the underground mine pool. This study concluded that metal laden mine water is discharging to the bedrock and alluvium via fractures, subsidence zones above mine stopes, and possibly faults (Morrissey, 1995).

2.5 Objectives of Recent Contaminant Hydrogeology Characterization Studies

Acid mine drainage (AMD) degrades the water quality in French Creek and the Blue River. Previous characterization studies have identified the Wellington-Oro Mine and Mill complex as the major source of metals loading. The interaction of surface and ground waters with sulfide-bearing rocks, mine workings, and surface mine waste produce acid solutions charged with heavy metals that are toxic to organisms. Surface and ground water pathways leading off the W-O site are potential contaminant avenues to French Creek. Surface water contamination pathways involve direct runoff of leachate from the surface mine spoil piles (roaster fines, mill tailings, and mine waste rock) during rainstorm events and spring snowmelt. Ground-water contamination pathways include discharge of mine water from the flooded underground mine workings into the alluvium and fractured bedrock and seepage of leachate from the surface spoils that eventually enter French Creek by ground-water discharge.

During 1996 and 1997, site and regional characterization studies were conducted by the following government agencies and private contractor:

- State of Colorado Division of Minerals and Geology (DMG),
- State of Colorado Department of Human Health and Environment (CDPHE),
- U.S. Geological Survey (USGS),
- U.S. Environmental Protection Agency (EPA) Region 8,
- U.S. Bureau of Reclamation (BOR), and
- American Geological Services, Inc. (AGS).

The characterization of contaminant hydrogeology of the W-O site involved:

1. surface mine waste studies,
2. mine pool studies,
3. surface and ground water quality studies,
4. continuous ground-water and mine pool water level monitoring,
5. installation of new monitoring wells,
6. aquifer testing,
7. subsurface flow evaluations on selected ground-water monitoring wells and the mine pool,

8. stable isotope tracer studies, and
9. salt tracer studies.

The objectives of characterizing the site contaminant hydrogeology were to (1) determine the relative contributions of metal loading from the various sources, (2) identify metal contaminant pathways and fate, and (3) establish pre-remediation environmental baseline conditions.

The potential sources of metal loading are the W-O mine pool and surface spoils. The pathways involve surface runoff from spoil piles and ground-water flow via the alluvial aquifer, placer tailings, fractured bedrock, and/or fault systems. Fate of metals refers to geochemical processes that may occur during the transport of metals from their source to French Creek. These processes may reduce the amount of metals that discharge to French Creek and the Blue River. The development of a hydrogeologic model involves the integration of metal sources, transport pathways, and metal fate. An understanding of the contaminant hydrogeology is necessary for the evaluation of remediation options.

3.0 French Gulch and Blue River Water Quality Studies

3.1 Abstract

Numerous water quality studies conducted in the French Gulch valley and the Blue River have demonstrated that a large portion of the heavy metals loading to French Creek and the Blue River are from the inactive Wellington-Oro mine and mill complex. Zn and Cd toxicity, poor fishery habitat, and low flows are probably responsible for the elimination of trout populations in French Creek below the Wellington-Oro site and reduced trout populations in the Blue River below the confluence with French Creek. State chronic and acute water quality standards are commonly exceeded for Zn and Cd in the impacted sections of French Creek and the Blue River. Other metals with elevated concentrations are Fe, Mn, and Pb.

A large portion of the ground-water contamination in the vicinity of the Wellington-Oro site has been interpreted to be due to underground Wellington-Oro mine pool discharge into the unmined bedrock and alluvial ground-water system. A significant amount of mine pool water apparently is discharging directly into the alluvial aquifer in the vicinity of the #3 Mine shaft. Contaminated ground-water discharging from seeps downgradient of the mine site suggest that ground-water flow is a major component to metal loading in French Creek. Elevated metals in domestic wells southwest of the mine site does not seem to originate from the Wellington-Oro site.

3.2 Introduction

Since 1989 there have been numerous water quality studies conducted in French Gulch and the Blue River. Water Quality studies have been performed by the Colorado Department of Public Health and Environment (CDPHE), the Environmental Protection Agency (EPA) Region VIII, and the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program (CDPHE, 1989; EPA, 1992, 1993a, 1993b, 1994, 1996a and 1996b, and NAWQA, 1997a). In addition to these studies, the Breckenridge Sanitation District (BSD) conducted periodic ground-water and stream sampling along the Blue River in the vicinity of the French Creek confluence from 1986 to 1994 (BSD, 1997). The Department of Wildlife (DOW) River Watch program, Summit County Water Quality Committee (SWQC), and the Northwest Colorado Council of Governments have also been performing periodic sampling along the Blue River since the spring of 1997. Other water quality data included:

- selected metals analysis (Fe, Zn, and Cd) on samples of ground-water, seeps, and French Creek associated with the stable isotope and mine

pool characterization studies (RAS, 1996a,1996b, 1997a, and 1997b) and

- CDPHE water quality data on domestic wells in the lower French Gulch area (CDPHE, 1996 and 1997).

The water quality studies have demonstrated that a large portion of the metal and sulfate loading to French Creek has been from the inactive Wellington-Oro (W-O) mine and mill site. The metals with the highest concentrations or ecological impact on the streams are Zn, Fe, Mn and Cd. The Cd and Zn concentrations have been the major contributors to fish toxicity in French Creek and the Blue River. The emphasis of this review of water quality data is on selected metals of concern and their relationship to water quality standards. In addition, this review summarizes ground-water quality in the vicinity of the W-O mine and mill site and French Gulch residential domestic wells.

3.3 Water Quality Standards

Under the federal Clean Water Act, each state was required to establish water quality standards for surface water bodies. A water quality standard is a law or regulation which consists of the beneficial designated use or uses for a water body or a segment of the water body and the water quality criteria which are necessary to protect the use or uses of that particular water body. A water quality standard serves a twofold purpose: (1) it establishes the quality goals for a specific water body and (2) it is the basis for establishing water quality based treatment controls strategies. Water quality criteria consist of numerical table values for the concentrations of specific chemicals in water, which protect the designated use. These criteria include both acute and chronic concentration values for the protection of aquatic life as well as values to protect human health. Chronic toxicity is any condition affecting reproduction, growth, or lethality measurable within one-tenth or more of a species' life span. Acute toxicity is measurable lethality in aquatic life following their exposure in 96 hours or less.

3.3.1 Blue River

The area of interest is the State of Colorado's aquatic life designation for two segments of the Blue River. Blue River Segment 1 is defined as the mainstream of the Blue River from the source to Dillon Reservoir except for the specific listing in Segment 2. Blue River Segment 2 is defined as the mainstream of the Blue River from the confluence with French Gulch to a point one mile above the confluence with the Swan River. Both segments have been designated as "Cold Water Aquatic 1". This classification has been used for waters that are currently capable of sustaining a wide variety of cold water biota, including sensitive species, or could sustain such biota due to correctable water quality conditions. Except for rivers with Outstanding Waters designation, this is the most stringent designation for aquatic life uses. The associated water quality numeric table

standards for specific metals are, therefore, also stringent values. These criteria are based on national scientific information about the effects of pollutants on aquatic life and the levels of pollutants in water that will generally ensure water quality adequate to support the designated use.

Because of the currently degraded water quality in Segment 2 of the Blue River, the State of Colorado Water Quality Control Commission (WQCC) has placed temporary modifications on the underlying chronic water quality criteria. These modifications were made because it will be difficult to address heavy metal pollution associated with historic mining activity in French Gulch and there is uncertainty as to how and when the underlying standards can be achieved. The modifications were originally based on ambient conditions or observed concentrations in Segment 2. This segment's ambient modification was temporary and expired on December 31, 1998. It is expected that this modification will be extended. The last extension of this modification occurred in the fall of 1996. The numeric water quality values associated with the Blue River Segment 2 temporary modification are not protective of the Cold Water Aquatic use classification.

3.3.2 French Creek

Below the W-O mine site, French Creek does not have water quality standards in place comparable to the Blue River. Instead, the State has set water quality standards at ambient conditions or observed concentrations due to the presence of substantial "irreversible" human-induced pollution. An aquatic life use has not been designated for this segment.

3.3.3 Numeric Water Quality Standards

The State of Colorado acute and chronic toxicity table standards for many metals are based on the hardness of the sampled water. Because of variable hardness associated with different sampling sites and events, there is not one fixed numeric standard concentration for a given substance. Cd and Zn concentrations in French Creek and the Blue River commonly exceed the State hardness adjusted toxicity standards. The other metals detected in French Creek and the Blue River are usually below State toxicity standards. In general, the hardness adjusted acute and chronic table standards for Zn in French Creek and the Blue River ranged from 60 micrograms per liter (ug/L) to 160 ug/L. The hardness adjusted chronic table standard for Cd ranged from 0.7 ug/L to 2.0 ug/L while the Cd acute table standard ranged from 5 ug/L to 14 ug/L (WQCC, 1995). To make comparisons of different sampling events and sites along French Creek and the Blue River for the hardness based standards, the EPA presented water quality plots for sampling sites as a relative percentage to the standard (EPA, 1997).

The French Creek and Blue River chronic toxicity table standards for Zn and Cd have been modified by the State to a fixed concentration (Table 3-1). The modified French Creek Cd chronic standard is 4.0 ug/L and the temporary modified Cd chronic Blue River standard is 4.3 ug/L. For Zn, the modified chronic standard for French Creek is 1,980 ug/L while the Blue River temporary modified chronic standard is 1,700 ug/L (WQCC, 1995). The State Cd and Zn acute toxicity table standards for French Creek and the Blue River were not changed.

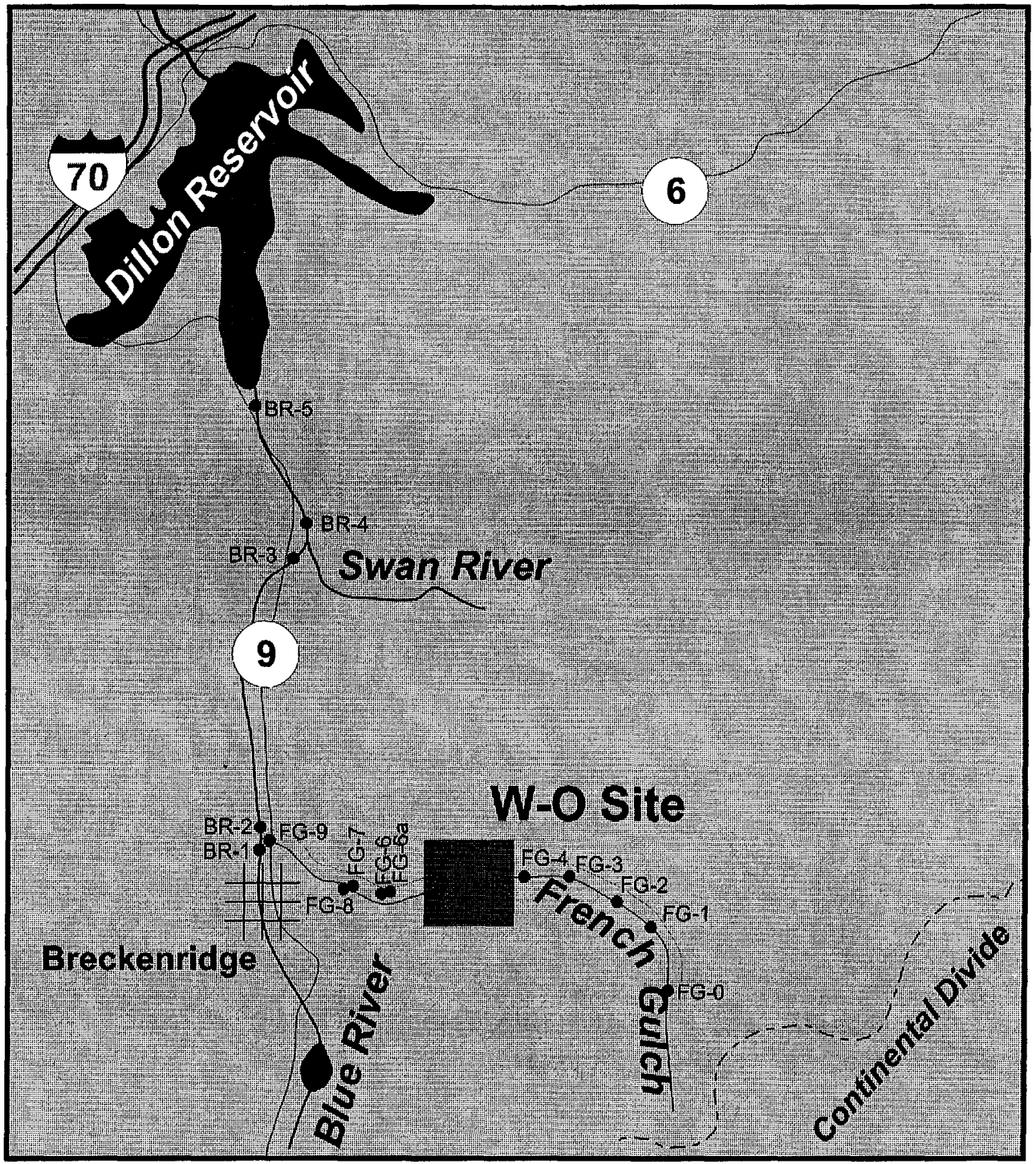
Table 3-1
French Creek and Blue River Modified Zn and Cd Chronic Standards

Stream (segment)	Zinc	Cadmium	Comment
Blue River (Blue River 2)	1,700 ug/L	4.3 ug/L	expired 12/31/98
French Creek (Blue River 11)	1,980 ug/L	4.0 ug/L	no expiration

3.4 French Creek and Blue River Water Quality

3.4.1 Summary of CDPHE and EPA Data

The major ion chemistry of French Creek above the W-O site is characterized by calcium bicarbonate. The calculated dissolved solids concentration in a July 1996 sampling event above the W-O site (EPA, 1996b) was 63 milligrams per liter (mg/L). This indicates that French Creek at the sampling site is a dilute headwaters stream (Kimball et. al., 1997). Below the mine site, the July 1996 sampling had calculated dissolved solids of 124 mg/L, nearly double that above the mine. The stream water type also had changed to calcium sulfate bicarbonate major ion chemistry. The Blue River and French Creek have near neutral to slightly basic pH values. Except for Fe, total recoverable metal concentrations are similar to dissolved metal concentrations in French Creek and the Blue River. Total recoverable Fe concentrations were usually much higher than dissolved concentrations in stream water, especially below the W-O mine site. This difference was probably due to the formation of Fe hydroxides, commonly in the form of colloidal material. A study by Kimball (1997a) for the NAWQA program evaluated the role of colloidal material in French Creek (Appendix 3-1). The Fe-rich colloidal material will readily aggregate and precipitate. This Fe-rich material can be observed as the ochre color (yellowboy) that coats sediments downstream of the W-O mine site. The colloidal material can scavenge other metals such as Zn, Cd, Cu, and Pb (Kimball, 1997a). A summary of the CDPHE and EPA water quality data is in Appendix 3-2.



Surface Water Quality Sample Locations

N

● FG-1 Surface Water Sample Location

Kilometers

0 8

0 5

Miles

Figure 3-1

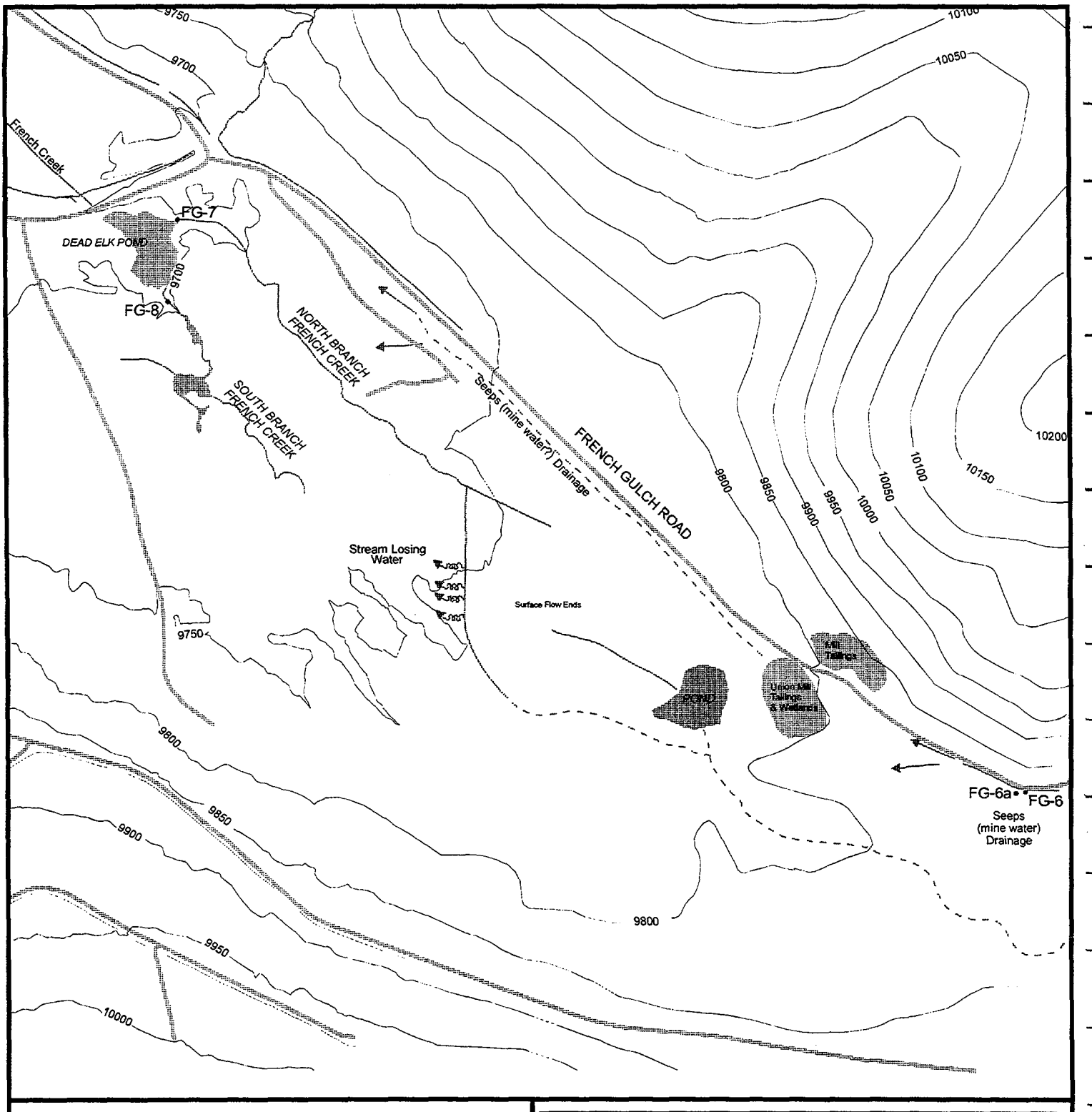


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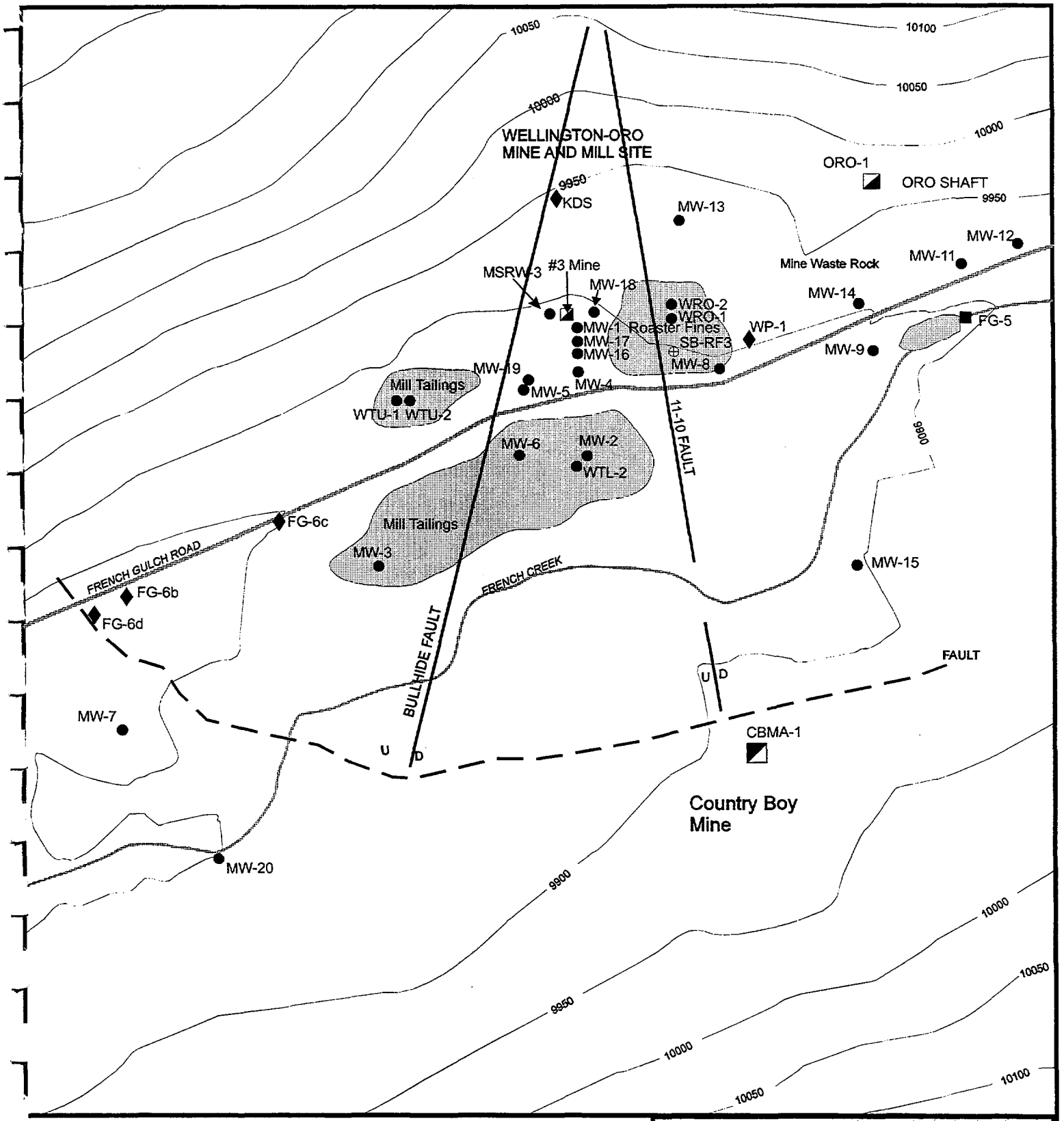
Figure 3-1a
Base Map Lower French Creek Area

Project Name: French Gulch

Project Number: CO97DE-056

Date: 12/19/97	Drawn By: MAA	Reviewed By: AM



Scale 1" = 250'

N

⊕ SBRF-3	Soil Boring
● MW-15	Monitoring Well (Locations are approximate)
◪ ORO-1	Mine Shaft
■ FG-5	Stream
♦ FG-6c	Seep

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Figure 3-2
Wellington-Oro Site Ground and Surface Water Sample Location Map

Project Name: French Gulch

Date: 12/19/97 | Drawn By: MAA | Reviewed By: AM

Table 3-2 summarizes the stream sites on French Creek and the Blue River that have been sampled since 1989. Figure 3-1 is a location map for the surface sampling sites in French Gulch and the Blue River. Figure 3-2 is a location map for the surface and ground-water sampling sites in the vicinity of the W-O mine site.

Water quality associated with the French Creek southern branch (FG-8 sampling site) was better than the other downstream sites. The southern branch receives minimal drainage from the W-O mine site (Figure 3-1a). The mine site is located on the northern side of the French Gulch valley. Consequently, the northern branch receives the majority of mine water drainage as observed at the FG-7 sampling site (Kimball et. al., 1997). FG-7 Zn and Cd concentrations were 2 to 5 times greater than the observed concentrations at FG-8. For most of the year the main French Creek tributary below the W-O mine site flows through the northern branch (Figure 3-1a). Therefore, any W-O mine drainage to the southern branch is believed to occur via alluvial ground-water discharge and subsurface flow in the placer tailings that originated from losing stream reaches associated with the northern branch. During peak high flow conditions, the main French Creek tributary may be breached with some surface flows reaching the southern branch. The FG-9 stream sampling site represents the merger of the two branches below "Dead Elk" Pond (Figure 3-1 and 3-1a). In the fall of 1998 surface cleanup project, the upgradient relatively clean main branch of French Creek was diverted to the south branch. The purpose of the diversion was to segregate clean stream water from the contaminated northern branch.

Table 3-2
French Creek and Blue River Sampling Sites

Stream Sampling Site	Description
FG-0	French Creek upstream of Farncomb Hill
FG-1	French Creek near the Wire Patch Mine
FG-2	French Creek due south of the McLeod Tunnel
FG-3	French Creek due south of Mineral Hill
FG-4	French Creek due south of X.10.U.8 (Extenuate) Inclined Shaft
FG-5	French Creek upstream of Wellington-Oro Mine Site
FG-7	North Branch of French Creek , Upstream of "Dead Elk" Pond, Downstream of Wellington-Oro Mine Site
FG-8	South Branch of French Creek, Upstream of "Dead Elk" Pond, Downstream of Wellington-Oro Mine Site
FG-9	French Creek approximately 50 meters upstream from confluence with the Blue River
BR-1	Blue River approximately 15 meters upstream from the confluence with French Creek
BR-2	Blue River approximately 50 meters downstream from the confluence with French Creek
BR-3	Blue River at the Tiger Run Resort, approximately 3.3 miles downstream from the confluence with French Creek

Figure 3-3 is a plot of stream discharge or total flow measurements for the French Creek and Blue River sampling sites. The June and July 1996 samplings were the only high flow events conducted since 1989. The discharge measurements on the Blue River and downstream of French Creek site FG-5 suggest that these stream segments are predominantly gaining reaches. Substantial stream flow losses on French Creek are indicated by the difference in discharge measurements between the FG-3 and FG-5 sites.

3.4.1a Cadmium

Figure 3-4 is a plot of dissolved Cd concentrations with the French Creek and Blue River modified chronic standards. Cd concentrations in French Creek above the W-O site (FG-5) and in the Blue River above the confluence with French Creek (BR-1) were usually below laboratory detection limits. Below the W-O site, the dissolved French Creek Cd concentrations at sampling site FG-7 ranged from 5.2 ug/L to 11.7 ug/L during seven sampling events. All of the FG-7 and FG-9 sampling events exceeded the French Creek State modified chronic Cd standard of 4.0 ug/L. Three out of eight sampling events for the FG-8 sampling site exceeded the modified standard. The Blue River sampling site below the French Creek confluence (BR-2) had dissolved Cd concentrations that ranged from 1.1 ug/L to 6.8 ug/L (Figure 3-4). Four out of eight sampling events exceeded the Blue River State modified Cd chronic standard of 4.3 ug/L.

Figure 3-5 is a plot of percentage of dissolved Cd relative to the State hardness adjusted chronic table standards. Table standards protect the designated use for the Blue River and French Creek above the W-O site. This plot shows that all the French Creek sampling sites downstream of the W-O site exceeded State chronic table standards by several orders of magnitude. The Blue River sampling sites below the confluence with French Creek (BR-2) were approximately four times the State hardness adjusted chronic table standards during low flows and twice the standards during high flow conditions. In contrast, the FG-7 and FG-9 French Creek sampling sites had their greatest percentage relative to table standards during high flow conditions (Figure 3-5).

Figure 3-6 is a plot of relative percentage of dissolved Cd to the State hardness adjusted acute table standards. The acute Cd table standards were only exceeded in the two 1996 high flow-sampling events at the FG-7 sampling site. The other sampling events at FG-7 and all the other sites on French Creek and the Blue River did not exceed the State hardness adjusted acute standards.

3.4.1b Zinc

Figure 3-7 is a plot of dissolved Zn concentrations with the French Creek and Blue River modified chronic standards. This plot shows low concentrations above the W-O site (FG-5), above the confluence on the Blue River (BR-1), and a few miles downstream of the French Creek confluence on the Blue River (BR-3). The dissolved Zn concentrations in French Creek at FG-5 ranged from 10 ug/L to 109 ug/L during seven sampling events. Zn concentrations on the Blue River above the confluence with French Creek (BR-1) ranged from 7 ug/L to 60 ug/L during eight sampling events. Downstream of the W-O site, the French Creek FG-7 sampling site ranged from 2,127 ug/L to 9,300 ug/L. All of the FG-7 sampling events exceeded the French Creek modified chronic standard for Zn of 1,980 ug/L. Further downstream from the FG-7, the FG-9 site exceeded the modified standard in five out of eight sampling events with the remaining three events very close to the standard. Below the French Creek confluence (BR-2), the Blue River dissolved Zn concentrations ranged from 367 ug/L to 4,200 ug/L. Four out of eight sampling events at this site exceeded the State modified chronic standard of 1,700 ug/L.

Figure 3-8 is a plot of relative percentage of dissolved Zn concentrations to the State hardness adjusted chronic table standards for Zn. As previously stated, table standards protect the designated use for the stream. This plot shows that all the French Creek sampling sites below the W-O site exceeded the chronic standards by several orders of magnitude. The upstream French Creek FG-5 site and the Blue River BR-1 site above the confluence with French Creek have Zn concentrations close to the State hardness adjusted chronic table standards for Zn. The Blue River site BR-2 exceeds the chronic table standards by several orders of magnitude, while the downstream BR-3 site is at the standards during low flows and exceeds the chronic table standards at high flows (Figure 3-8). It is believed that the natural background concentration of Zn is high due to the regional geology and historical mining activity throughout the area. This is why the BR-1 and FG-5 sites have Zn concentrations close to table standards.

Figure 3-9 is a plot of relative percentage of dissolved Zn concentrations to the State hardness adjusted acute table standards. The acute toxicity table standards for Zn are very similar to the chronic toxicity table standards. Consequently, the State acute toxicity standards are exceeded by several orders of magnitude downstream of the W-O site on French Creek and on the Blue River just below the confluence with French Creek.

3.4.1c Other Metals

The other metals that were detected at elevated levels in French Creek and the Blue River are Pb, Fe, Mn, Cu, and Al. The concentration levels for these metals are usually below State standards. The hardness adjusted chronic table

standards for dissolved Pb was exceeded during several sampling events in the French Creek sampling sites downstream of the W-O site (Figure 3-10). Dissolved Al concentrations exceeded the State chronic standard of 87 ug/L during one sampling event at the French Creek FG-7 site. The State's total recoverable Fe chronic standard of 1,000 ug/L was also only exceeded during one sampling event at the downstream Blue River BR-3 site while the other sampling sites had total Fe concentrations below the standard. The State dissolved chronic standards for Fe have not been exceeded during the sampling events (Figure 3-11). The total recoverable Mn chronic standard of 1,000 ug/L was exceeded in two out of seven sampling events at the French Creek FG-7 site. The other sites had total recoverable Mn concentrations below the standards. Cu had dissolved concentrations consistently less than State chronic and acute toxicity table standards.

3.4.2 Summary of NAWQA Data

In 1991, the U.S. Geological Survey began a National Water-Quality Assessment (NAWQA) program. The long-term goals of the NAWQA program were to describe the status and trends in the quality of a large, representative part of the U.S. surface and ground water resources and to identify the major natural and human factors that affect the quality of these resources (Driver, 1994). In addition to water quality, this program also evaluates contaminants in biological tissue and streambed sediment. Seven sites in the Upper Colorado River Basin were sampled by NAWQA to assess the occurrence and distribution of contaminants in fish livers and bed sediment (Table 3-3). These sites have similar geology, climate, and habitat (NAWQA, 1997b).

Table 3-3
NAWQA Upper Colorado River Basin Sampling Locations

Stream Sampling Site	Description
Blue	Blue River below French Creek near Breckenridge, CO (similar to EPA site BR-2)
Baker	Colorado River below Baker Gulch near Grand Lake, CO
Gore	Gore Creek at mouth near Minturn, CO
East	East River below Cement Creek near Crested Butte, CO
Gunn 32	Gunnison River at County Road 32 near Gunnison, CO
Uncom	Uncompahre River near Ridgway, CO
Gunn T.	Gunnison River below Gunnison Tunnel near Montrose, CO

The results of trace elements analysis in the fish livers and bed sediment show levels of Cd to be highest on the Blue River below French Creek as compared to the other sites in the NAWQA study (Figure 3-12). The Cd concentration in bed sediment at the Blue River site is 11 parts per million (ppm). This exceeds the

probable effect level of 3.5 ppm (NAWQA, 1997b). Adverse biological consequences are predicted to occur frequently at concentrations above the probable effect levels. The Zn and Pb bed sediments probable effect guidelines were also exceeded. The Zn guideline is 315 ppm and the Pb guideline is 91 ppm. Figure 3-13 is a plot of Cd, Zn, and Pb levels for bed sediment in French Gulch at the FG-9 sampling site. The probable effect levels for these metals were also exceeded at this site.

There are no existing guidelines for metal concentrations in fish livers. Elevated levels for Cd, Zn and Pb in fish livers were observed (NAWQA, 1997b). Figure 3-12 also shows the Cd concentrations in fish livers for the Upper Colorado River Basin sampling locations.

The NAWQA water quality stream sampling sites for French Creek and the Blue River are listed in Table 3-4. Results of the 1996 high flow sampling event for Zn, Cd, Pb, and Mn are compared with the EPA results in Figures 3-14 through 3-20. Comparisons with State table value and modified standards showed similar patterns to the historic EPA and CDPHE water quality sampling events previously discussed.

3.4.2a French Creek

Above the Country Boy Mine (TS-3°) and W-O sites, dissolved Zn concentrations in French Creek were less than the State acute and chronic table standards and the French Creek modified chronic standard (Figure 3-14). The dissolved Cd concentrations were also less than the State chronic table standards and the French Creek modified chronic standard above the W-O site (Figure 3-15). Below the W-O mine site, Cd and Zn dissolved concentrations exceeded State table standards. The modified Cd chronic standard was also exceeded below the W-O site. Dissolved Pb concentrations were consistently lower than the State acute table value standards (Figure 3-16). The State chronic table Pb standards were slightly exceeded at the FG-1° sampling site above the W-O, and sampling sites downstream from FG-7° (Figure 3-16). The FG-1° site is located near the Wire Patch Mine. For dissolved Mn, the State chronic standards were not exceeded (Figure 3-17).

3.4.2b Blue River

Dissolved concentrations of Cd and Zn did not exceed the Blue River modified chronic standards at any stream sites during the 1996 NAWQA and EPA high flow sampling events (Figures 3-18 and 3-19). Above the confluence with French Creek, dissolved Zn concentrations in the Blue River were less than the State acute and chronic table standards (Figure 3-18). The dissolved Cd concentrations were also less than the State chronic table standards above the French Creek confluence (Figure 3-19). Below the confluence, dissolved Zn

Table 3-4
NAWQA French Creek and Blue River Sampling Sites

AGS Designated NAWQA Stream Sampling Sites	NAWQA Designated Stream Sampling Sites (ID#)	EPA Equivalent Stream Sampling Sites	Description
FG-0°	FRENCH GULCH ABV FARNCOMB HILL (392838105572900)	FG-0	French Creek above Farncomb Hill, over 2.25 miles upstream of W-O site
FG-1°	FRENCH GULCH ABOVE RICH GULCH NR LINCOLN, CO (392908105583600)	FG-1	French Creek above Rich Gulch near Lincoln, CO, over 1.25 miles upstream of W-O site.
TS-3°	FRENCH GULCH AT COUNTRY BOY MINE (392855106005200)	None	French Creek at Country Boy Mine, just below road to Country Boy
TS-4°	FRENCH GULCH BLW FORD GULCH (392849106011500)	None	French Creek below Ford Gulch, approximately 0.25 miles downstream of W-O mine site
FG-7°	FRENCH GULCH ABV GIBSON GULCH (392907106013900)	FG-7	French Creek above Gibson Gulch, over 0.6 miles downstream of W-O mine site, approximately 100 meters upstream of EPA sampling site FG-7
FG-9°	FRENCH GULCH AT BRECKENRIDGE, CO (9046530)	FG-9	French Creek just upstream of confluence with Blue River, similar to EPA sampling site FG-9
BR-1°	BLUE RIVER AT ADAMS ST AT BRECKENRIDGE, CO (392846106024600)	BR-1	Blue River at Adams Street in Breckenridge, over 0.75 miles upstream of French Creek confluence
BR-2°	BLUE RIVER BELOW FRENCH GULCH NR BRECKENRIDGE, CO (392947106024500)	BR-2	Blue River over 0.25 miles downstream from French Creek confluence.
BR-4°	BLUE RIVER NEAR DILLON, CO. (9046600)	BR-4	Blue River near Swan Mountain road before it flows into Dillon Reservoir

concentrations exceeded the State table standards. The State Cd chronic table standard was also exceeded from the French Creek confluence to sampling site BR-3. Dissolved Pb concentrations were consistently lower than the State acute and chronic table standards. The State Mn chronic standard of 50 ug/L was exceeded at sampling sites BR-2 and BR-2° (Figure 3-20).

3.4.3 Summary of Breckenridge Sanitation District Data

In May of 1997, AGS received a digital copy of the Blue River water quality data that was compiled by the Breckenridge Sanitation District (BSD) from 1986 to 1994 (BSD, 1997). The EPA requested that AGS integrate the BSD data with the EPA water quality data. The BSD Blue River stream sites are summarized with the EPA sites in Table 3-6. Ground-water monitoring wells were located west of the Blue River between Cemetery Road and County Road #3 in the vicinity of the "Airport" site (Figure 3-21). The "Airport" site is approximately ¼ to 1 mile downstream of the confluence with French Creek. The purpose of the BSD water quality study was to evaluate the impact of wastewater sludge land application.

Table 3-6
Environmental Protection Agency (EPA)
and
Breckenridge Sanitation District (BSD)
Blue River Stream Sampling Sites

Stream Sampling Site	Description
BR-1	EPA site approximately 50 feet upstream from the confluence with French Creek
BR-2	EPA site approximately 115 feet downstream from the confluence with French Creek
River #0	BSD site at Rec. Center Bridge, approximately 600 feet downstream from the confluence with French Creek
River #1	BSD site at Cemetery Road, approximately 1,040 feet downstream from the confluence with French Creek
River #2	BSD site at County Road, approximately 6,500 feet downstream from the confluence with French Creek
BR-3	EPA site at Tiger Run Resort, approximately 17,400 feet downstream from the confluence with French Creek
BR-4	EPA site approximately 17,600 feet downstream from the confluence with French Creek, 65 feet upstream of the confluence with Swan River

The BSD water quality data included nitrogen species (ammonia, nitrate, organic, and total), pH, total phosphorous, and selected dissolved metals (Al, Cd, Cu, Pb, Ni, and Zn). Except for Zn, the detection limits for the metals were above the observed EPA concentrations for the Blue River. Consequently, only the BSD Zn concentrations could be used to compare with the EPA Blue River water quality data. The BSD stream sites provided additional coverage between the EPA BR-2 and BR-3 stream sites, a crucial impacted segment of the Blue River below the confluence with French Creek and above the "rockpile" where most of the Blue River surface flow disappears. Figures 3-22, 3-23, and 3-24 are plots of EPA and BSD dissolved Zn concentrations with distance downstream from French Creek during low flow sampling events. September 1992, October 1993, and August 1994 were the only periods in which the BSD and EPA sampling events corresponded with similar flow conditions. In September of 1992, between Cemetery Road, just below the confluence with French Creek, and County Road #3, the dissolved Zn concentrations decreased from over 2,000 ug/L to 210 ug/L (Figure 3-22). A similar decrease was observed in the October 1993 and August 1994 sampling events (Figures 3-23 and 3-24). The Zn concentrations in this segment were above State hardness adjusted chronic standards. A significant increase in flow on the Blue River between Cemetery Road and County Road #3 was observed during fish shocking activities. This increase in flow was attributed to a west-bank ground-water fed tributary. The tributary was observed to have an abundant fish population. Bill Schroeder from the EPA Region 8 Lab estimated that the tributary might contribute from one-fifth to one-fourth of the observed Blue River flow (Schroeder, pers. comm., 1997). There was no flow measurements conducted in this area. Below the "rockpile" and just above the confluence with the Swan River, the Blue River dissolved Zn concentrations were consistently below State chronic standards (Figures 3-22, 3-23 and 3-24). It appears that the dilution from clean ground-water inflow to the Blue River may be responsible for a significant portion of the decrease in Zn concentrations.

Stream discharge rates are only available for the EPA data (Figure 3-25). The EPA total flow measurements showed that there were significant increases in the Blue River stream flow between the French Creek confluence (BR-2) and EPA stream site BR-3. As previously discussed, these flow increases were probably due to ground-water inflows. Multiplying the stream discharge by Zn concentration results in total Zn loading associated with each sampling site (Figure 3-26). The Blue River stream segment between BR-2 and BR-3 consistently displayed decreases in total Zn loading. These decreases cannot be explained by ground-water dilution. The loading decreases may be due to natural attenuation and/or loading increases associated with the ground-water flow at the BR-3 Blue River site. Most of the surface flow disappears in the "rockpile" above the BR-3 site. It is possible that some of the metal laden surface waters that flows into the "rockpile" is not daylighting at the Blue River site BR-3, but remains as subsurface or ground-water flow. In addition, geochemical processes in the "rockpile" and associated ground-water flow may result in the

precipitation of metals, including Zn. This is commonly referred to as natural attenuation.

Figures 3-27 and 3-28 show high and low flow (May and September) ground-water dissolved Zn concentrations for the 1992 BSD data. As previously mentioned, the BSD data did not include flow measurements. The low Zn concentrations in the most distant western monitoring wells to the Blue River implies that the ground-water on the west side of the Blue River valley was relatively clean compared to the instream Blue River concentrations. The high Zn concentrations at monitoring wells #6 and #7 suggest minimal mixing in this area with clean ground-water. In contrast, the upstream monitoring well #3, which is relatively close to the Blue River, had low Zn concentrations suggesting that this area is being influence by clean ground-water. The greater decrease in Zn concentrations between the River sites #1 and #2 in low flow conditions suggest that a relatively constant clean ground-water flow to the river have greater dilution influence during low stream flows.

Figures 3-29 and 3-30 are plots of the seasonal variations in dissolved Zn concentrations for BSD Blue River sites #0 (Rec. Center Bridge) and #2 (County Road #3). The range in seasonal flows for the Blue River below the confluence with French Creek was from less than 10 cubic feet per second (cfs) to over 200 cfs (Figure 3-25). Dissolved Zn concentrations in the Blue River just below the confluence with French Creek varied from approximately 500 ug/L during high flow conditions to above 2,000 ug/L during low flow conditions (Figure 3-29). In contrast, the downstream BSD Blue River sampling site at County Road #3 had its higher seasonal Zn concentrations, over 350 ug/L, associated with high flow conditions while the lower concentrations, below 200 ug/L, corresponded to low flow conditions. These variations between sampling sites could be explained by a relatively constant clean ground-water inflow that has greater dilution influence during low flow conditions. Based on the observed reduction in Zn concentrations and assuming the reduction was due to dilution, the magnitude of ground-water flow in the Blue River alluvial valley and placer material could be greater than 100 cfs. As previously discussed, ground-water inflow in this segment of the Blue River has been documented by Bill Schroeder during fish shocking activities in 1997 (Schroeder, pers. comm., 1997). The significant ground-water flow with its possible associated metal attenuation capacity may also explain the reduction in downstream Blue River zinc loading (Figure 3-26).

3.5 Wellington-Oro Mine and Mill Site Ground-Water Quality

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. Eight ground-water-monitoring wells were initially drilled at the site in 1991. Additional wells were drilled in 1993, 1994, and 1996. Two of the wells drilled in 1996 (MW-19 and MW-20) were funded by the EPA Headwaters Grant to the Colorado Division of Minerals and Geology (DMG). Monitoring well MW-20 was drilled as a background alluvium monitoring well on the south side of French Gulch valley downgradient from the W-O site. MW-19 was drilled for the purpose of completing a well in the alluvium, Bullhide Fault, and fractured shale bedrock. MW-19 was completed with a continuous slotted liner for determining flow directions and rates between the hydrologic units using borehole geophysical methods. The BOR drilled seven wells and soil borings in 1996. The abbreviated designations for the BOR wells and soil borings are EXO-1, EXO-2, WRO-1, WRO-2, WTU-1, WTU-2, and WTL-2. Table 3-6 summarizes the monitoring well completion intervals. The well locations are plotted on Figure 3-2. Different prefixes have been used in the past to designate the monitoring wells. For consistency, with the exception of the BOR wells and soil borings, this report uses the (MW) prefix to designate ground-water-monitoring wells. The pre-1994 well completions at the site commonly included two inch diameter PVC well casing with at least two separate five or ten foot screens. Most of the (MW) monitoring wells were sampled in water quality studies conducted in 1993, 1994, and 1996 (EPA, 1993b, 1994, 1996a and 1996b). Multiple screened intervals were usually not isolated during sampling, although metal concentrations were commonly higher in water samples from the upper alluvial-screened intervals when isolated in monitoring wells MW-6, MW-7, and MW-8. The monitoring wells that had screened intervals isolated with a packer system during sampling were designated by upper (U) or lower (L) screened interval with their well number.

During the June 1996 sampling event, the USGS NAWQA program, in coordination with the EPA and DMG, sampled and analyzed five ground-water monitoring wells (MW-2, MW-12, MW-13, MW-15, and MW-20), three ground-water seeps (KDS, 1121, and FG-6C), and the Oro Mine Shaft (ORO-1). Appendix 3-3 is a compilation of water quality data from the monitoring wells since 1992. Figures 3-31 through 3-36 are plots of pH, total recoverable metal concentrations (Zn, Cd, Fe, Pbg, and Mn) and sulfate concentrations for sampling events since 1993. These plots include monitoring wells and seeps segregated by the following classifications:

- clean background wells,
- contaminated alluvial wells,
- contaminated multiple screened alluvial and bedrock wells,
- contaminated bedrock wells,
- contaminated seeps and roaster fines, and
- contaminated mine pool water.

Table 3-6
Summary of Ground-water Monitoring Wells

Well	Top Alluvium (ft below surface)	Top Bedrock (ft below surface)	Total Depth (ft below surface)	Screened Intervals (ft below surface)	Comments
MW-1	6	42 (clay) 44 (shale)	50	22-27 (5') 33-43 (10)	contaminated alluvial well at mine site
MW-2	22	41 (porphyry)	47.5	37-47 (10)	contaminated alluvial and porphyry well below mill tailings, downgradient of mine site
MW-3	6	53 (shale)	55	15-25 (10') 45-50 (5')	contaminated alluvial well below mill tailings, downgradient mine site and Bullhide Fault
MW-4	7	55 (clay) 56 (shale)	64	20-30 (10') 46-51 (5') 58-63 (5')	contaminated alluvial and shale bedrock well at mine site
MW-5*	5	52 (shale)	55	20-30 (10') 50-55 (5')	contaminated alluvial and shale bedrock well downgradient of mine site and near Bullhide Fault
MW-6*	25	40 (clay) 42 (shale)	54	34-44 (10') 49-54 (5')	contaminated alluvial and shale bedrock well below mill tailings, downgradient mine site, and near Bullhide Fault
MW-7	12	50 (porphyry)	52	18-23 (5') 38-48 (10')	contaminated alluvial well downgradient mine site and mill tailings
MW-8*	5	43 (shale)	46	15-20 (5') 35-45 (10')	contaminated alluvial well downgradient roaster fines and near 11-10 Fault
MW-9	17	51 (clay) 52 (shale)	54.5	43-53 (10')	clean alluvial well upgradient mine site
MW-11	10	29 (shale)	43	23-28 (5') 38-46 (10')	clean alluvial and shale bedrock well upgradient mine site
MW-12	NP	10 (porphyry)	46	40-45 (5')	clean porphyry bedrock well upgradient mine site
MW-13	13	28 (shale)	47	36-46 (10')	contaminated shale bedrock well below roaster fines and mine waste, near 11-10 Fault
MW-14	2.5	38 (shale) 101 (porphyry)	278	268-278 (10')	clean 11-10 Fault well upgradient mine site

Table 3-6 continued

Well	Top Alluvium (ft below surface)	Top Bedrock (ft below surface)	Total Depth (ft below surface)	Screened Intervals (ft below surface)	Comments
MW-15	3	15 (shale)	46	36-46 (10')	clean shale bedrock well, south side valley, east of Country Boy Mine
MW-16	8	46.5 (porphyry) 70 (shale)	91	71-91 (20')	contaminated shale bedrock well at mine site, observation well during 1994 aquifer tests
MW-17	9	55 (porphyry) 70 (shale)	93	70-90 (20')	contaminated shale bedrock well at mine site, pump well during 1994 aquifer tests
MW-18	7	39 (shale)	43	20-40 (20')	contaminated alluvial well at mine site, pump well during 1994 aquifer tests
MW-19	8	51 (shale)	110	30-110 (80')	contaminated alluvial, Bullhide Fault, and bedrock well
MW-20	0	20 (porphyry)	50	15-25 (10')	clean alluvial well south side valley, downgradient mine site
MSRW-3	0	45 (shale)	110	68-110	relief well for #3 Mine Shaft, open hole completion using washed rock, mine stope or cave-in possible below 97 feet
EXO-1	NP	NA	13.6	7.8-12.8	X10U8 mine waste soil boring
EXO-2	NP	10.2? (shale)	10.2	4.7-9.7	X10U8 mine waste soil boring
WRO-1*	14.5?	NA	18.1	14.1-18.1	contaminated roaster fines/alluvial well
WRO-2*	14.2?	NA	16.6	6.7-11.7	contaminated roaster fines well
WTU-1*	NP	NA	13.5	10.5-13.5	north mill tailings well
WTU-2*	NP	NA	8.0	3.0-8.0	north mill tailings well
WTL-2	NP	NA	19.5	14.1-19.1	contaminated south mill tailings well
SBRF-3*	NP	NA	13	NA	soil boring in roaster fines, 2" PVC pipe open at total depth

NP - not present
NA - not applicable
* - plugged and/or abandoned during Fall 1998 surface waste cleanup project

Dissolved and total recoverable metal concentrations were usually very similar with the exception of Pb and occasionally Fe and Mn that had lower dissolved concentrations.

3.5.1 Clean Background Monitoring Wells

The clean background wells were MW-9, MW-11, MW-12, MW-14, MW-15, and MW-20 (Figures 31a through 31g). Monitoring wells MW-9 (alluvium), MW-11 (shale bedrock and alluvium), MW-12 (porphyry bedrock), and MW-14 (11-10 Fault) were immediately upgradient of the W-O site (Figure 3-2). The MW-15 shale bedrock well was upgradient of the W-O site and located on the south side of the French Gulch valley, east of the Country Boy Mine. MW-20 (alluvium and porphyry bedrock) was downgradient of the W-O site and located immediately south of French Creek. The deep 11-10 Fault monitoring well, MW-14, was drilled with a polymer-based fluid that plugged the well screen and resulted in low metal and sulfate concentrations during initial water quality studies. As this well has been purged and developed during multiple sampling events, the metal and sulfate concentrations have increased, but the concentrations have remained relatively low and are considered clean background ground-water. With the six sampling events conducted in 1996 and 1997 between the EPA and stable isotope studies, it is believed that the concentrations have stabilized in MW-14 and the well has been completely developed.

Discounting the 1993 and 1994 concentrations in MW-14 when the well screen was plugged with the polymer-based drilling fluid, the ranges of background concentrations for all the clean background wells are:

- 33 ug/L to 5,278 ug/L for Zn,
- below laboratory detection limits to 28 ug/L for Cd,
- 0.2 mg/L to 16.6 mg/L for Fe,
- 0.03 mg/L to 5.2 mg/L for Mn,
- 0.05 ug/L to 47.4 ug/L for Pb, and
- 16.7 mg/L to 560 mg/L for sulfate (SO_4).

The background monitoring wells had near neutral waters with pH values that ranged from 6.5 to 7.8 standard units (s.u). The high sulfate concentrations were associated with the 11-10 Fault well while the high metal concentrations were associated with the bedrock and/or 11-10 Fault wells.

3.5.2 Mine Pool

The Wellington-Oro and Country Boy mine pool waters were not analyzed in sampling events prior to 1996. This discussion presents the results of the 1996 sampling events. The W-O mine waters were also sampled during characterization studies in 1997 and 1998. The results from these studies are

reviewed in section 7 of this report. Selected metals (Zn, Cd, and Fe) for the W-O mine pool waters were also analyzed during stable isotope tracer studies in 1996 and 1997 (RAS, 1996a, 1996b, 1997a, and 1997b). The results from these studies are discussed in section 5 of this report.

The County Boy mine is located due south of the W-O site on the south side of the French Gulch valley (Figures 3-1 and 3-2). The Country Boy mine pool sample came from a discrete adit discharge at the main mine portal. This discharge flows to a wetland area immediately northwest of the Country Boy and eventually drains into French Creek.

The W-O mine pool has been sampled at two different locations; the #3 Mine shaft relief well (MSRW-3) and the Oro Mine shaft (ORO-1). The #3 Mine shaft has a depth from surface of 110 feet and intersects a mine level that was not directly connected to the main Oro levels (Figure 3-37). The Oro Mine shaft is over 600 feet in depth and intersects seven mine levels. The Oro Shaft was sampled with a bailer on a 100-foot line or by the USGS NAWQA submersible pump on a 100-foot hose and line. Water levels for the Oro Mine shaft during sampling ranged from 69 feet to 88 feet below surface.

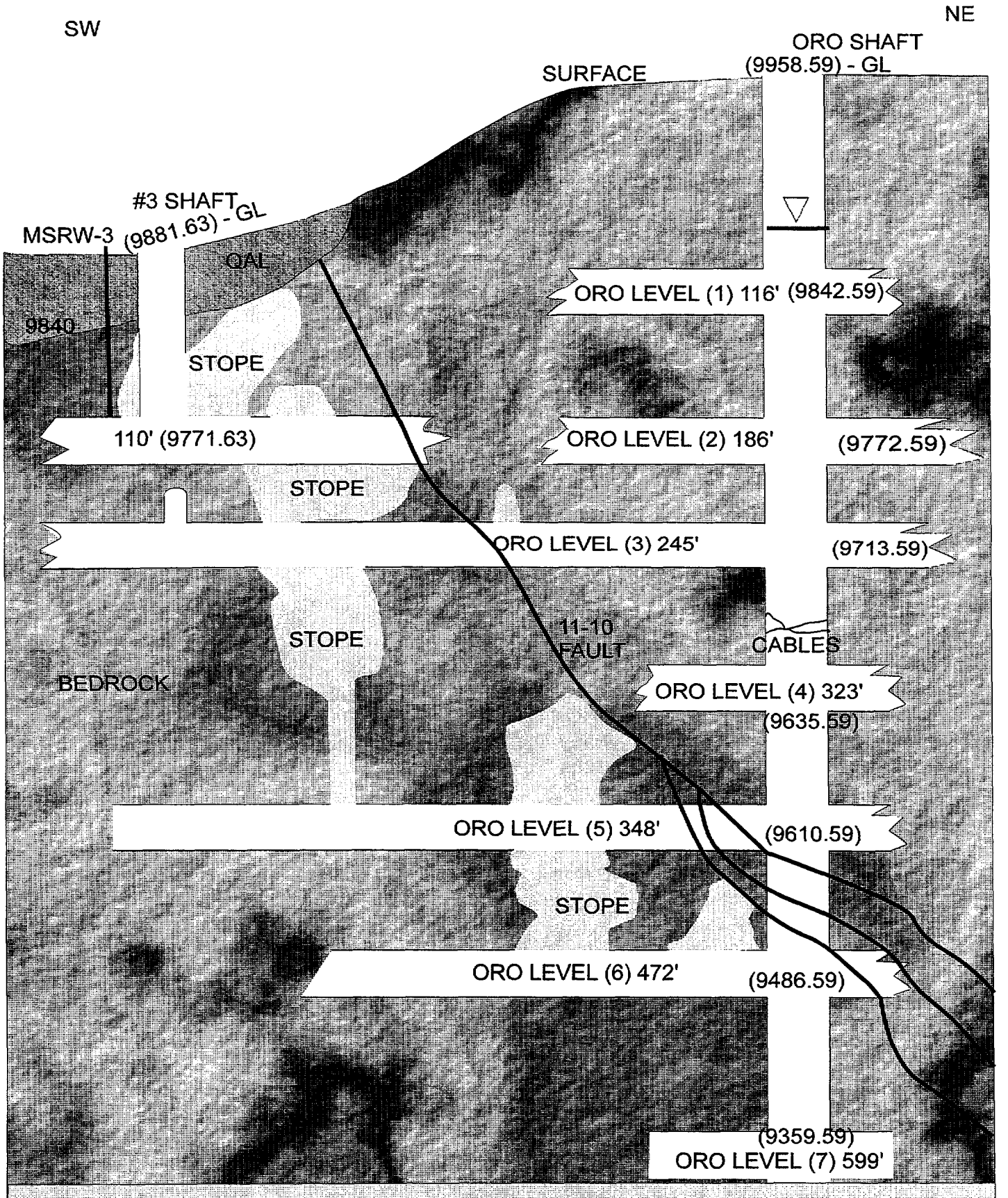
The W-O mine pool waters were more acidic than the near neutral Country Boy Mine water (Figure 3-32a). The upper Oro Shaft mine pool had slightly lower pH values than the #3 Mine shaft relief well. Metals and sulfate concentrations for the W-O mine pool samples were orders of magnitude greater than the Country Boy concentrations (Figure 3-32a through 3-32g). This is probably due to the significantly greater amount of water that flows through the W-O mine. W-O mine pool concentrations ranged from:

- 166,840 ug/L to 216,770 ug/L for Zn,
- 278 ug/L to 651 ug/L for Cd,
- 76.8 mg/L to 175.7 mg/L for Fe,
- 33.9 mg/L to 50.0 mg/L for Mn,
- 453.3 ug/L to 727.6 ug/L for Pb, and
- 1,290 mg/L to 2,360 mg/L for sulfate (SO_4).

The water quality between the #3 Mine relief well and the upper portion of the Oro Mine shaft varied. The concentrations were generally higher in the #3 Mine relief well, especially for Fe, Mn, and SO_4 (Figures 3-32d, 3-32f, and 3-32g). See section 7 of this report for further discussions on the W-O mine pool chemistry.

3.5.3 Contaminated Alluvial Monitoring Wells

The monitoring wells that had screened interval(s) in predominantly the alluvial aquifer were MW-1, MW-3, MW-7, MW-8, and MW-6U. Except for the MW-8U August 1994 sampling event and MW-7 water quality results, the pH, metal concentrations, and sulfate concentrations were similar to the W-O mine pool



SCHEMATIC DIAGRAM OF THE ORO AND #3 SHAFTS

MINE LEVEL DEPTHS MEASURED FROM GROUND SURFACE

(elevation in feet above sea level)

NOT TO SCALE

DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

Figure 3-37

(Figure 3-33a to 3-33g). The MW-8U August 1994 concentrations were orders of magnitude greater than the W-O mine water and other contaminated alluvial monitoring wells and had significantly lower pH values. The MW-7 concentrations were consistently lower than the other contaminated alluvial wells and mine water and had near neutral water.

MW-8 was located immediately downgradient of the roaster fines (Fig. 3-2). During remedial activity on the roaster fines in the fall of 1998 this well was plugged and abandoned. It is believed that the high August 1994 concentrations associated with the upper-screened interval in MW-8 were being influenced by leachate from the roaster fines. Monitoring well MW-7 was the furthest downgradient contaminated alluvial well from the W-O site (Figure 3-2). The lower concentrations associated with this well were believed to be due to dilution with clean alluvial ground-water and possibly natural attenuation. Subsequent direct flow measurements with a colloidal borescope measured preferential flow velocities in the alluvium to be as high as 460 feet per day (see section 7 of this report). Injection of a tracer in the alluvium also suggested significant flow and dilution associated with the alluvial ground-water (see section 4 of this report).

3.5.4 Contaminated Bedrock Monitoring Wells

The monitoring wells that were completed or sampled in the fractured shale bedrock were MW-13, MW-16, and MW-6L. The metals concentrations for MW-16 and MW-6L were usually lower than the mine pool waters, especially the mine water from MSRW-3 (Figures 3-34b through 3-34f). Sulfate concentrations for these wells were comparable to the mine pool (Figure 3-34g). It is believed that mine water is discharging into the fractured bedrock in the area of these monitoring wells. It is possible that natural attenuation or retardation of metals is occurring with fracture flow in the bedrock. Sulfate is usually conservative, consequently the sulfate concentrations in the bedrock remain similar to the mine waters.

Zn, Cd, Mn, and SO_4 concentrations were much higher in MW-13 than the mine pool. MW-13 had very low pH in the June 1996 sampling (Figure 3-34a). It was believed that the high concentrations associated with MW-13 and low pH were due to leachate from the nearby roaster fines and waste rock. The MW-13 Fe concentrations were lower than the mine pool while Pb concentrations were similar to the mine pool.

3.5.5 Contaminated Alluvial and Bedrock Monitoring Wells

The monitoring wells that had multiple screened intervals in the alluvial aquifer and bedrock were MW-2, MW-4, MW-5, and MW-6. Except for MW-2, these wells had multiple screened intervals that had at least one screened interval in the alluvium and shale bedrock (Table 3-6). MW-2 completion was a single screen ten feet in length that covered the base of the alluvium and top of the

porphyry bedrock. The alluvium and bedrock wells were very similar in metal and sulfate concentrations to the bedrock only monitoring wells (MW-16 and MW6L) (Figures 3-35b through 3-35g). The pH values indicated that these wells had ground-water that ranged from slightly acidic to neutral (Figure 3-35a).

3.5.6 Ground-water Seeps

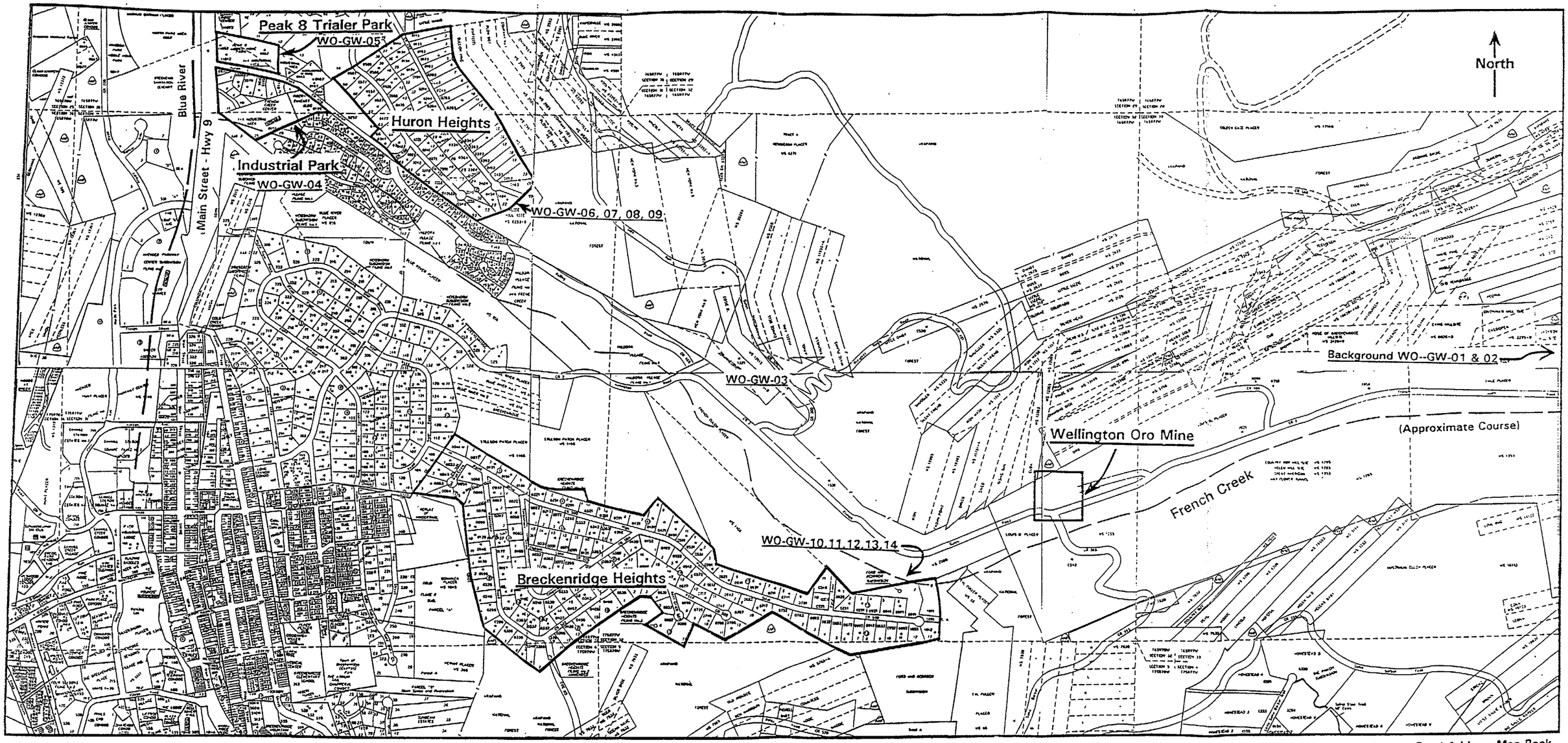
There have been many seeps sampled in the vicinity of the W-O site, especially in the 1996 water quality studies. The FG-6 and FG-6A through FG-6D sites were associated with seeps along the south side of French Gulch Road immediately downhill from the W-O site (Figure 3-2). These seeps appear to flow at a fairly constant rate throughout the year. The 1121 and 1140 sites were seeps at the base of placer tailings piles that flow directly into French Creek. These seeps were downstream from the W-O site. The MGB-1 was a seep in the middle of Magnum Bonum Drive in the French Creek subdivision over a mile downstream of the W-O site. The WP-1 site was a seep that only flows during peak high flow conditions. This seep was located at the base of the main waste pile immediately north of French Gulch Road and east of the roaster fines. The KDS (Kenny Dog Spring) seep was located northwest of the W-O site. Based on mapping of the mine workings in the Lovering (1934) study, it is believed that this seep originated from an old prospect adit or tunnel along the Bullhide Fault that was isolated from the W-O workings.

Except for FG-6C and WP-1, the seeps had lower metal and sulfate concentrations than the W-O mine pool (Figures 3-36b through 3-36g). FG-6D, KDS, and MGB-1 had significantly lower concentrations. FG-6C had concentrations slightly higher than the W-O mine pool waters while the concentrations in the WP-1 seep had concentrations that were significantly higher than the W-O waters. FG-6C is the closest seep to the W-O #3 Mine and the Bullhide Fault (Figure 3-2). The WP-1 concentrations were similar to the saturated portion of the roaster fines, which was sampled with the soil boring SBRF-3. The roaster fines (SBRF-3) and WP-1 seep were strongly acidic while most of the other seeps were slightly acidic to neutral (Figure 3-36a).

3.6 French Gulch Domestic Well Water

In October of 1996, the Colorado Department of Public Health and Environment (CDPHE) conducted domestic well sampling in the French Gulch area (Figure 3-38). This sampling identified two residences in the Breckenridge Heights subdivision (491 and 511 High Point) with high levels of Mn (7,000-10,300 ug/L) (Appendix 3-4). These residences along with additional nearby Breckenridge Heights domestic wells were incorporated in the CDPHE April 1997 sampling program (Table 3-7, Figure 3-39). One of the April sampling residences (531 High Point) also had elevated levels of Cd (12 ug/L) and Pb (42 ug/L) in addition

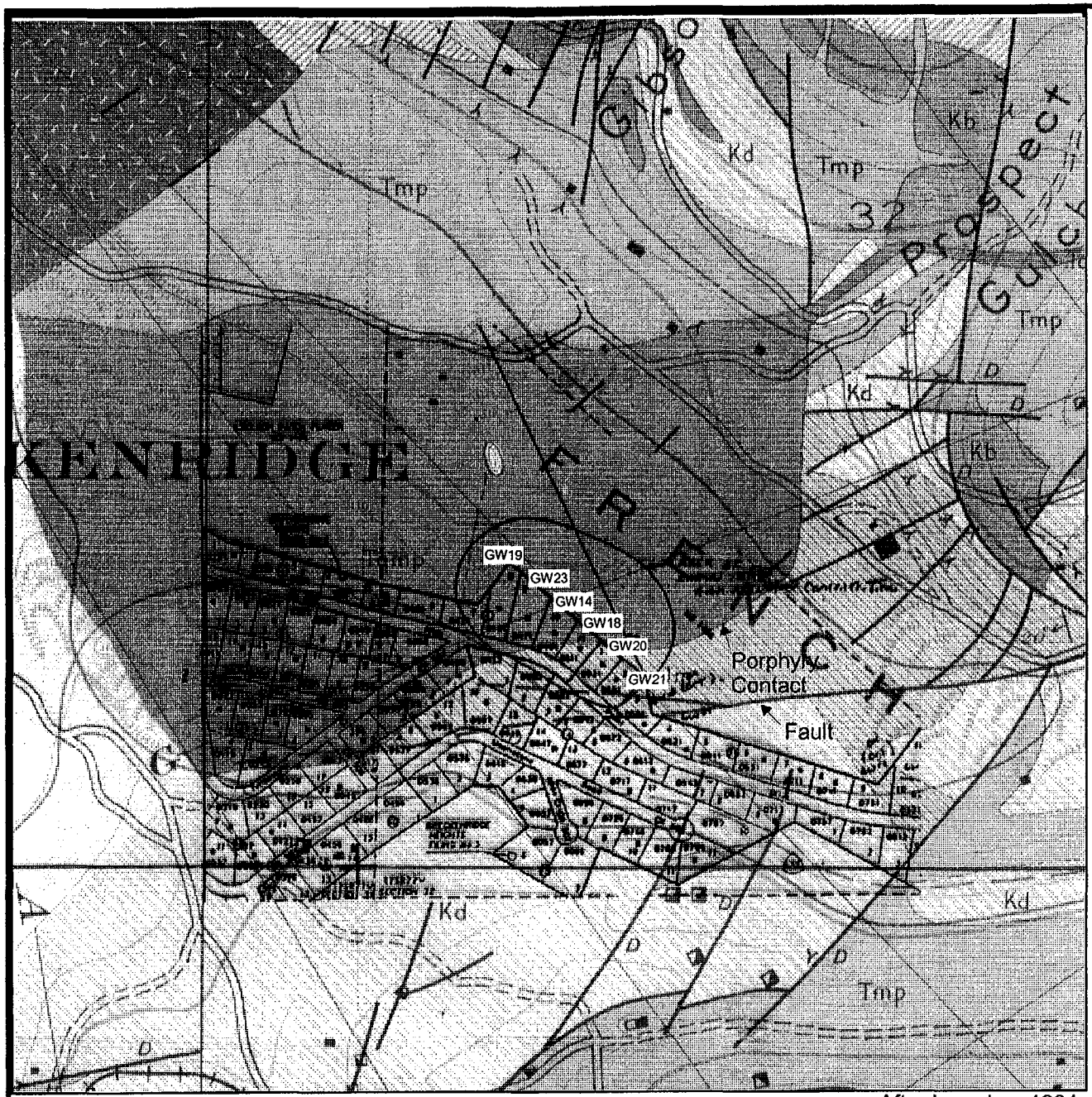
October 1996
Domestic Ground-water Sample
Location Map



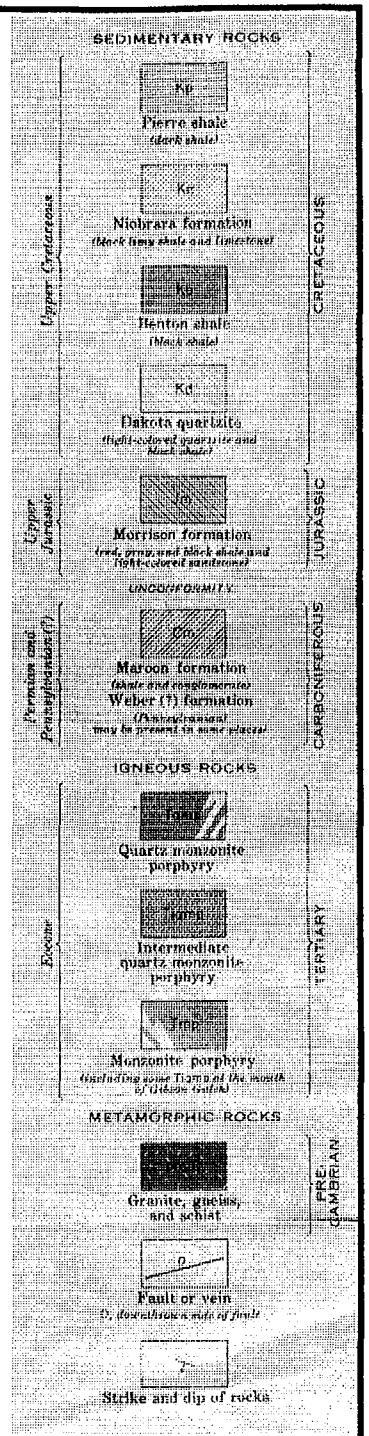
Source: Summit County Rural Address Map Book

Figure 3-38

From CDPHE, 1996



After Lovering, 1934



Geologic Map of the Breckenridge Heights Area

Figure 3-39

Table 3-7
Colorado Department of Public Health and Environment French Gulch Domestic Well Sample Sites
April 1997

Sampling Site	Description
GW-01	3821 French Gulch Road, background upstream W-O site
GW-14	491 High Point, Breckenridge Heights Subdivision
GW-18	511 High Point, Breckenridge Heights Subdivision
GW-19	451 High Point, Breckenridge Heights Subdivision
GW-20	531 High Point, Breckenridge Heights Subdivision
GW-21	621 High point, Breckenridge Heights Subdivision
GW-23	471 High Point, Breckenridge Heights Subdivision

to Mn (3,250 ug/L) prior to treatment. These Cd and Pb levels exceeded drinking water standards.

Johanna Miller (EPA Region VIII) requested that American Geological Services (AGS) Inc. compile Mn data from "clean" background wells in the Wellington-Oro (W-O) mine and mill site area. The concern was that the elevated metal levels in the Breckenridge Heights domestic wells were originating from the W-O site. AGS compiled metal data from selected background monitoring wells, W-O mine water, a mine water contaminated bedrock well, and representative background and mine contaminated stream sites. This information was integrated with the local geology to infer the origin of the Mn and other elevated ground-water metal levels in the Breckenridge Heights area. Based on the evaluation carried out by AGS, it was concluded that the domestic wells elevated metal levels are unlikely to originate from the W-O mine and mill complex.

The Breckenridge Heights subdivision is located approximately ¾ to 1 mile east of the town of Breckenridge. This area is approximately ½ mile west-southwest of the W-O site on the south side of the French Gulch alluvial valley (Figure 3-38). The W-O site is located on the north side of French Gulch valley and French Creek. Most of the well depths for the sampled domestic wells were unknown, although the well with the highest manganese concentrations (491 High Point) had a reported depth of 230 feet. It was assumed that most of the sampled domestic wells have depths similar to the 491 High Point well. The thickness of the alluvial material in the Breckenridge Heights was not determined in this evaluation, but based on experience in the area, it should be less than 50 feet thick, where present. Therefore, the domestic wells are most likely completed in bedrock. According to USGS geologic mapping by Lovering (1934), the bedrock in the Breckenridge Heights area consists of the Jurassic Morrison and Cretaceous Dakota Formations which are cut by a large Tertiary quartz monzonite porphyry body (Figure 3-39). The domestic wells with elevated metal

concentrations appear to be either associated with the contact between the porphyry and the Morrison Formation or with an east-west trending fault system that cuts the Morrison and Dakota formations. This fault system may connect with the major faults associated with the W-O underground workings, which is approximately ½ mile northeast of the subdivision. The fault system has the potential to act as conduits for contaminated W-O mine water to the subdivision's bedrock aquifer. Water levels were not available for the domestic wells. Consequently, hydraulic gradients between the W-O mine and the domestic wells could not be determined.

Table 3-8 is a summary of the sample sites used in this evaluation (Figures 3-1 and 3-2). Figure 3-40 is a plot of manganese (Mn) concentrations from selected sampling sites. The background or "clean" W-O monitoring wells have Mn concentrations that range from 40 ug/L to over 5,000 ug/L. The large difference between total and dissolved concentrations for MW-15 is believed to be due to the well not being fully developed. The W-O mine water has Mn concentrations from 40,000 to 50,000 ug/L. The Breckenridge Heights untreated domestic wells that were sampled in April 1997 have Mn concentrations that ranged from 3,250 ug/L to 10,300 ug/L. Three out of the four untreated Breckenridge Heights domestic wells sampled in April 1997 exceeded the observed highest background monitoring well at the W-O site (MW-14). MW-14 is a deep 11-10 Fault well completed at 277 feet. The high levels of Mn in this well have been attributed to the natural mineralization associated with the 11-10 fault zone and the fractured Cretaceous shale in which the fault cuts. The other background monitoring wells have Mn concentrations less than 100 ug/L. The background bedrock wells (MW-12 and MW-20) are believed to have low Mn because the area that they penetrated was not naturally mineralized by faults or fracture systems. Figure 3-41 is a plot of Zn concentrations. The background W-O monitoring wells have Zn concentrations from 30 ug/L to 5,000 ug/L. Zn concentrations for the W-O mine water ranged from 100,000 to over 200,000 ug/L. The high background Zn concentration was also associated with the fault well MW-14. The sampled Breckenridge Heights untreated well water had Zn concentrations that ranged from 525 ug/L to 1,910 ug/L which were within the observed background in the vicinity of the W-O site. Figure 3-42 is a plot of selected metal concentrations for stream sites along French Creek and the four untreated domestic wells sampled in April of 1997. French Creek site FG-5 represents the clean or background creek water upstream of the W-O site while FG-7 is the downstream-contaminated stream site. These sites most likely reflect the alluvial ground-water associated with these locations. Fe is low in the stream sites due to oxidation and resulting precipitation of Fe hydroxides (yellowboy). All the Breckenridge Heights untreated wells have higher Mn and lower Zn concentrations than FG-7. Pb, Cd and Zn are low for the domestic wells except for GW-20B (531 High point).

Table 3-8
Comparison Sites
Wellington-Oro Mine and Mill Site

Sampling Site	Description
MW-12	ground-water, background porphyry bedrock well upgradient mine site
MW-14	ground-water, background 11-10 Fault well upgradient mine site
MW-15	ground-water, background shale bedrock well, south side valley, east of Country Boy Mine
MW-16	mine water, contaminated shale bedrock well at #3 Mine Shaft site
MW-20	ground-water, background alluvial well south side valley, downgradient mine site
MSRW-3	mine water, contaminated relief well for #3 Mine Shaft
FG-5	stream water, background upstream mine site
FG-7	stream water, contaminated, downstream mine site

Major ion chemistry can be used to infer the origin of ground waters. Figure 3-43 is a plot of calcium (Ca) concentrations for the Breckenridge Heights untreated wells and the W-O mine water. The mine water has concentrations that range from nearly 400 mg/L to over 450 mg/L. The high Ca is due to the mine workings being associated with Cretaceous shales. The shales contain Ca-bearing minerals and rock types that can release Ca into the shale and mine waters. This is also evident in the MW-14 fault well that had Ca concentrations of 590 mg/L in the June 1996 EPA sampling. The Ca-rich mine waters also influence French Creek. Upstream of the W-O mine site Ca concentrations were around 13 mg/L while downstream the mine water contaminated stream site FG-7 had Ca concentrations over 20 mg/L. The increase in Ca is due to the discharge of Ca-rich mine and ground waters into the stream. The untreated water associated with the domestic wells in Breckenridge Heights had Ca concentrations that ranged from 3.9 mg/L to 17.3 mg/L. These low concentrations suggest minimal influence of Ca-rich mine and Cretaceous shale ground-water in the Breckenridge Heights domestic wells.

The review of bedrock geology in the area of Breckenridge Heights indicated a potential pathway of W-O mine water via an east-west fault system. Most of the domestic wells appear to be associated with the contact between intrusive porphyry and the Jurassic Morrison Formation with the exception of 531 High Point well (GW-20B) which had the high cadmium (Cd) and lead (Pb) concentrations. This well may be associated with the fault zone (Figure 3-39). With the exception of Mn, other metals such as zinc in the domestic wells are low in concentration compared to W-O mine water and associated downgradient-monitoring sites. The domestic wells are more similar to the background monitoring wells in the vicinity of the W-O complex than the W-O contaminated

sites. The lack of high Ca in the Breckenridge Heights wells indicates the absence of Cretaceous shale bedrock and suggests that the elevated levels of Mn, Cd and Pb is not related to the Ca-rich W-O mine waters. Mineralization associated with contact metamorphism along the intrusive porphyry and Morrison formation and within the fault zone was probably responsible for the high levels of Mn, Cd and Pb in the ground-water associated with the Breckenridge Heights area. Maps from Lovering (1934) showed some prospecting 3/8 of a mile southwest of the subdivision. This prospecting could have been exploring the mineralization along the porphyry contact. The Morrison Formation is not a good host for economic ore accumulations, which may explain the lack of prospecting success in the area and the low Zn and other metal concentrations in the local ground-water.

3.7 Summary and Conclusions

Surface and ground water quality studies have demonstrated that most of the heavy metal and sulfate pollution to French Creek and the Blue River have been from the Wellington-Oro Mine and Mill complex. This pollution has resulted in Zn and Cd concentrations that exceed State table value standards in French Creek and the Blue River. The influence of French Creek heavy metal pollution on the Blue River has been observed for two to three miles below the confluence. Other metals such as Pb, Mn, Fe, and Al have elevated concentrations in French Creek and the Blue River and will occasionally exceed water quality standards.

The ground-water in the vicinity of the mine site and the Wellington-Oro mine pool waters have metal and sulfate concentrations much higher than the stream waters. Two ground-water monitoring wells, MW-13 and MW-8U, had metal concentrations much higher than mine pool waters and appear to be influenced by leachate discharging from the surface roaster fines and mine waste piles. This suggests that a significant amount of metal loading from the roaster fines and mine waste is associated with ground-water discharge.

The contaminated alluvium monitoring wells in the vicinity of the mine site have metal and sulfate concentrations similar to the W-O mine pool waters while the contaminated bedrock wells, shale and porphyry, had lower metal and sulfate concentrations. This implies that a significant amount of W-O mine pool water is discharging directly into the alluvium. A downgradient contaminated alluvium monitoring well, MW-7, had lower concentrations than the contaminated wells near the mine site. This could be due to local clean ground-water flow in the alluvial aquifer and placer tailing piles diluting the contaminated mine pool waters and possibly causing natural attenuation of metals.

The elevated concentrations associated with downgradient seeps from the W-O site, 1121 and 1140, suggest that ground-water flow pathways can transport a significant amount of metals and sulfate. The FG-6 seeps along French Gulch

Road were very similar in water quality to the W-O mine pool. These seeps probably represent a portion of the mine water discharge into the ground-water system. The elevated metals in domestic water wells south of French Creek appear to originate from local mineralization associated with faults and contact metamorphism and not from the W-O mine complex.

4.0 Salt Tracer-Injection Studies

4.1 Abstract

In July of 1996, the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program conducted stream tracer-dilution, alluvial ground-water tracer, mine pool tracer, and synoptic sampling studies in the vicinity of the Wellington-Oro Mine complex. This work was partially funded by an Environmental Protection Agency Region VIII Headwaters Grant to the State of Colorado Division of Minerals and Geology (DMG).

Hydrologic flow pathways and stream hydrologic properties were evaluated using three different salt tracer injections. A lithium chloride tracer in the upper portion of the Oro Shaft mine pool did not dilute and disperse, and was not detected at the downgradient monitoring sites. This suggests that the mine pool in the Oro shaft is poorly mixed and there is not a direct hydrologic connection between upper Oro mineshaft and the #3 Mine Shaft or downgradient metal contaminated alluvium and stream. It can be implied from these results that the lower mine pool is the primary source of metals to French Creek and/or significant mine water flow is bypassing the upper portion of the Oro shaft. The sodium bromide tracer that was injected in an alluvial ground-water well was not detected in the downgradient alluvial monitoring well or in the stream. It was assumed that the tracer was either diluted below detection limits before it reached the monitoring well and stream or the tracer flow pathway did not intersect the monitoring well and stream. Variations in downstream French Creek discharge and metal concentrations were quantified by applying a sodium chloride (common table salt) tracer and synoptic sampling to the stream. This study showed that up to 30% of stream flow could be occurring in the streambed cobbles and gravels. This type of flow is referred to as transient and can not be measured by conventional flow meter methods. The instream tracer and synoptic sampling study was able to identify subreaches of French Creek where the majority of metal loading occurred. 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 of the mine site. It is believed that the source of the contamination in the fault water and seeps is the Wellington-Oro mine pool.

4.2 Introduction

The historic dredging of French Gulch for metal mining completely disrupted French Creek and its associated alluvial valley material resulting in large dredge tailing piles covering the valley floor. This dredging activity produced a very complex zone of alluvium that exchanges water with the stream (hyporheic zone) and an unnatural stream channel. The stream channel locally displays a

complicated pattern of stream segments that bifurcate, have significant gaining and losing reaches, and has branches that emerge into and re-emerge from the dredge piles. In addition to the disruptive effects of placer operations in the stream bed, mining and mill operations at the Wellingtion-Oro site deposited mill tailings in the valley across from the mine site and roaster fines tailings and mine waste at the site (Plate 1). The lower portions of this mine and mill wastes are saturated by ground-water. The complex hydrogeology produced by the interaction of mining activities with the faulted and fractured bedrock geology makes it difficult to formulate a consistent picture or conceptual model of the interaction of the various sources of water and metals to French Creek.

The primary objectives of conducting salt tracer studies at French Gulch were to:

1. quantify the amount of metals entering French Creek;
2. determine the location and type of major metal inputs (ground-water versus surface runoff) to French Creek;
3. determine whether the metals stay in the stream; and
4. characterize the hydrology between the underground mine pool, the alluvial aquifer, and French Creek.

There were four aspects to the salt tracer-injection studies at French Gulch:

1. instream tracer-dilution;
2. synoptic sampling;
3. alluvial ground-water tracer injection; and
4. mine pool tracer injection.

The amount of metals entering the stream is referred to as mass or metal loading and is calculated as the product of metal concentration and stream discharge. Traditional stream flow or discharge measurements are obtained by dividing the stream into small segments. The cross-sectional areas for these segments are measured and combined with average water velocity measurements determined from a flow meter. Summing the measurements of all sections results in a discharge value for the entire stream. This method is applicable to streams that have channel bottoms and banks that are smooth (Kimball, 1997b). The French Gulch water quality sampling events conducted by the Colorado Department of Public Health and Environment (CDPHE) and the U.S. Environmental Protection Agency (EPA) since 1989 determined stream discharges by this method.

Mountain streams typically have stream bottoms that are covered with cobbles that can contain a significant portion of the stream flow. This flow cannot be measured by a flow meter. Consequently, accurate discharge measurements are difficult to obtain in mountain streams (Kimball, 1997b). The water in the streambed cobbles is referred to as transient storage. It was believed that the dredging of French Gulch and disruption of the original French Creek streambed made discharge measurements by traditional methods unreliable.

Precise measurements of discharge in mountain streams have been determined using a conservative salt tracer in the stream (Kimball, 1997b). These measurements are based on the dilution of the tracer as it moves downstream. Discharge can be determined from the amount of tracer dilution. The known concentration of injected tracer and the rate at which the tracer is added to the stream are used to calculate the mass of tracer introduced to the stream. Stream discharge can be quantified downstream from an injection point by using measurements of tracer concentration upstream and downstream from the injection point. The following equation calculates stream discharge.

$$Q_s = (C_i \times Q_i) / (C_B - C_A)$$

where:

Q_s	=	discharge of the stream
C_i	=	tracer concentration in the injection solution
Q_i	=	rate of the injection into the stream
C_B	=	tracer concentration downstream from the injection point
C_A	=	tracer concentration upstream from injection point

This method assumes that the stream is not losing water. The tracer also can be used to characterize hydrologic parameters such as the velocity of stream flow, travel time in the stream, the mixing of solutes, the quantity of inflow from tributaries and ground-water, and transient storage in the streambed cobbles (Kimball, 1997b). Synoptic sampling is the collection of samples from many locations along the stream over a short period of time. Metal concentrations from the synoptic sampling are combined with the discharge measurements to develop mass or metal loading profiles along the stream.

In July of 1996, the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program conducted stream tracer-dilution, alluvial ground-water tracer, mine pool tracer, and synoptic sampling studies in French Gulch. This work was partially funded by an EPA Region VIII Headwaters Grant. Appendix 4-1, "Quantification of Metal Loading and Ground-water Surface-water Interactions in French Gulch," is the USGS report on this study.

The alluvial ground-water and mine water tracer studies involved slug injection of salt tracers into an alluvial ground-water well and the Oro Shaft. The purpose for the alluvial tracer was to quantify the interaction of the stream with the alluvium. The purpose of the Oro Shaft tracer was to define the pathways of mine water to the alluvium and stream. Various salt tracers were used to differentiate between the stream, alluvial and mine waters during these studies. Sodium chloride (NaCl) tracer was injected into the stream, sodium bromide (NaBr) tracer was injected into the alluvial ground-water monitoring well MW-9, and lithium chloride (LiCl) tracer was injected into the mine via the Oro Shaft (Plate 1). Tracer

samples were collected from selected wells in the bedrock, alluvium and #3 Mine Shaft, and at selected sites along the stream (Plate 1). These samples were analyzed by the USGS for bromide, lithium and chloride using atomic adsorption spectrophotometry (AA) and ion chromatography (IC) methods. During the continuous instream NaCl injection a set of detailed geochemical samples were collected as part of the synoptic study (Appendix 4-2). These samples were analyzed by the U.S. EPA Region VIII laboratory using ion chromatography, atomic adsorption, and inductively coupled plasma-atomic emission spectrometry (ICP-AES) methods. The U.S. EPA Region VIII laboratory also conducted a geochemical background study of samples collected from selected stream, mine (Wellington-Oro and Country Boy mines) and well sites prior to the tracer injection (Appendix 4-3). EPA chloride concentrations tended to be shifted approximately 1 to 2 mg/L higher than USGS concentrations. This suggests a calibration problem in either the EPA or USGS laboratories. For consistency, the USGS report and this summary utilized the USGS chloride concentrations.

Plate 1 summarizes the stream sites, stream inflows, ground-water wells and mine shaft locations incorporated into the USGS salt tracer and synoptic studies at French Gulch. This work was conducted during the week of July 22, 1996. Tracer sampling on selected stream sites, ground-water wells, and mine water also continued in August and September of 1996. This study was performed during the falling limb of the French Gulch hydrograph during a dry week (Figure 4-1). The discharge data for French Gulch in Figure 4-1 was from the USGS gaging station near the confluence with the Blue River (USGS, 1997). Discharge at the gaging station ranged from 12 to 15 cubic feet per second (cfs) during the week of July 22. The hydrograph peaked at 80 cfs six weeks prior to this study on June 10. Low flow discharge during the winter of 1996 appeared to stabilize at this gaging station around 2 cfs (USGS, 1997).

4.3 Salt Tracer Studies Summary

4.3.1 Instream Tracer Study

4.3.1a Introduction

This study was able to quantify the downstream profile of metal concentrations and metal or mass loading during the study period. The study also identified stream subreaches where the majority of metals are entering French Creek. There were over fifty stream and inflow or tributary sites used for tracer and synoptic sampling. These sites were identified with the "FG" prefix. Six instream locations, usually sampled in mid-stream, were used as transient sampling sites and were designated with the prefix "T" (Plate 1). In addition to conducting tracer and synoptic sampling of the transient sites, these sites were also used to establish tracer arrival times, plateau concentrations, travel time between sites, and cumulative travel time downstream.

Due to losing reaches in the stream, large transient storage, and inflows with variable chloride concentrations, accurate discharge measurements were not possible by simple dilution modeling from the continuous salt injection. During the study, spot tracer injections above the transient sites resulted in instantaneous discharge measurements at each of the transient sites. A detailed stream discharge profile between transient sites T3 and T4 was possible from the spot injection above T3 due to the gaining nature of this stream section (Plate 1). Detailed stream discharge profiles were not possible between T2 to T3 and T4 to T6 transient sites because these reaches experienced major losses of flow. Between T2 and above T3 and the Country Boy Mine road surface flows nearly disappeared into the placer tailings (Plate 1). Immediately upstream of T3, and in the vicinity of the Country Boy Mine road, significant flow was added back to French Creek by large springs.

4.3.1b Discharge Measurements

Accurate discharge or flow measurements are needed to evaluate and quantify mass or metal loading along French Creek. Figure 4-2 is a comparison between the traditional flow meter discharge measurements and the spot injection discharge measurements. Flow meter and spot injection discharge measurements were nearly identical for the T2 and T3 transient sites. This would suggest that there was minimum flow within the streambed cobbles and very small transient storage at these sites. These sites appear to be dominated by fine grained bed sediments with low permeability. The T1 transient site had a spot injection discharge measurement several magnitudes higher than the flow meter measurement. The USGS report stated that the spot injection discharge measurement for this site was too high because there was poor mixing of the tracer into stream.

The spot injection discharge measurements for transient sites T4 and T6 are 30 percent greater than the flow meter measurements. The difference may be attributed to a large portion of flow occurring in the cobble bottoms in these stream segments, which can not be measured with a flow meter. At transient site T5, the tracer injection indicated less flow than the flow meter. The stream hydrology was very complex between transient sites T4 and T6 with observable major losses and gains of flow along the stream associated with the large cobble dredge piles. This complex hydrology may be responsible for the unreliable discharge measurements from both the spot injection and flow meter.

Figure 4-3 is the discharge profile for French Gulch including the detailed profile between T3 and T4. This discharge profile was based on the spot tracer injection measurements. The profile does not include the T1 and T5 transient sites because of their questionable results. The discharge is extrapolated between T4 and T6.

The trace of two major faults that intersect the underground Wellington-Oro mine workings cross French Creek at approximately 760 meters (11-10 Fault) and 930 meters (Bullhide Fault) distance downstream from injection (Plate 1). The locations of the faults in Plate 1 and figures 4-3 and 4-4 were based on mapping by Lovering (1934). These faults appear to be associated with significant increases in flow along French Creek (Figure 4-3).

The flow just downstream of the 11-10 Fault at transient site T3 was 304 liters per second (10.7 cfs). The flow increased to 372 liters per second (13.1 cfs) at transient site T4 which is downstream from the Bullhide Fault. This flow increase also corresponded to significant differences in pre-injection chloride concentrations along French Creek (Figure 4-4). Pre-injection chloride concentration at T2 was 0.08 mg/L. Chloride concentration increased to 0.84 mg/L at T4. The increase in pre-injection chloride concentrations in French Creek is probably due to the seepage of bedrock ground-water from the faults and alluvial ground-water from the placer dredge material and alluvium. The bedrock ground-water has higher background chloride concentrations than the stream water prior to injection.

The variable chloride concentrations also affected the instream and inflow tracer concentrations during the tracer-dilution study. The tracer injection at T1 (0 meters) increased stream chloride concentrations from a background of 0.08 mg/L to over 3.25 mg/L (Figure 4-5). Figure 4-5 is the downstream profile of USGS chloride concentrations from the synoptic sampling. Between 84 meters and 631 meters there was no significant decrease in the instream chloride concentrations. This section of French Creek experienced almost a complete loss of surface flow during the study. The 631-meter distance from injection corresponds to the French Creek stream site FG-9d that is at the end of the culvert below Country Boy Mine road (Plate 1).

Upstream from T3 (799 meters), large inflows of bedrock and alluvial ground-water with chloride background concentrations of 0.08 mg/L (alluvial ground-water) and 0.84 mg/L (bedrock ground-water), resulted in the stream tracer concentration to decrease from 3.3 mg/L to 0.4 mg/L. This occurred between 631 meters (FG-9d) and the 11-10 Fault at 744 meters (Figure 4-5). Inflow chloride concentrations between 744 and 881 meters from the right-bank (north side) exceeded instream concentrations while left-bank (south side) inflows were similar to the instream chloride concentrations of 0.4 mg/L at 744 meters. The right-bank inflows probably represent a mixture of fault water (bedrock ground-water) and salt tracer laden underflow water that originated from the upstream losing subreach between 84 and 631 meters. The left-bank inflow probably represent a mixture of fault water, Country Boy Mine adit discharge, and alluvial ground-water that was flowing along the southern portion of the French Gulch alluvial valley and observed to daylight as springs in the vicinity of the Country Boy Mine road. The alluvial ground-water does not contain the salt tracer because it bypassed the injection point on the north side of the valley (Plate 1).

The instream chloride concentration below 799 meters most likely represents the mixture of salt tracer laden stream water, alluvial and bedrock (fault) ground-water, and the Country Boy Mine adit water. In summary, the discharge increase between transient sites T2 and T4 is due to a combination of inflow sources:

1. bedrock ground-water seepage from the 11-10 and Bullhide faults;
2. underflow water that originated from upgradient surface stream losing subreach;
3. Country Boy Mine adit discharge; and
4. alluvial and placer dredge ground-water.

4.3.1c Synoptic Sampling

The selection of synoptic sampling sites was based on bracketing all of the visible inflows and potential inflow areas along French Creek. Above transient site T3 and the fault seepage areas, the major ion chemistry indicated that the water in French Creek was mostly a calcium bicarbonate type. At transient site T2, the dissolved solids concentration was 63 mg/L. Downstream of the mine site at T6, the dissolved solids increased to 124 mg/L and the water changed to a calcium sulfate-magnesium carbonate type. The interaction of surface and ground waters with sulfide-bearing rocks, mine workings and surface mine waste produced the sulfate waters.

The oxidation of sulfide minerals and associated acid mine drainage also contributed substantial amounts of metals to the ground and surface waters. The metals with the highest concentration in French Creek are zinc (Zn), iron (Fe), manganese (Mn), and cadmium (Cd). Upstream from transient site T2 all metal concentrations were either low or below detection. The highest metal concentrations in French Creek were observed at the downstream transient site T6 (Plate 1). The T6 site corresponds to the State and EPA FG-7 stream-sampling site.

Metals concentrations were variable for sampled inflows to French Creek. There were only minor tributary inflows to French Creek with most of the inflows related to ground-water seeps and springs. Inflows with high metal concentrations occurred on both sides of the stream between the 11-10 and Bullhide faults (Plate 1). The high metal inflows on the Country Boy Mine side or left-bank of the stream displayed metal and/or sulfate concentrations much higher than the Country Boy Mine adit water (Figure 4-6). This would suggest that most of the metals in the left-bank inflows between the 11-10 and Bullhide faults originated from fault seepage and not mine water from the Country Boy Mine. The EPA measured the flow from the Country Boy Mine adit be 0.316 cfs or 9 liters per second (L/s). In comparison, the observed flow increase of 0.5 cfs or 14 L/s across the Bullhide Fault is likely due to fault seepage because there were no visible inflows in this subreach (Plate 1 and Figure 4-3). Downstream of the

Bullhide Fault all the inflows are from the right-bank. The highest metal concentration inflow was FG38 followed by FG44 (Plate 1).

Downstream profiles of metal and sulfate concentrations exhibited similar patterns (Figures 4-7 and 4-8). Significant increases in concentrations were observed in the vicinity of the 11-10 and Bullhide faults and between 2200 to 2536 meters downstream from injection. The sulfate concentrations began to increase upstream from the 11-10 and Bullhide faults while the metals concentration abruptly increased at the faults. The increase in concentrations for sulfate and metals correlated downstream between 2200 to 2536 meters (Figures 4-7 and 4-8). The initial sulfate instream concentration increase corresponds to the left-bank (south side) inflows between 694 and 745 meters. These are the inflows that had low chloride concentrations during the synoptic study and probably represent southern flow of the alluvial ground-water. A higher sulfate background for the alluvial ground-water compared to the instream sulfate background would not be unusual. This was observed in the background alluvial and bedrock monitoring well samples that had sulfate concentrations from 17 mg/L to 100 mg/L. The background sulfate stream concentrations were approximately 10 mg/L. The higher sulfate background alluvial ground-water would explain the increase in sulfate concentrations above the 11-10 Fault. Since the alluvial ground-water upgradient of the W-O site has low metals concentrations, metal concentrations remained low until the faults were crossed. Significant increases in sulfate and metals occurred at 2200 (FG55) and 2536 (TS-6) meters (Figures 4-7 and 4-8). The French Creek stream channel split at 1725 meters (Plate 1). The northern flow of this split gained substantial inflow and metal-sulfate rich water at 1826 meters (FG39b) which is just below a pond. This northern flow disappeared into the dredge pile cobbles and a portion of it apparently re-emerged above 2200 meters at FG54. This re-emergent flow appears to be responsible for the increase in sulfate and metals at 2200 meters. The metals and sulfate increase at TS-6 (2536 meters) seems to be related to FG44 and FG56 inflows (Plate 1). These inflows apparently originated from the Wellington-Oro mine drainage seeps that flow along French Gulch Road. The USGS report refers to these seeps as Bullhide Fault surface drainage.

4.3.1d Mass or Metal Loading Profiles

Combining the detailed synoptic sampling of stream and inflow sites with the stream discharge profile yields metal or mass loading profiles (Figure 4-9). The loading profiles show where major effects of the mine water discharge were occurring and indicates the relative contributions from inflows and faults. Relative contributions were expressed as a percentage of loading compared to the transient site T6 (2536 meters). These percentages indicate that most of the sulfate (64%), Mn (74%), and Zn (67%) loading was occurring between 2200 and 2536 meters downstream of injection (Plate 1). In contrast, the majority of Cd loading (66%) was occurring in the vicinity of the 11-10 and Bullhide faults between 760 and 930 meters (Figure 4-9). Potential loading associated with the

Country Boy Mine adit discharge based on the EPA flow measurement and water chemistry was less than 1% for sulfate, Mn, Zn and Cd. A possible explanation for the Cd loading difference from the faults versus the downgradient seeps that discharge into the stream at 2200 and 2536 meters downstream of injection could be its ability to sorb to iron hydroxides preferentially over the other metals and sulfate. The flow pathway for Wellington-Oro mine drainage from the site via the seeps along French Gulch Road has a large component of surface and shallow alluvial flow. This type of flow exposes the water to oxidation which is evident by the "yellowboy" or iron hydroxide precipitates observed along French Gulch Road. In addition, the flow pathway intersects the artificial wetlands across from the Union Mine, which may also preferentially sorb Cd over the other metals. Further work would have to be conducted to fully understand the geochemical properties of Cd and the other metals in French Gulch.

Estimations of fault water seepage, alluvial ground-water discharge, and mass loading can be made from the data (Table 4-1). The increase in stream discharge due to the Bullhide Fault as previously discussed was approximately 0.5 cfs or 14 L/s. This same segment of stream experienced a doubling of instream Zn concentration due to Bullhide Fault seepage or discharge (Figure 4-10). A Bullhide Fault water discharge into the stream with a Zn concentration of 23,621 ug/L would result in the observed instream Zn concentrations of 1,570 ug/L downstream of the Bullhide Fault at FG25. A similar analysis for Cd calculated 122 ug/L concentration for the Bullhide Fault water. It is believed that the metal and sulfate contamination associated with the faults originated from the W-O underground mine pool.

Table 4-1 summarizes the discharge, Cd and Zn concentrations, and loading estimates for the inflows associated with the stream segment between the 11-10 and Bullhide faults. This analysis assumes that all the salt tracer laden water that was lost to the placer dredge tailings below the T2 site re-emerges at the FG25 site. This study refers to the lost stream water below T2 as stream underflow. The assumption that all the underflow re-emerges above FG25 results in a conservative estimate of 7.1 cfs for the alluvium and placer dredge ground-water discharge into the stream since it was determined from the difference between the measured discharge at stream site FG-25 and the other inflow sources. It is likely that a significant portion of lost stream flow remains as underflow or subsurface flow in the placer tailings and alluvium. In this case, the contribution to stream flow by alluvial ground-water not influence by the stream salt tracer would be higher than 7.1 cfs.

The Zn and Cd concentrations for the 11-10 Fault in Table 4-1 were estimated from the right-bank (north) inflow at FG15 (840 meters). FG15 was the most contaminated inflow observed between the 11-10 and Bullhide faults. Briant Kimball from the USGS conducted a multivariate Q-mode factor analysis on water quality parameters to determine the relative percentages of (1) tracer laden

Table 4-1
Estimation
of
French Creek Flow Sources and
Zinc and Cadmium Loading
Between 11-10 and Bullhide Faults

Inflow Sources/ Stream	Estimated Discharge (cfs)	Estimated Discharge (L/s)	Zn-dissolved (ug/L)	Zn-loading (mg/sec)	Cd-dissolved (ug/L)	Cd-loading (mg/sec)
Bullhide Fault	0.5*	14*	23621	331	122	1.7
11-10 Fault	0.31	8.8	24380	215	114	1.0
Country Boy	0.316*	8.9*	2796*	24.9	2*	0.02
Qal/Placer Ground water	7.1	201	7.3-37.2*	1.5-7.5	0-1*	0-0.2
Tracer laden Stream Underflow	4.8*	136	15.5-30*	2.1-4.1	0-1*	0-0.1
French Creek @ FG25	13.0*	368*	1572*	579	8.0*	2.9

"*" - Discharge and concentrations measured during Salt Tracer Study
"**" – Measured discharge or stream flow at T2

stream water (underflow), (2) fault seepage, and (3) alluvial and placer dredge ground-water that bypassed the salt injection (B. Kimball, pers. comm., 1997). Figure 4-11 is a trilinear plot of the multivariate Q-mode analysis showing the estimated contributions of these three sources for each inflow. Inflow sites were designated by their distance from injection. This plot shows the left-bank (south) inflows were dominated by low chloride alluvial ground-water that bypassed the salt injection. The right-bank (north) inflows are dominated by tracer laden stream water (underflow) that represents the re-emergence of the stream water lost in the placer dredge tailings below the T2 site. Mine water and bedrock ground-water seepage via the faults was observed in varying degrees for the inflows. For example, according to the trilinear plot the FG15 (840 meters) right-bank (north) inflow is composed of approximately 67% fault water, 6% alluvial ground-water, and 27% tracer laden stream or underflow water (Figure 4-11). Calculating the corresponding Zn and Cd concentrations in the fault water portion of the FG15 inflow results in 24,380 ug/L Zn and 114 ug/L Cd. These concentrations are very similar to the independently calculated Bullhide Fault water concentrations. Similar concentrations were also calculated for the fault water portion of the left-bank (south) inflow associated with the 840-meter distance (FG19). Calculations for the other inflows fault water concentrations

varied by an order of magnitude, which may reflect the error involved with this method. Table 4-1 demonstrates the influence of ground-water recharge to French Creek downstream of the 11-10 and Bullhide faults. The combined bedrock ground-water discharge via faults and alluvial ground-water discharge to French Creek was at least 7.91 cfs, over 60% of the flow measured at stream site FG25.

Table 4-2
Comparison
of
French Creek Zinc and Cadmium Loading

Sampling Station	Discharge (cfs)	Discharge (L/s)	Zn-dissolved (ug/L)	Zn-loading (mg/sec)	Cd-dissolved (ug/L)	Cd-loading (mg/sec)
French Creek FG25	13.0*	368*	1572*	579	8.0*	2.9
French Creek TS-6	13.3*	377*	4511*	1699	11.5*	4.33
Difference TS-6 & FG25	0.3	9		1120		1.43
Mine Seeps FG-6B	0.226*	6.4*	149,000*	954	114*	0.73
% Contribution Mine Seeps		71%		85%		51%

"*" - Discharge and concentrations measured during Salt Tracer Study

Table 4-2 is a comparison of French Creek Zn and Cd loading immediately downstream from the 11-10 and Bullhide faults (FG25), TS-6, and mine seeps along French Gulch Road (FG-6B) (Plate 1). Between FG25 and TS-6 there was an increase in stream discharge of 9 L/s with a corresponding increase in Zn and Cd loading of 1120 mg/sec and 1.43 mg/sec, respectively. It was observed during the salt tracer study that most of the inflows downstream of the fault area appeared to originate from surface drainage along the northern side of French Gulch. The sampling station FG-6B represents surface flow from the culmination of several ground-water seeps along French Gulch Road near the mine site (Plate 1). The discharge measured by the EPA for FG-6B during this study represents 71% of the observed flow increase, 85% of the observed increase in Zn loading, and 51% of the observed increase in Cd loading between the French Creek sampling sites of FG25 and TS-6. It is believed that the seeps along French Gulch Road represent a small portion of the mine water that is

discharging into the ground-water. A large portion of the metal loading associated with the W-O mine pool may also be transported via ground-water flow in the vicinity of TS-6. Consequently, the observed surface flow loading at TS-6 and FG-6B may not be representative of the combine ground and surface flow system.

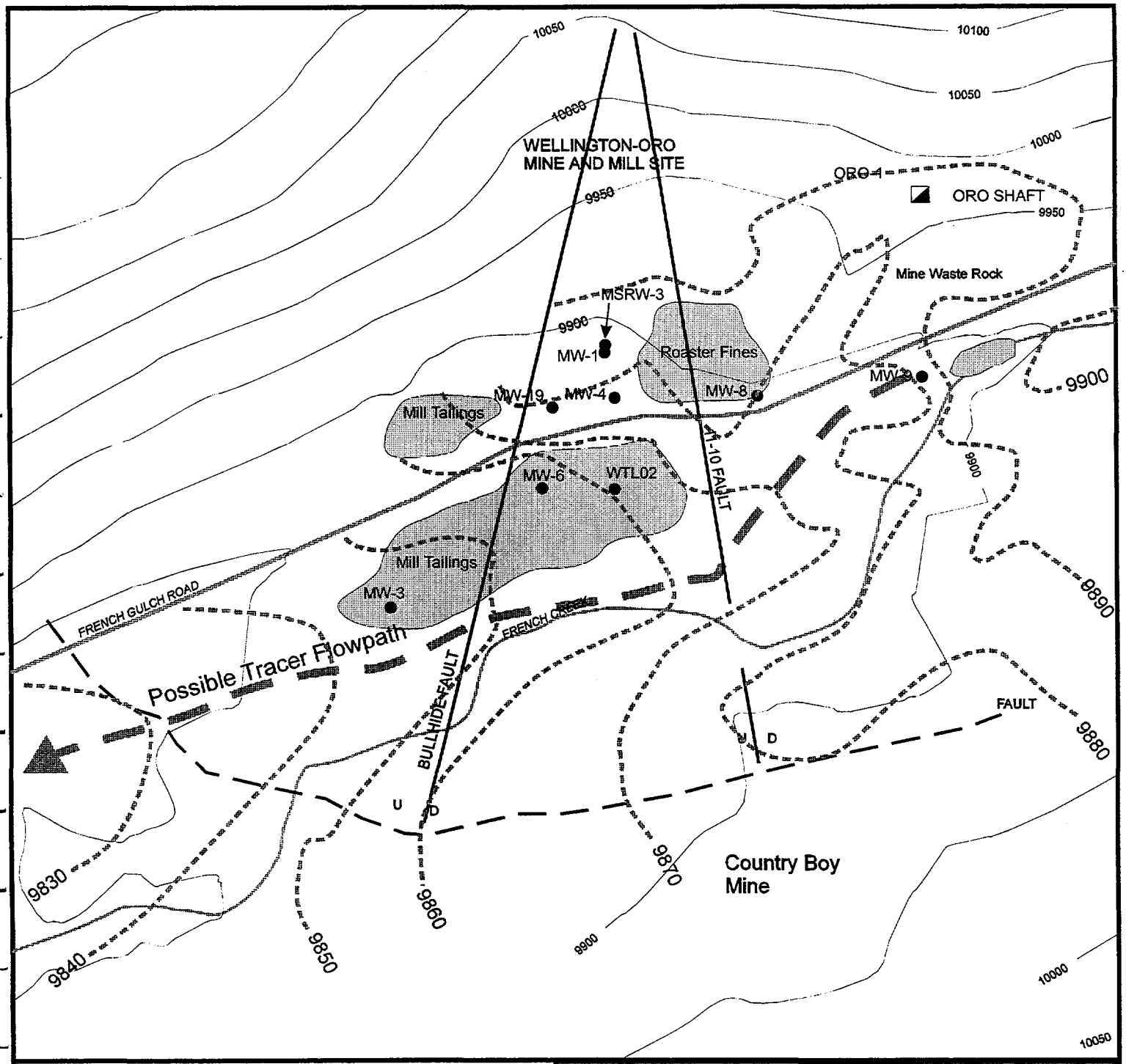
4.3.2 Alluvial Ground-water Salt Tracer Study

A slug of salt tracer was injected into the alluvial monitoring well MW-9 the morning of July 23, 1996 (Plate 1). The tracer consisted of one kilogram of NaBr mixed with 3 liters of deionized water. The tracer dispersed over a 24-hour time period. Bromide (Br) was not detected in samples from the downgradient alluvial monitoring well MW-3 or at any of the stream sampling sites (Plate 1).

The USGS report presented three possible explanations for the tracer not being detected. First, there was no certainty that the downgradient alluvial well MW-3 or the stream was along the flow path for the Br tracer moving in the alluvial aquifer. Figure 4-12 is the water table map for high flow conditions in June of 1996. Based on the contour interpretations of water level data, a possible flow path from MW-9 has been drawn. This pathway shows that the tracer could have bypassed both the alluvial well MW-3 and the French Creek stream channel. Second, the tracer could have been diluted and dispersed below detection limits by the time it arrived at either the well or stream. Third, the travel time for the alluvial aquifer and the stream could have been greater than the time period of sampling events. Average linear velocities for the alluvial aquifer were estimated from pumping tests conducted in 1994 to range from 3 to 22 feet per day (Morrissey, 1995). In contrast, a colloidal borescope in 1998 measured a preferential flow zone in the alluvial well MW-3 to be as high as 460 feet per day (see section 7 of this report). The distance between the alluvial wells MW-9 and MW-3 is approximately 1000 feet. Thus, the travel time for the tracer to reach MW-3 could range from 2 to 333 days. The stream and MW-3 were monitored on an hourly basis for days after injection and on a monthly basis for several months after injection. The high flow rate also implies significant volumes of alluvial ground-water may be flowing down the valley.

4.3.3 Mine Pool Salt Tracer Study

A slug of salt tracer was injected into the Oro Mine shaft the morning of July 23, 1996 (Plate 1). The tracer consisted of three kilograms of LiCl mixed with five liters of deionized water. The tracer was delivered to the upper mine pool with 100 feet of plastic garden hose. This depth corresponded to the top of mine water level (Figure 4-13). Figure 4-14 is a plot of chloride concentrations with time for the Oro Mine shaft, the #3 Mine shaft relief well MSRW-3, and the alluvial monitoring well MW-3 (Plate 1 and Figure 4-13). Figure 4-15 is the plot of



Scale 1" = 250'

9850 Groundwater Elevation

Possible Tracer Flowpath

N

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Figure 4-12
Potential Flow Pathway
Alluvial Salt Tracer

Project Name: French Gulch

Project Number: CO97DE-056

Date: 12/19/97 | Drawn By: MAA | Reviewed By: AM

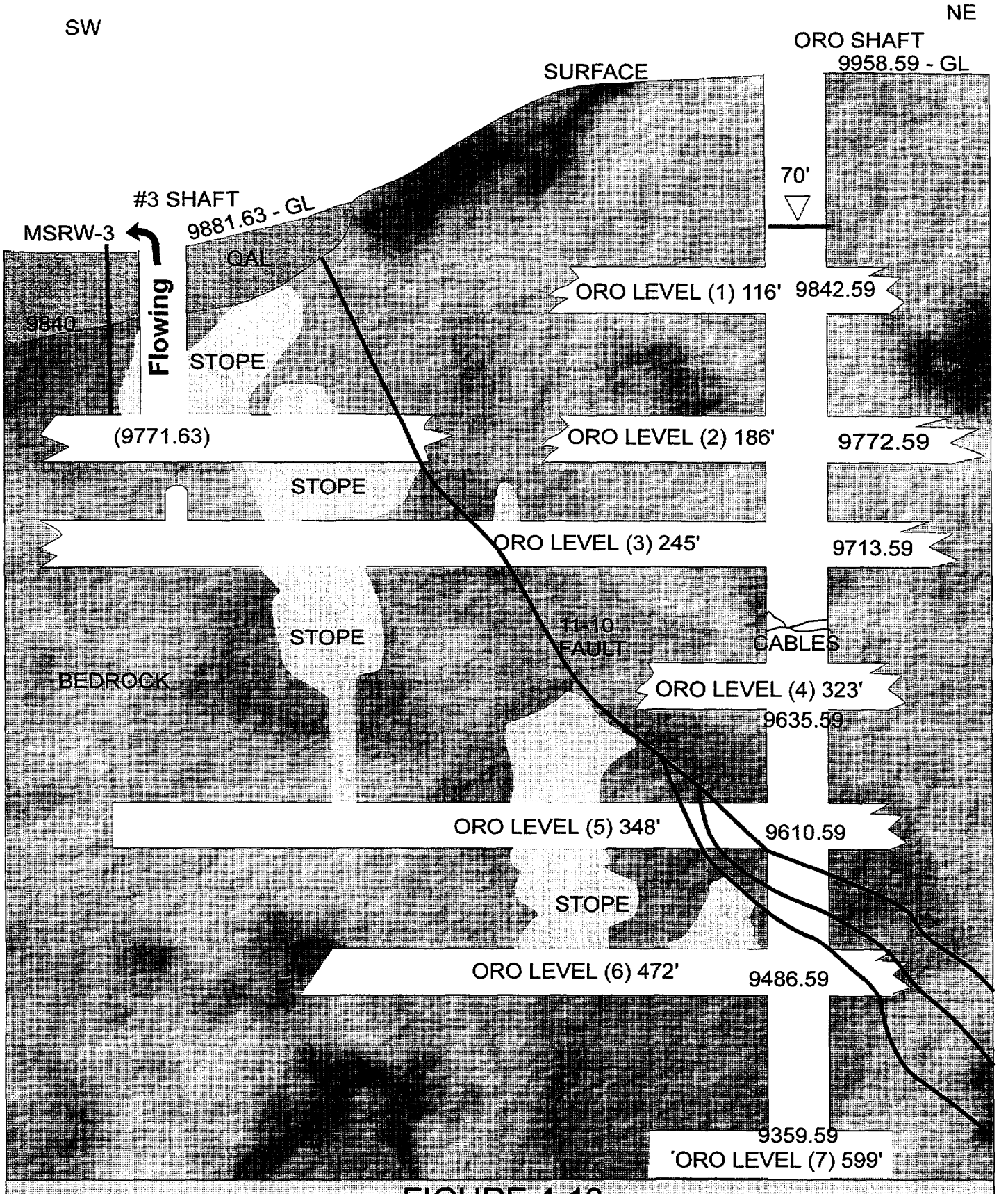


FIGURE 4-13

SCHEMATIC DIAGRAM OF THE ORO AND #3 SHAFTS

High Flow Conditions DEPTH MEASURED FROM ORO SURFACE

NOT TO SCALE

DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC

AFTER LOVERING (1934)

Li with time for the Oro Shaft. After tracer injection, the Oro Mine shaft displayed an initial increase in Cl and Li concentrations followed by several weeks of elevated concentrations of around 23 mg/L for Cl and 0.5 mg/L for Li. These elevated concentrations are several orders of magnitude greater than the background of 1 to 2 mg/L for Cl and near zero for Li (Figures 4-14a and 4-15). There was no Li detected or variations in Cl in the #3 mine relief well (Figure 4-14b) or the alluvial well MW-3 (Figure 4-14c). After the initial tracer mixing in the Oro Mine shaft there was not the continual decrease in concentrations as one would expect if the upper mine pool water was moving out of the shaft and flowing downgradient to MSRW-3 or the alluvial monitoring well MW-3. The USGS report interpreted the tracer results to indicate that:

1. the upper portion of the Oro shaft is hydraulically separated from the downgradient #3 Mine shaft, the ground-water system that supplies contaminated water to the downgradient bedrock, alluvium, and stream, and
2. the lower portion of the mine pool is the source of contamination.

It is possible that the mine pool in the upper portions of the Oro shaft is stratified and isolated from the other workings resulting in the top of the mineshaft being stagnant and/or significant mine water flow is bypassing the upper portions of the Oro shaft.

4.4 Summary and Conclusions

The salt tracer studies conducted in French Gulch during the week of July 22, 1996 were able to quantify the stream profile of metal concentrations and mass loading from above the Wellington-Oro mine site to the EPA and State stream sampling site FG-7. Within this stream segment the studies were also able to identify subreaches where the majority of metals were entering French Creek. The mine pool tracer work suggested that the upper portion of the mine pool in the Oro Shaft was not the source of metals in the contaminated ground and stream water downgradient from the Wellington-Oro mine site. The salt tracer that was injected into the alluvial ground-water was apparently diluted by ground-water flow or the tracer flow path did not encounter any of the downgradient monitoring sites. This study was unable to quantify the interaction of the stream with the alluvium because of the lack of alluvium tracer detection.

There was significant inflow of metals associated with the seepage from the 11-10 and Bullhide faults as they crossed French Creek near the W-O site during the tracer study. At the time of study, this seepage accounted for 66% of the Cd loading and 33% of the Zn loading that was observed at stream site FG-7. The majority of metal and sulfate loading (64% sulfate, 74% Mn, and 67% Zn) and stream flow increases downstream of the faults can be attributed to Wellington-Oro mine seeps along French Gulch Road and possibly ground-water discharge

into the stream above the FG-7 site. A significant amount of loading associated with the ground-water system may not be accounted for at stream site FG-7. This study was able to determine that ground-water discharge into French Creek between the 11-10 and Bullhide faults added a significant amount of flow to the stream.

The LiCl tracer injection into the top of the mine pool at the Oro Shaft did not disperse and remained above natural background for months after injection. The persistence of the tracer in the upper mineshaft and the lack of detection in the downgradient monitoring sites suggests that there was not an active flow pathway between the upper portion of the Oro mineshaft, the #3 Mine shaft, and metal contaminated ground waters that eventually discharge into French Creek. This implies that there is poor mixing of mine waters in the Oro shaft. Based on these observations, the lower portions of the mine pool could be inferred to be the source of metals to French Creek or significant mine water is bypassing the upper portions of the Oro Mine shaft. See section 7 of this report for further discussions on mine water pathways to the downgradient contaminated stream and ground-water system.

5.0 Stable Isotope Studies

5.1 Abstract

Oxygen and hydrogen stable isotope studies were performed in the vicinity of the Wellington-Oro site in 1996 and 1997. An Environmental Protection Agency (EPA) Region VIII Headwaters Grant to the State of Colorado Division of Minerals and Geology (DMG) funded these studies. Stable isotopes have been used as natural conservative tracers because snowmelt, surface waters, and ground waters can have distinctive stable isotopic compositions that are a function of the water molecule's structure.

The stable isotope studies have demonstrated that snow melt waters in the French Gulch valley were ^{18}O depleted compared to the Wellington-Oro (W-O) mine pool, and surface and ground waters in the valley. The oxygen isotope composition of the snowmelt ranged from -19.4‰ to -27.2‰. The oxygen isotopes for the mine, surface, and ground-water samples had a limited range of compositions (-19.0‰ to -17.2‰) during both low flow and high flow sampling events. This limited range has been interpreted to be due to the dominance of regional bedrock ground-water discharge that appears to influence the mine pool and French Creek. Although the mine, surface, and ground waters had similar isotopic compositions, there were two statistically distinct groups; (1) mine water and (2) French Creek and alluvial ground-water. The mine water was slightly ^{18}O depleted compared to French Creek and the ground-water associated with the alluvial aquifer. The mine waters oxygen isotope composition ranged from -19.0‰ to -18.5‰. The French Creek/alluvial ground-water oxygen isotope composition ranged from -18.2‰ to -17.4‰. Possible explanations for the ^{18}O depletion of the mine waters are:

1. *the mine waters have had a greater influence from snow melt waters over time than the creek and alluvium waters;*
2. *the source of water in the mine pool originated from a higher elevation and lower temperature precipitation events; and/or*
3. *the mine waters have not been significantly influenced by relatively ^{18}O rich surficial waters (i.e. rain events).*

The lack of shifts towards the greater ^{18}O depleted snow melt for the mine and ground waters during high flow sampling suggests that the volume of water associated with the local site spring snow melt events are small compared to the mine pool and the alluvial and bedrock ground-water system. The mine pool oxygen isotopes slightly shifted towards the ^{18}O rich isotope signature of the alluvial ground-water and French Creek during high flow sampling events. This suggest that the mine pool, alluvial ground-water and French Creek had similar recharge sources. The results of the isotope studies imply that regional bedrock

ground-water is the recharge source to the mine pool, alluvial ground-water, and French Creek.

The isotope signature of ground-water associated with the 11-10 Fault showed the greatest seasonal shifts. This is possibly due to the fault water being influenced by snowmelt and can also indicate that the fault was a major conduit for water. The stream sites above of the mine site also displayed significant shifts in isotope compositions while below the 11-10 and Bullhide faults and the mine site, French Creek displayed minor shifts during snowmelt events. This would suggest that flow increases in French Creek during spring runoff events were significantly influenced by snowmelt above the site and the 11-10 Fault. The lack of significant isotopic shifts below the faults and mine site suggests that the stream in high flow conditions was still predominantly fed by regional bedrock ground-water.

The isotopic signature of metal contaminated alluvial ground-water in monitoring wells between the 11-10 and Bullhide faults and contaminated ground-water that is discharging from seeps downgradient of the site was similar to the W-O mine pool signature. The similar isotopic signature suggested that W-O mine water was the major source of metal contamination to the alluvial ground-water and French Creek below the W-O site. The following conclusions can be made from the isotope studies:

1. *percolation or infiltration of site snowmelt water was not a major source of recharge water to the W-O mine pool;*
2. *infiltration of snowmelt into the surface spoils (roaster fines, mill tailings, and mine waste rock) was not a major source and transport mechanism for metals to the alluvial ground-water and French Creek; and*
3. *regional bedrock ground-water was the major source of recharge water to the W-O mine pool, the alluvial ground-water system, and French Creek below the mine site.*

5.2 Introduction

Isotopes are multiple species of the same chemical element. Isotopes have the same atomic number for a particular element but different atomic weights due to varying numbers of neutrons in the nucleus. Stable isotope studies are based on the ability of isotopes to fractionate, or separate into light and heavy fractions during some geologic processes. Stable isotopes are not involved with any natural radioactive decay processes.

Oxygen and hydrogen are used in stable isotope studies because they fractionate readily, are common elements, have a relatively large difference in mass between their isotopes, and have one isotope that is much more abundant

than the other (Fetter, 1994). There are two stable isotopes for hydrogen, ^{1}H and ^{2}H (deuterium), and there are three stable isotopes for oxygen, ^{16}O, ^{17}O and ^{18}O. Stable water molecules have nine different combinations of isotopes with atomic masses that range from 18 to 22. $^{1}H_2{}^{16}O$ is the most abundant and lightest water molecule with a much higher vapor pressure than the heaviest form, $^{2}H_2{}^{18}O$ (Fetter, 1994). Changes in water phase fractionate the hydrogen and oxygen isotopes. The liquid to gas phase change results in the heavier water molecules concentrating in the liquid phase. Consequently, water that evaporates from the ocean is isotopically lighter than the water left behind, and precipitation is isotopically heavier with more ^{2}H and ^{18}O than the vapor remaining in the atmosphere (Fetter, 1994).

Oxygen and hydrogen stable isotopes have been shown to be natural tracers in ground and surface water studies (Kendall and McDonnell, 1993, Kennedy and others, 1986, McDonnell and others, 1991, McDonnell and Kendall, 1992, Rodhe, 1987, and Sklash and Farvolden, 1982). These isotopes have been used to recognize waters with differing sources and to evaluate hydrologic processes such as evaporation, interactions between surface and ground waters, and subsurface fluid mixing. Oxygen and hydrogen isotopes in the ground waters of mountain valleys in Colorado tend to be uniform because the water was derived from a mixture of precipitation (rain and snow melt) from many storms over a long period of time. Water from snow melt can also tend to be isotopically uniform because of the mixing of water derived from the melting of snow and the relatively uniform temperatures and storm origins associated with winter snowstorms. In contrast, the isotopic signatures of individual rain events commonly exhibit a wide range of stable isotope compositions, which depends both on storm origin and on the temperature of precipitation. In general, precipitation derived from higher elevations and lower temperatures tend to be isotopically lighter than precipitation derived from lower elevations and higher temperatures.

Ratios of isotopes in a water sample are determined using mass spectrometry. The isotope ratios measured in water samples are $^{18}O/^{16}O$ and $^{2}H/^{1}H$. These isotope ratios are compared with the isotopic ratio of standard mean ocean water (SMOW). The comparisons are made by means of the parameter del (δ), which is defined as:

$$\delta^{18}O\ (‰) = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{SMOW}} - 1 \right] \times 10^{3}$$

$$\delta^{2}H\ (‰) = \left[\frac{(^{2}H/^{1}H)_{sample}}{(^{2}H/^{1}H)_{SMOW}} - 1 \right] \times 10^{3}$$

The results are expressed as deviation in parts per thousand (‰). When δ^2H is plotted as a function of $\delta^{18}O$ for water found in continental precipitation, an experimental linear relationship known as the global meteoric water line has been found. This line is described by the following equation (Mayo, Muller, and Ralston, 1985).

$$\delta^2H = 8\delta^{18}O + 10$$

In 1996, the State of Colorado Division of Minerals and Geology (DMG) contracted Radon Abatement Systems (RAS), Inc. to conduct stable isotopes and selected metal concentration (Cd, Fe, and Zn) studies in French Gulch. RAS subcontracted the isotope work to Isotope Solutions, Inc. and the selected metal analyses to Quanterra Environmental Services. The DMG funding for this work originated from an U.S. EPA Region VIII Headwaters Grant. These studies were designed and conducted in three phases.

The objective of the Phase I investigation was to provide a baseline for stable isotopic and selected metal concentrations for mine water, ground waters, surface waters and snow pack during low flow conditions in the vicinity of the Wellington-Oro (W-O) mine and mill complex. The primary purpose of this Phase I baseline study was to determine if there was sufficient stable isotopic contrast between the snow melt, mine, ground, and surface waters prior to spring runoff. Phase I baseline sampling was conducted on March 20, 1996. Appendix 5-1 contains the RAS, Inc. Phase I Report. A Phase II stable isotope investigation was contingent on the Phase I results demonstrating a sufficient isotopic contrast. Based on the Phase II results and success, a third phase was conducted in the winter and spring of 1997.

5.3 Phase I Stable Isotope Summary

Figures 5-1 and 5-2 are plots of French Creek discharge from the gaging station near the confluence with the Blue River (USGS, 1996) and climatological data including snow pack from Dillon Reservoir and Hoosier Pass for the month of March (NOAA, 1996, and NRCS, 1996). The surface elevation of the study area in French Gulch ranges from 9,700 to 9,970 feet. The Hoosier Pass station records water equivalent content of the snow pack and temperature data for the U.S. Department of Agriculture National Resources Conservation Service (NRCS) Water and Climate Center. This station is located approximately 8.5 miles south of French Gulch and is at an elevation of 11,400 feet. These data would most likely represent the conditions of snow pack and temperature for the upper French Gulch Basin or headwaters for French Creek above the study area.

The Dillon Reservoir station records precipitation, temperature, and depth of snow pack for the U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA) National Weather Service. This station is

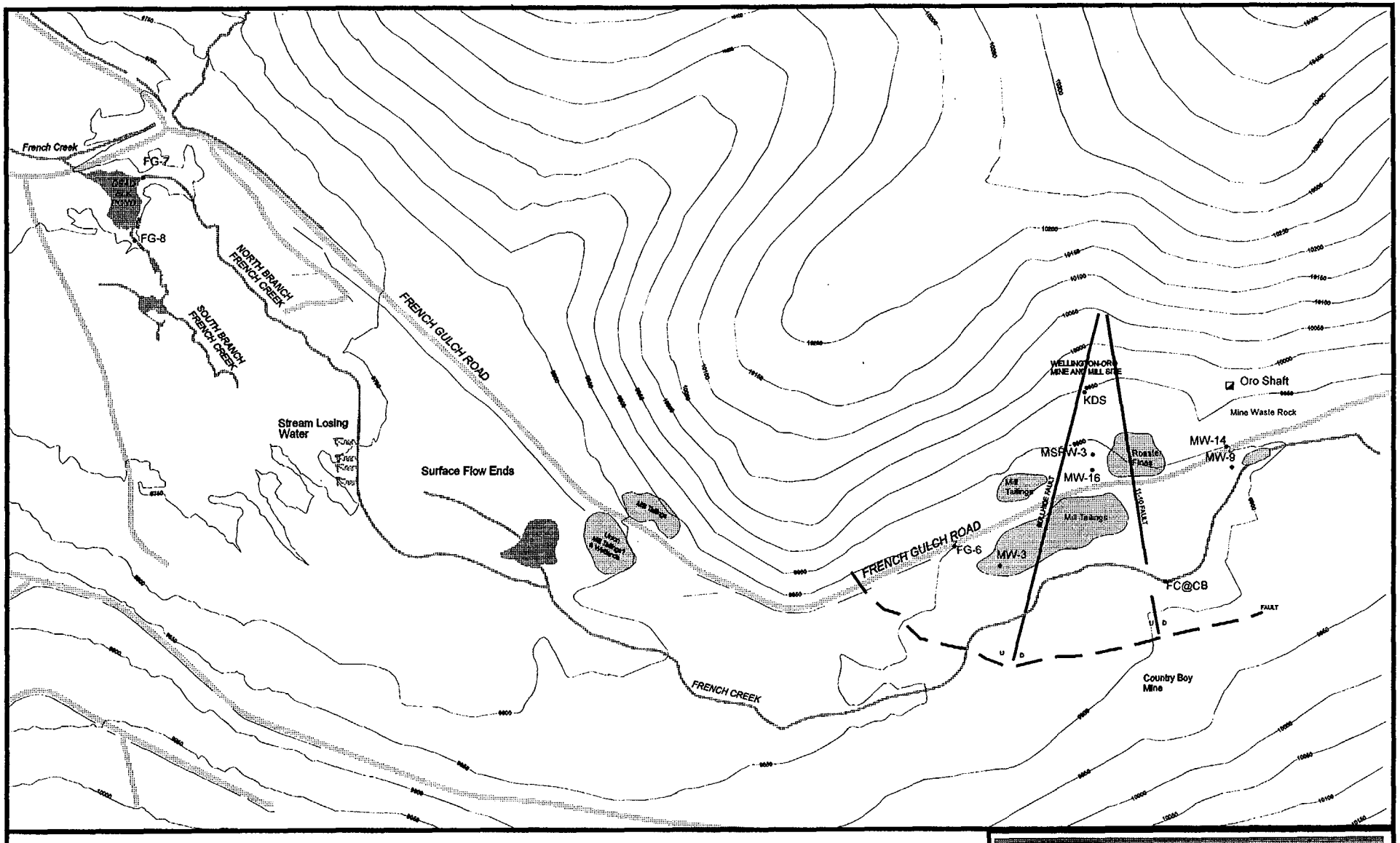
located approximately 10 miles north of French Gulch and is at an elevation of around 8,900 feet. These data would most likely represent the depth of snow pack, temperature and precipitation in the vicinity of the study area. For any quantitative analysis at the W-O site, an elevation correction and water equivalent estimation of the snow pack would need to be made.

French Creek discharge data indicates that baseline sampling on March 20, 1996 appears to have occurred during stabilized low flow conditions. The snow water equivalent data from Hoosier Pass indicates that the snow pack was stable and there were no major snowmelt events in the upper French Gulch Basin during the month of March (Figure 5-1). The temperature and snow pack data from Dillon Reservoir suggests that there may of been some local melting of snow in the study area during warm periods in March, although some of the decrease in snow pack depth may be due to compaction and sublimation (Figure 5-2).

The snow pack data for the Dillon Reservoir station does not include water equivalent content of the snow and the Hoosier Pass station does not record snow depth. Consequently, evaluation of compaction, sublimation and snowmelt in the study area using the Dillon and Hoosier Pass data was not possible.

The sample locations for the Phase I Stable Isotope Study are shown in Figure 5-3. Table 5-1 summarizes the Phase I sample sites. The RAS sample #FG0006 was incorrectly described in the Phase I report (Appendix 5-1) as a French Creek sample. This sample location is associated with a ground-water seep (FG-6C) along French Gulch Road. RAS sample #FG0008, roaster fines soil boring (SBRF-3), was incorrectly referred to as a ground-water "spring" sample in the discussion section of the Phase I report (Appendix 5-1). This sample should represent the ground-water-saturated portion of the roaster fines waste pile, but was collected from the soil boring using a bailer. The Phase I stable isotope and metal concentration results for this roaster fines water sample may be suspect base on the collection method. In March of 1996, the roaster fines boring SBRF-3 only had one foot of water. This boring was not purged because of the minimal water and a very slow recovery rate. Consequently, the water sample was taken from the first bailer. The water collected in SBRF-3 during the Phase I sampling may contain residual stagnant water from higher flow conditions that probably impacted the stable isotope and metal concentration results (see further discussion below).

The stable isotopic results for the Phase I sampling event are plotted with the global meteoric water line (MWL) in Figure 5-4. All samples fall on or near the global MWL indicating that the data are reasonably accurate and precise (pers. comm. B.M. Smith, Isotope Solutions, 1996). Figure 5-5 is a detailed view of the $\delta^{18}O$ versus $\delta^{2}H$ plot with the global MWL. Three samples (KDS, FG-6C and SBRF-3) are slightly to the right of the global MWL which suggests minor evaporation (pers. comm. B.M. Smith, Isotope Solutions, 1996). Two of these samples, KDS and FG-6C, are the spring/seep sample locations where minor



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N

MW-16 Sample Location

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Figure 5-3
French Gulch Phase I & II Stable Isotope Sample Location Map

Project Name: French Gulch

Project Number: CO97DE-056

Date: 12/19/97 | Drawn By: MAA | Reviewed By: AM

Table 5-1

Phase I Sample Sites for the French Gulch Stable Isotope Investigation

RAS Sample #	Sample Type	Location	Comments
FG0001	ground-water	MW-14	Clean, 11-10 fault, shale bedrock
FG0002	ground-water	MW-9	Clean, lower Qal, upgradient from mine
FG0003	ground-water	MW-16	Contaminated, shale bedrock at mine site
FG0004	ground-water	MW-3	Contaminated, upper & lower Qal, below mill tailings
FG0005	mine water	MSRW-3	Contaminated, Relief well for #3 Mine Shaft
FG0006	ground-water seep	FG-6C	Contaminated seep south side French Gulch Road
FG0007	ground-water seep	KDS	Contaminated, Kenny Dog Spring
FG0008	ground-water	SBRF3	Contaminated, Roaster Fines soil boring
FG0009	French Creek	FC@CB	Clean, Above culvert at Country Boy Mine, upstream from mine site
FG0010	Snow	composite Sample	At MW-9 location
FG0011	French Creek	FG-7	Contaminated, downstream from mine site, north inflow to Dead Elk Pond

evaporation would be common. The roaster fines soil boring sample location (SBRF-3) is at a position most distant from the global MWL indicating that evaporation has modified its isotope compositions. Evaporation would be unusual for ground-water in a soil boring unless it has been stagnant for a long period of time. As previously discussed, the SBRF-3 Phase I water sample probably represents stagnant water because the soil boring was not purged prior to sampling.

All the mine water, alluvial ground-water and French Creek samples exhibit a limited range of oxygen ($\delta^{18}O$ from -17.4 to -18.9‰) and hydrogen ($\delta^{2}H$ from -131 to -142‰) isotopic compositions, with the exception of the Kenny Dog Spring ($\delta^{18}O$ =-21‰ and $\delta^{2}H$ = -159‰). The isotopic similarity of alluvial ground-water and French Creek implies that the principal source of water in the creek is regional bedrock ground-water. An explanation presented in the RAS Phase I Report for the lower isotope values from the Kenny Dog Spring is mixing of the spring water with over 30% surficial snowmelt (see example of isotopic mass balancing for two component water mixtures page 4 of Phase I Report -

Appendix 5-1). Subsequent isotope sampling supports this mixing model. There was a strong oxygen isotopic contrast between the mine water, alluvial ground-water and French Creek samples ($\delta^{18}O$ =-18.3 $\pm$ 0.6‰) and the snow pack ($\delta^{18}O$=27.2‰). It was concluded that this contrast provides a sufficient difference to conduct meaningful mass balance calculations during snowmelt events with a precision of a few percent (RAS, 1996a).

Although the waters collected during the Phase I investigation exhibit a limited range isotopic composition reflecting the regional bedrock ground-water dominance of the low flow hydrologic system, there are two statistically significant groupings observed (Figure 5-5). Discounting the Kenny Dog Spring sample because of snow melt contamination, the two groupings are; (1) MSRW-3, MW-16 and FG-6C and (2) FC@CB, FG-7, SBRF-3, MW-9 and MW-14. MW-3 isotopic composition falls between the two groups. Group #1 represents mine water while group #2 represents French Creek and ground-water (alluvium and bedrock). The isotopic signature of the ground-water associated with the shale bedrock at the mine site (MW-16) and the seep along French Gulch Road (FG-6C) are nearly identical to the mine water (MSRW-3). Discounting the isotope values from SBRF-3 due to potential evaporation, the highest oxygen isotope value (^{18}O-rich) for group #2 is -17.7‰ from sample location MW-14. If this value represents the baseline conditions for regional bedrock ground-water, the slight shifting to lower oxygen values within group #2 possibly indicates minor mixing with ^{18}O-poor snowmelt and/or mine water. The position of MW-3 between the two groups suggests a higher percentage (up to 45%) of mine water contribution in this alluvial well on the west-side of the mill tailings and Bullhide Fault (Figure 5-3).

5.4 Phase II Stable Isotope Summary

The purpose of the stable isotopic tracer studies was to resolve the roles of mine water, ground-water and surface water during high flow conditions associated with the major spring snow melt in the area of the Wellington-Oro Mine and Mill complex. The DMG proceeded with a Phase II investigation because the Phase I data demonstrated the isotopic contrast between snow melt, mine water, ground-water, and French Creek in the study area. Phase II involved sampling eleven sites from the mine, ground and surface waters three times during the peak flow and declining flow of French Creek in the spring and summer of 1996. There were two sample sites added to the Phase II investigation: FG-8 (south inflow to Dead Elk Pond) and #3 Mine shaft. The #3 Mine shaft was sampled only once as a field quality control to compare with the #3 Mine Shaft Relief Well (MSRW-3). Water samples were analyzed for oxygen and hydrogen isotopic composition, as well as Cd, Fe, and Zn concentrations. Appendix 5-2 contains the Phase II Final Report.

French Creek discharge began to rise in early May when the high elevation snow pack started to decline (Figure 5-6). The lower elevation or study area snow pack had mostly disappeared by late April and early May (Figures 5-7 and 5-8). French Creek discharge reached a plateau around 60 cfs by May 17. The mine and many of the ground-water wells at the mine site were flowing at this time. A multi-day storm event started on May 25 (Figure 5-8). This event was rain and snow at the mine site and a snow event in the upper French Gulch Basin. French Creek discharge peaked on the first day of the storm at 80 cfs and steadily declined as the temperature decreased and the upstream snow pack slightly increased to a plateau of 10 inches water equivalent (Figure 5-6). French Creek discharge began a steep rise in early June when the upper basin snow pack declined rapidly (Figure 5-9). The French Creek hydrograph reached a second peak at 80 cfs on June 10 immediately after the upper French Gulch snowmelt was complete. The first Phase II isotope sampling event occurred on June 10.

The stable isotopic results for the Phase II June 10 samples have been plotted with the global meteoric water line (MWL) in Figure 5-10. All samples fall on or near the global MWL indicating that the data are reasonably accurate and precise (pers. comm. B.M. Smith, Isotope Solutions, 1996). Two distinct isotopic groups are still present during this sampling. The mine water (Group #1) contains sample locations MSRW-3, MW-16, KDS, FG-6C and MW-3. The creek and alluvial and bedrock ground-water (Group #2) contains sample locations SBRF-3, MW-14, MW-9, FC@CB, FG-7 and FG-8. The sample locations for Group #2 are identical to Phase I with the addition of the new French Creek stream sample FG-8. The highest oxygen isotopes value (^{18}O-rich) for Phase I baseline conditions for Group #2 was -17.7 ‰. The slightly greater shift to lower oxygen values for most of the sample locations within Group #2 compared to Phase I results suggest an increased mixing with ^{18}O-poor snow melt and/or mine water during the peak high flow conditions (Figures 5-5 and 5-10).

The Group #1 (mine water) in the June 10 sampling included the same sample locations as the Phase I results with the addition of the KDS and MW-3 locations (Figure 5-10). The Kenny Dog Spring (KDS) isotope results plot within the mine water group. This supports the model of snowmelt contaminating the Phase I KDS sample in March. The MW-3 sample location was a mixture of mine and alluvial ground-water in the low flow Phase I sampling. Under peak high flow conditions this sample location appears to be dominated by mine water discharge or has greater influence from snowmelt.

The mine pool water level increased over fourteen feet between low flow conditions in March and peak high flow conditions on June 10. The isotope signature for the mine water (group #1) is very similar between Phase I (low flow conditions prior to snowmelt) and the June 10 sampling results (Figures 5-5 and 5-10). This similarity indicates that at the time of sampling, water from ^{18}O depleted snowmelt did not significantly contribute directly to the rise in the mine

pool levels. If direct snowmelt infiltration was the major source of recharge water to the mine, the mine waters should have shifted towards the isotopic signature of the snowmelt. Group #1 (mine water) appears to be slightly shifted to right of the global MWL and towards higher oxygen values for the June 10 sampling compared to Phase I baseline sampling in March 1996 (Figure 5-10). This shift suggests a slightly evaporative isotopic signature for the mine water and regional bedrock ground-water influence. There are at least three possible explanations for the evaporative signature:

1. the mine water rise intercepted stagnant mine water that had been exposed to headspace during low flow conditions,
2. the regional bedrock ground-water recharge that contributed to the over fourteen feet of mine water level rise had a slight evaporative character and was slightly more ^{18}O-rich than the mine water, and
3. the shift is within the precision and accuracy range of the isotope analytical data.

French Gulch discharge steadily declined after the June 10 French Creek peak-flow (Figure 5-11). The next isotope-sampling event occurred on June 27. This sampling event was three days after a rainstorm (Figure 5-11). A few wells at the mine site, including the #3 Mine Shaft, were still flowing at this time. The stable isotopic results for the Phase II June 27 samples are plotted with the global meteoric water line (MWL) in Figure 5-12. All samples fall on or near the global MWL indicating that the data are reasonably accurate and precise (pers. comm. B.M. Smith, Isotope Solutions, 1996). Two distinct isotopic groups are still present during this sampling. The mine water (Group #1) contains sample locations MSRW-3, MW-16, KDS, FG-6C, MW-3 and MW-14. Group #2 contained creek and alluvial ground-water sample locations SBRF-3, MW-9, FC@CB, FG-7 and FG-8.

The 11-10 fault well, MW-14, switched from Group #2 (June 10) to Group #1 (June 27). The fault well is completed at 277 feet. It is believed that this shift is due to a delayed response of mixing with ^{18}O-poor snow melt water that infiltrated from the surface along the 11-10 fault plane or was due to snow melt recharging the regional bedrock ground-water upgradient from the fault. This shift was not due to metal contaminated mine water because there was not an associated significant increase in metals (Figure 5-13). The groupings for the June 27 sampling are the same as June 10 except for the MW-14 sampling location.

The June 27 group #2 isotope results are more scattered compared to the June 10 sampling and Phase I results. The surface samples in the June 27 group #2 (FG-7, FG-8, and FC@CB) consistently fall slightly above the global MWL (Figure 5-12). This could be caused by mixing with rainwater which tends to have a higher hydrogen isotopic composition, although this position above the global MWL is very close to the precision and accuracy of the analytical methods

(pers. comm. B.M. Smith, Isotope Solutions, 1997). By June 27, snowmelt should have had no direct effect on the surface waters (Figure 5-9). The shift to ^{18}O-poor values for locations downstream of the mine site (FG-7 and FG-8) compared to upstream of the mine site (FC@CB) suggests:

1. mine water mixing (up to 30%) is occurring in these downstream locations, and/or
2. the bedrock ground-water that is recharging the stream at FG-7 and FG-8 was influenced by earlier upgradient snowmelt that recharged the regional ground-water system.

The last Phase II sampling event was conducted on July 22. This sampling also occurred three days after a rainstorm (Figure 5-14). The stable isotopic results for the Phase II July 27 samples have been plotted with the global meteoric water line (MWL) in Figure 5-15. All samples fall on or near the global MWL indicating that the data are reasonably accurate and precise (pers. comm. B.M. Smith, Isotope Solutions, 1996). The groupings for the July 27 isotopic results are less distinctive than the previous sampling events. Group #1 (mine water) consists of MSRW-3, MW-16, MW-3 and KDS. Group #2 only contains the French Creek sample locations FC@CB, FG-7 and FG-8. The SBRF-3 (roaster fines soil boring) was not plotted because the hydrogen isotope composition was not determined for this sample. The ^{18}O-isotope value of -17.8‰ for SBRF-3 suggests that this sample would remain in Group #2. The deep fault well MW-14 has begun to shift back to the signature of the baseline bedrock ground-water and French Creek water represented by Group #2. The FG-6C seep location appears to have shifted from a mine water signature to a mixture of mine water (Group #1) and alluvial ground-water (Group #2). The shift to a higher (^{18}O-rich) oxygen isotope value for MW-9 sample (-17.4‰) places this sample at a value above the baseline value previously observed for bedrock ground-water (-17.7‰). Further sampling would be necessary to refine the bedrock ground-water baseline values. These baseline values are very important in quantifying mixing models.

Most of the isotopic data appears to be shifted to the left or above the global MWL for the July 22 samples (Figure 5-15). This shift is very close to the precision and accuracy of the analytical data, although the consistent shift may be due to the influence of slight mixing with rainwater. All the French Creek samples upstream and downstream of the mine site plot very close together suggesting that the volume of mine water mixing with stream water was minimal at the time of sampling.

Table 5-2
Phase III Additional Sample Sites for the French Gulch Stable Isotope Investigation

RAS Sample #	Sample Type	Location	Comments
FG0072 FG0095	Snow	composite sample	Clean, 1.25 miles upstream of W-O site, near FG-1
FG0059 FG0109	ground-water	MW-2	Contaminated, Qal/porphyry, below W-O site and mill tailings, near new mill tailings well WTL-02
FG0062 FG0100	ground-water	MW-11	Clean, shale bedrock (Qal/bedrock @ high flow), above W-O site
FG0069 FG0097	ground-water	MW-12	Clean, porphyry bedrock, above W-O site
FG0063 FG0107	ground-water	MW-13	Contaminated, shale bedrock, near main mine waste and roaster fines surface piles
FG0054* FG0108	ground-water	WTL-02	Contaminated, new mill tailings well near MW-2
FG0102	ground-water	WRO-1	Contaminated, new roaster fines well
FG0075 FG0086	ground-water seep	1121	Contaminated, at base of dredge piles downstream from W-O site
FG0076 FG0088	ground-water seep	FG-6D	Clean Qal (?) seep from under dredge tailings pile near contamianted mine seeps
FG0106	ground-water seep	Qal	Qal seep at #3 Mine
FG0070 FG0096	French Creek	FG-1	Clean background, 1.25 miles upstream from W-O site
FG0073 FG0082	French Creek	FG-9	Contaminated, near USGS flow gauge at confluence with Blue River
FG0074 FG0091	French Creek	FG-15	Contaminated, pool adjacent to creek (north side) near 11-10 Fault & Country Boy Mine
FG0077 FG0087	French Creek	TS-4	Contaminated USGS site, below Bullhide Fault
FG0101	Mine Pool	Oro	Contaminated, top mine pool near 70 ft below surface
FG0083	Rain	Grab sample	Clean, near FG-9 site (May sample event)

* RAS (1997a) Mine Pool Characterization Study

5.5 Phase III Stable Isotope Summary

The objective of the Phase III stable isotope study was to complete a full cycle of sampling during low and high flow conditions. Phase III involved two additional sampling events; (1) another low flow baseline sampling event in March of 1997 and (2) a sampling event at the end of May 1997 that corresponded to the rising limb of the French Creek hydrograph. In addition to the Phase I and II sampling

locations, fourteen ground and surface water sampling locations and additional snow samples were incorporated into the study to provide supplemental mine, ground-water, snow, and creek coverage. Table 5-2 summarizes the additional Phase III sample locations. As with Phase I and II, water samples were analyzed for oxygen and hydrogen isotopic composition, and Cd, Fe, and Zn concentrations. Appendix 5-3 contains the Phase III RAS report. Figures 5-16 and 5-17 are plots of French Creek discharge from the USGS. gaging station near the confluence with the Blue River (USGS, 1997) and climatological data including snow pack from Dillon Reservoir and Hoosier Pass for the month of March 1997 (NOAA, 1997 and NRCS, 1997). The first Phase III sampling event was performed on March 12 and 13. The French Creek discharge data indicated that the Phase III baseline sampling occurred during stabilized low flow conditions with a stream discharge of 2 cfs. The temperature and snow pack data from Dillon Reservoir suggested that there might have been some local melting of snow in the W-O mine site area during the sampling period (Figure 5-16). The snow water equivalent data from Hoosier Pass shows that the high elevation snow pack was stable and suggests that there were no major snow melt events in the upper French Gulch headwaters region during the month of March 1997 (Figure 5-17).

Figure 5-18 is a plot of the $\delta^{18}O$ versus $\delta^{2}H$ for the Phase III March 1997 results on Phase I and II sample locations. All of the samples fall near the global MWL indicating that that the data are reasonably accurate and precise. The March 1997 baseline results display very similar patterns to the March 1996 baseline results (Figure 5-5). The 1997 results appear to be slightly more scattered and fall consistently below the global MWL. As with the March 1996 data, the seeps (KDS and FG-6C) and the roaster fines soil boring SBRF-3 were most distant from the global MWL. There were still two statistically significant groupings in the 1997 baseline results. In contrast to the 1996 baseline results, the 1997 KDS sample did not have a significant snow melt contribution and plotted within the mine water Group #1 with the #3 Mine shaft relief well, the mine site shale bedrock well (MW-16), and the downgradient ground-water seep (FG-6C) (Figure 5-18). The deep 11-10 fault well MW-14 was shifted towards a more ^{18}O-poor isotope composition compared to the 1996 baseline results suggesting that local snow melt infiltration may have been influencing the fault in March of 1997. Similar to the 1996 baseline results, the MW-3 isotopic composition plotted between the mine water group #1 and French Creek/alluvial ground-water Group #2. In addition, the Phase III results also showed a slight shift to lower oxygen values within Group #2 for the downstream creek sites. This may be due to minor mixing with ^{18}O-poor snow melt and/or mine water.

French Creek discharge began to rise in early May 1997 when the high elevation snow pack started to melt (Figure 5-19). The lower elevation or mine site area snow pack had melted out in March and April of 1997 (Figures 5-16 and 5-20). The 1997 stream hydrograph peaked on June 5 at 122 cfs (Figure 5-21). Similar to the 1996 stream hydrograph (Figure 5-9), a second peak in June of 1997

occurred immediately after the high elevation snowmelt was complete. The second Phase III sampling was conducted on May 29 and 30 during the rising limb of the stream hydrograph when the stream discharge ranged from 30 cfs to 40 cfs (Figure 5-19). During the sampling on May 29, there was a rain event and a rain sample was collected at the FG-9 stream site for isotope analyses.

The oxygen isotope compositions ($\delta^{18}O$) of the snow in March and May of 1997 ranged from -19.4‰ to -23.6‰. The March 1996 snow at MW-9 had an $\delta^{18}O$ composition of -27.2‰. The 1997 snow samples were also statistically lower in oxygen isotope compositions than the mine water, bedrock and alluvial ground-water, and French Creek. The Phase III snow sampling confirmed the Phase I conclusions that there was sufficient contrast between snow melt waters and the mine, ground, and stream waters in French Gulch to conduct meaningful mass balance calculations during spring snow melt events.

The May 1997 stable isotope results for the Phase I and II samples have been plotted with the global MWL in Figure 5-22. As with the March 1997 baseline results, all of the samples plotted below the global MWL. The mine Group #1 included the same sampling locations as the March 1997 baseline results with the addition of MW-3 and MW-14. There were no significant shifts in the oxygen isotope compositions for the mine group between the March baseline conditions and the high flow May conditions (Figures 5-18 and 5-22). The lack of a shift towards the lighter or lower $\delta^{18}O$ snow suggests that the spring recharge water that was driving the rise in the W-O mine pool did not originate directly from snow melt infiltration above the mine workings. In contrast, the Group #2 French Creek/alluvial ground-water showed a significant shift in the clean upstream site (FC@CB) and slight shifts in the clean shallow alluvial ground-water (MW-9) location and the downstream locations (FG-7 and FG-8) towards the $\delta^{18}O$-poor snow melt. This would suggest that the high elevation snowmelt waters were influencing the upstream areas of French Gulch while the downstream locations were being dominated by regional bedrock ground-water and/or mine water discharge. It is possible that the $\delta^{18}O$-rich rain event on May 29 may have masked some of the surface water shifts towards the $\delta^{18}O$-poor snowmelt.

The greater up-valley influence of snowmelt in French Creek was also demonstrated with the Phase III supplemental stream sampling locations. Figure 5-23 is a plot of all the Phase III isotope results for stream sample locations in the March baseline conditions and May high flow conditions. The two locations with the greatest shifts towards the $\delta^{18}O$-poor snowmelt were the clean FG-1 and FC@CB locations. FG-1 was located over 1.25 miles upstream of the W-O site. FC@CB (French Creek above County Boy Mine) was located immediately upgradient of the 11-10 Fault (Figure 5-3). The USGS Salt Tracer study documented significant flow increases and metal loading in French Creek below the 11-10 and Bullhide faults (Kimball et. al., 1997). This flow increase was interpreted to be due to bedrock ground-water discharge from the faults and

alluvial and placer ground-water discharge. The contaminated TS-4 stream-sampling site was just downstream of the Bullhide Fault. The TS-4 location and subsequent downstream locations FG-7, FG-8, and FG-9 displayed smaller shifts towards the $\delta^{18}O$-poor snow melt compared to the upstream locations for the May sampling event (Figure 5-23). This would suggest that there was a greater influence of regional bedrock ground-water and/or mine water discharge to French Creek below the 11-10 and Bullhide faults than the upstream sites. Mixing models using a -20‰ oxygen isotope composition for the snow melt calculated over a 50% snow melt contribution to stream flow above the 11-10 Fault and less than 15% snow melt contribution to stream flow below the Bullhide Fault.

5.6 Isotope and Metal Concentrations Trends

5.6.1 Supplemental Phase III Ground-water and Mine Locations

5.6.1a Oro Mine Shaft

The Oro Mine shaft was sampled for stable isotopes in January of 1997 as part of the low flow mine characterization study (RAS, 1997a), in May of 1997 as part of the Phase III stable isotope investigation, and in June 1998 as part of the high flow mine characterization study. The stable isotope results for the Oro mine pool is also discussed in section 7 of this report. The present discussion of stable isotopes focuses on the 1997 results.

The 1997 winter sampling was accomplished with a discrete point sampler at a depth of 116 feet below the surface. The May sampling was accomplished with a bailer at approximately 68 feet below the surface. This depth corresponded to the top of the mine pool water at the time of sampling. Figure 5-24 is a comparison of the Oro Mine shaft and #3 Mine shaft oxygen stable isotope and selected total recoverable metal concentration results for 1997. The two mineshafts exhibited different trends in metal concentrations and isotope signature. The oxygen isotopes for the #3 Mine were constant (-18.5‰) while the top of Oro Mine pool displayed a significant shift between low and high flow conditions. The -19.0‰ $\delta^{18}O$ value for the January sampling suggested that the top of the Oro Mine pool had a greater influence over time from $\delta^{18}O$-poor snow melt than the #3 Mine shaft water. The May sampling of the Oro Mine shaft showed a shift to more $\delta^{18}O$-rich (-17.6‰) water. It is possible that the relatively $\delta^{18}O$-rich rain event during the May sampling event, which was -17.0‰ in $\delta^{18}O$ composition, and/or recharge from $\delta^{18}O$-rich bedrock ground-water, were responsible for this large compositional shift for the Oro shaft mine pool. The lack of shifts towards $\delta^{18}O$-poor snowmelt during the spring flow surge implies that water from direct snowmelt infiltration is not a significant recharge source to the mine pool.

5.6.1b MW-2

The metal contaminated monitoring well MW-2 was completed at the base of the alluvium and top of the porphyry bedrock in the south mill tailings area due south of the #3 Mine site. Figure 5-25 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The baseline oxygen isotope signature of -18.2‰ suggests that this well's water was composed of a mixture of W-O mine water and alluvial/bedrock ground-water (Figure 5-18). The May sampling event showed a slight δ^{18}O-poor shift to -18.5‰. This slight shift could be the result of mixing with a relatively greater amount of contaminated mine pool water and/or clean alluvial ground-water that had been influenced by snow melt similar to the upgradient French Creek FC@CB sampling site (Figure 5-18). The lower Cd and Zn concentrations for the May sampling event suggest dilution with clean ground-water. The higher Fe concentrations in May could imply an additional source of Fe independent from the W-O mine pool, possibly the roaster fines and/or mill tailings.

5.6.1c MW-11

This clean background monitoring well upgradient from the #3 Mine site has a dual screen completion in the shale bedrock and alluvium. During low flow conditions the water level in this well is below the alluvium screen. Figure 5-26 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The baseline oxygen isotope signature of -17.6‰ suggests that this well was composed predominantly of alluvial/bedrock ground-water (Figure 5-18). The May sampling event showed a slight δ^{18}O-poor shift to -18.0‰. The increase in metals associated with this shift suggests a slight mixing with δ^{18}O-poor mine water and/or infiltration of δ^{18}O-poor snowmelt that leached metals from surface spoil piles.

5.6.1d MW-12

This clean background monitoring well upgradient from the #3 Mine site has a porphyry bedrock completion. Figure 5-27 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The baseline oxygen isotope signature of -18.0‰ suggests that this well was composed of either a mixture of δ^{18}O-poor W-O mine water and bedrock ground-water or bedrock ground-water that had been influenced by local δ^{18}O-poor snow melt (Figure 5-18). The very low metal concentrations in this well do not support any W-O mine water influence. The May sampling event showed a very slight δ^{18}O-poor shift to -18.1‰ with no significant increases in metal concentrations. It is possible that the bedrock ground-water in this May sampling was being influenced by δ^{18}O-poor snowmelt.

5.6.1e MW-13

The metal contaminated monitoring well MW-13 has a shale bedrock completion in the vicinity of the roaster fines and mine waste surface piles. Figure 5-28 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The baseline oxygen isotope signature of -17.3‰ suggests that this well was predominantly composed of bedrock ground-water (Figure 5-18). The May sampling event showed a similar $\delta^{18}O$ value. The metal concentrations in this well were orders of magnitude greater than the W-O mine pool concentrations (Figure 5-24). The oxygen isotopes were very similar to the roaster fines (SBRF-3) (Figures 5-18 and 5-22). Consequently, the source of metal contamination in this well has been interpreted to be leachate from the roaster fines and mine waste piles.

5.6.1f WTL-02

The U.S. Bureau of Reclamation in the fall of 1996 drilled the WTL-02 monitoring well. This well is a shallow mill tailings completion with a screen interval from 14.1 feet to 19.1 feet below surface (BOR, 1997a). WTL-02 was sampled for stable isotope investigations in January of 1997 as part of the mine characterization study (RAS, 1997a) and in May of 1997 as part of the Phase III stable isotope investigation. Figure 5-29 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The baseline oxygen isotope signature of -18.9‰ suggests that this well was predominantly composed of W-O mine water (Figure 5-18). This $\delta^{18}O$ value was slightly lower than typical values of mine water observed from the #3 Mine. The January sampling of this well was performed during a near blizzard snowstorm. The $\delta^{18}O$-poor snow may have slightly contaminated the isotopic composition of this well when the wellhead was left open during purging. The May sampling event showed a significant $\delta^{18}O$-rich shift to -17.5‰ with relatively small changes in metal concentrations. This May $\delta^{18}O$ value implies significant mixing with a clean alluvial ground-water source uncontaminated by snow melt or surface infiltration from the $\delta^{18}O$-rich rain event (-17.0‰) that occurred the day prior to sampling.

5.6.1g WRO-1

The U.S. Bureau of Reclamation in the fall of 1996 also drilled the WRO-1 monitoring well. This well was a shallow roaster fines completion with a screen interval from 14.1 feet to 18.1 feet below ground surface (BOR, 1997a). This well was not sampled during low flow conditions because it was dry. A comparison with the May sampling results for the WRO-1 well and the roaster fines soil boring (SBRF-3) showed similar metal levels and isotopic compositions from -17.2‰ to -17.7‰ (Figure 5-30). This would suggest that the source of the water in the saturated portion of the roaster fines was the alluvial/bedrock

ground-water and the high metal levels were due to leachate from the roaster fines (Figure 5-18). The roaster fines metals concentrations were also orders of magnitude greater than the mine water concentrations (Figure 5-24).

5.6.1h 1121 Seep

The 1121 contaminated seep was located at the base of the dredge tailings downgradient of the W-O site. Figure 5-31 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The oxygen isotope signature of -18.0‰ suggests that this seep was composed of a mixture of W-O mine water and French Creek/alluvial ground-water (Figure 5-18). The mine water source for contamination appears to be supported by the relative proportions of metal (Cd, Zn, and Fe) concentrations in the seep which display a similar pattern to the #3 and Oro mine water (Figures 5-24 and 5-31).

5.6.1i FG-6D Seep

The FG-6D seep was located in the vicinity of highly contaminated seeps along French Gulch Road, including the FG-6C seep. FG-6D was observed during the EPA sampling studies to have lower metal and sulfate concentrations than the nearby seeps (EPA, 1996a and 1996b). Figure 5-32 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The oxygen isotope signature of -17.8‰ suggests that this seep was predominantly composed of alluvial ground-water (Figure 5-18). In contrast, the FG-6C seep had metal concentrations and isotopic signatures similar to the W-O mine water. Metals concentrations for the FG-6D seep were much lower than the W-O mine water and the other seeps in the area. The lower concentrations are probably due to dilution with relatively clean alluvial ground-water (Figures 5-24 and 5-32).

5.6.1j FG-15

This was a USGS sampling site used during the July 1996 salt tracer study (Kimball et. al., 1997). The salt tracer study identified the FG-15 site as one of the most contaminated pools or inflows to French Creek. FG-15 was located on the north bank of the creek just below the trace of the 11-10 Fault. The salt tracer study concluded that the metal and sulfate contamination in this pool originated from the W-O mine and were discharged to the pool via 11-10 fault seepage. Figure 5-33 is a plot of oxygen stable isotope and selected total recoverable metal concentration trends for the 1997 baseline and high flow sampling events. The March baseline oxygen isotope signature of -17.8‰ and low metal concentrations suggest that this seep was predominantly composed of clean French Creek and alluvial ground water (Figure 5-18). The May sampling event showed a slight $\delta^{18}O$-poor shift to -17.93‰ and a significant increase in Cd and Zn concentrations. The Cd and Zn concentrations are similar to fault water concentrations calculated in the review of the salt tracer study (see section 4 of

this report). These data would suggest that the source of spring high flow contamination in this seep was the W-O mine pool and the pathway was the 11-10 Fault.

5.6.2 Phase I and II Sample Locations

Figures 5-34 through 5-38 summarizes the metal concentrations and oxygen isotope trends for sampling locations associated with the isotopic Group #1 mine waters consistently sampled in the three isotope investigation phases. Figures 5-39 through 5-43 summarize the metal concentrations and oxygen isotope trends for sampling locations associated with isotopic Group #2 French Creek and alluvial ground waters. With the exception of the Kenny Dog Spring (KDS) samples (Figure 5-38), all the locations inferred to be dominated by mine water have very high selected metal concentrations. The mine water metal concentrations (Figures 5-34 through 5-37) are several orders of magnitude greater than the observed concentrations associated with the French Creek and clean background alluvial ground-water (Figures 5-39 through 5-43) and the KDS samples (Figure 5-38).

The water sampled directly from the W-0 mine pool, Mine Shaft Relief Well #3 (MSRW-3) and the #3 Mine shaft, displayed peak concentrations during the high flow conditions, which is especially evident with Cd concentrations (Figure 5-34). A similar trend is generally displayed in samples from the mine seep FG-6C (Figure 5-35) and the alluvial monitoring well MW-3 immediately downgradient of the Bullhide Fault (Figure 5-36). The increase in Fe concentrations in July for FG-6C and MW-3 implies an additional Fe source for these locations not directly related to the mine water. The mine site shale bedrock well MW-16 shows fairly consistent concentration levels for the selected metals (Figure 5-37).

The French Creek samples at FG-7 location (Figure 5-39) consistently display higher selected metal concentrations than the other creek samples (Figures 5-40 through 5-43). Metal concentrations decreased during the June sampling events for the FG-7 samples due to dilution caused by increased discharge associated with high flow conditions (Figure 5-39). Most of the stream sites displayed minor shifts towards $\delta^{18}O$-poor snowmelt during the springtime flow surges. These stable isotope trends suggests that a significant portion of the increase in spring discharge was due to regional bedrock ground-water inflow and not snowmelt runoff to the stream. The only stream site that showed a significant springtime snowmelt influence was FG@CB in May of 1997 (Figure 5-42).

The highest concentrations of metals in the study were found in ground-water samples collected from the roaster fines (Figure 5-43). The isotope trends also suggest that the source of the water in the saturated portions of the roaster fines is alluvium and bedrock ground-water and not local infiltration of snow melt or underground mine water.

5.7 Summary and Conclusions

The isotope studies demonstrated that 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 the French Gulch valley. The oxygen and hydrogen isotopic uniformity of the mine, surface, and ground waters during low and high flow conditions in the French Gulch valley suggest that direct snow melt infiltration only contributed a small proportion of the water responsible for:

1. the springtime increased flow in French Creek below the mine site and
2. water level rises in the ground-water and mine pool.

The water flowing in French Creek during the June crest had isotopic compositions comparable to alluvial and bedrock ground-water. These waters were also isotopically similar to the mine pool waters. Although the stable isotopic compositions were generally uniform, there were small but consistent differences between the mine water isotopic compositions and French Creek and alluvial/bedrock ground-water isotopic compositions. Selected metal concentrations (Cd, Zn , and Fe) were elevated and showed similar trends over time for the samples identified by their isotopic signature as mine water with the exception of the Kenny Dog Spring (KDS) samples and the shale bedrock (MW-16) samples. These samples had lower metal concentrations that were relatively constant over time suggesting that they were partially isolated from the W-O underground mine complex or metals were naturally attenuated.

Metal loading from fault seepage at the mine site and ground-water seeps downgradient from the site appeared to originate from the mine pool. The isotope signature from ground-water associated with the 11-10 Fault and the stream sites above the W-O site displayed the greatest shifts in compositions. This suggests that snow melt runoff has a greater influence on the upgradient portions of French Creek. It appears that the bedrock ground-water associated with the 11-10 Fault displays a delayed response from upgradient snowmelt that recharges the regional bedrock ground-water system. There may be some influence on the 11-10 Fault by direct snowmelt infiltration. The isotope data showed that the W-O mine pool and bedrock ground-water discharge influences contaminated alluvial ground-water between the 11-10 and Bullhide faults and seeps and stream sites downgradient of the faults. The lack of W-O mine water shifts towards the ^{18}O-poor snowmelt during the spring flow surge indicates that direct snowmelt infiltration above the mine workings is not a major source and pathway for recharge water to the underground mine. There were actually slight isotopic shifts in the mine water during the spring flow surges towards the relatively ^{18}O-rich bedrock ground-water. This suggest that regional bedrock ground-water that is recharged by headwater snowmelt is the recharge source and pathway to the underground mine workings. Faults that cut the mine

workings, especially the upgradient eastern portion of the workings, are probably the major pathways of bedrock ground-water into the W-O mine.

6.0 Mine Pool and Ground Water Level Monitoring Study

6.1 Abstract

Water levels for the #3 Mine pool, alluvial aquifer and fractured shale bedrock in the vicinity of the #3 Mine site were continuously monitored with an automated datalogging system from July 11, 1996 to May 22, 1997. The #3 Mine, alluvial aquifer and the Oro Mine shaft were also continuously monitored from late March 1998 to September 2, 1998. United States Geological Survey (USGS) discharge gage data on French Creek and climatic data from nearby weather and snow survey stations were integrated with the water level data. These studies evaluated the hydrologic responses to spring snowmelt and storm events and assessed the hydrologic connection between the mine pool, ground-water systems and French Creek. The 1996/1997 study was funded by an Environmental Protection Agency (EPA) Region VIII Headwaters Grant to the State of Colorado Division of Minerals and Geology and an EPA interagency agreement with the United States Bureau of Reclamation (BOR).

The monitored water levels suggest that the fractured shale bedrock and alluvial aquifer at the mine site are acting as one hydraulically connected unit that is communicating with the mine pool. The hydraulic properties of the fractured bedrock and faults appear to control the rate of mine inflow and outflow. The water levels indicate that mine pool water was flowing at a relatively constant rate throughout the monitoring periods into the alluvium and fractured shale bedrock at the #3 Mine site.

The W-O underground mine workings accommodate spring high flow conditions by:

(1) *increased discharge area,*
(2) *rising mine pool levels, and*
(3) *prolonged peak water levels and extended drainage periods after high flow conditions.*

The initial rise of the mine pool and ground water levels in late March and April of 1997 and 1998 appeared to be driven by local site snowmelt. The rise in May and June of 1997 and 1998 was driven by the snowmelt associated with the high elevation French Gulch headwater region and the more protected areas above the Wellington workings. Because the geometry and associated water volumes for mine water elevations are unknown, it is difficult to assess the volume contribution of the various recharge sources. The significant increase in French Creek discharge in May and June of 1996, 1997 and 1998 was also attributed to snowmelt in the high elevation headwater region. Individual storm events and peak discharges on French Creek had no effect on the ground and mine pool water levels.

This study has concluded that:

(1) *there are minimal direct pathways for surface water, French Creek, and snowmelt to enter the Oro or Wellington mine workings;*
(2) *infiltration of snowmelt above the mine workings is not a major source and pathway of recharge water to the W-O mine pool;*
(3) *spring snowmelt is recharging the bedrock ground-water system,*
(4) *the mine pool is being recharge by lateral and deep ground-water flow via the fractured bedrock and fault systems,*
(5) *the major pathway of mine recharge water is most likely upgradient mine workings that intercept lateral and deep regional bedrock ground-water flow, especially flow associated with fault systems (i.e. Great Northern/J fault system);*
(6) *the volume of water from storm events was very small compared to the ground-water system, snowmelt, and the mine pool, and*
(7) *the alluvial ground-water and French Creek are probably minor sources of recharge water to the mine pool.*

6.2 Introduction

The purpose of monitoring the ground water levels at the Wellington-Oro (W-O) mine site was to:

(1) determine the vertical flow and direction of flow between the mine pool, alluvial aquifer and the shale bedrock during different seasonal flow regimes;
(2) determine the hydrologic response of the mine pool and alluvial and fractured shale aquifers during spring snowmelt and storm events;
(3) assess the hydrologic connection between the mine pool, aquifers, and French Creek; and
(4) determine the source of recharge water into the mine pool.

The monitoring occurred during 1996, 1997, and the spring and summer of 1998. This study was funded by an EPA Headwaters Grant to the State of Colorado Division of Minerals and Geology (DMG) and an interagency agreement between the Environmental Protection Agency (EPA) and the United States Bureau of Reclamation (BOR).

6.3 Methodology

For the 1996/1997 monitoring, a Campbell data logger and encoders with a manual float and counter weight system were installed in the #3 Mine shaft, the shale bedrock monitoring well MW-17 and the alluvial monitoring well MW-18 (Figure 6-1a). This system recorded hourly water levels from July 11, 1996 to

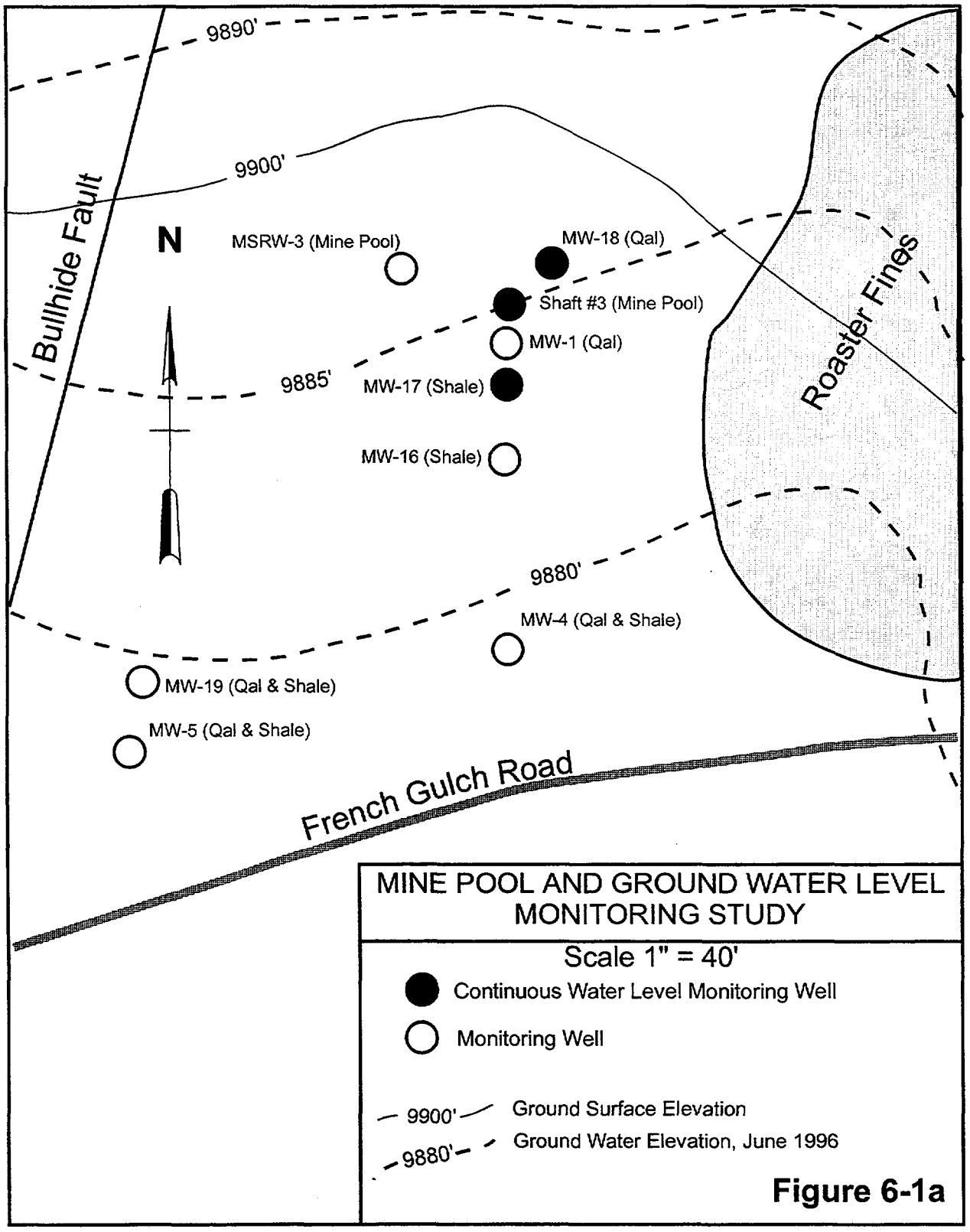

9890'
9900'
Bullhide Fault
N
MSRW-3 (Mine Pool)
MW-18 (Qal)
Shaft #3 (Mine Pool)
MW-1 (Qal)
9885'
MW-17 (Shale)
MW-16 (Shale)
Roaster Fines
9880'
MW-4 (Qal & Shale)
MW-19 (Qal & Shale)
MW-5 (Qal & Shale)
French Gulch Road
MINE POOL AND GROUND WATER LEVEL MONITORING STUDY
Scale 1" = 40'
Continuous Water Level Monitoring Well
Monitoring Well
9900'
Ground Surface Elevation
9880'
Ground Water Elevation, June 1996

Figure 6-1a

May 22, 1997. This time interval represents the duration when these wells were not flowing. The BOR leased the data logger and encoders and purchased supporting equipment from the United States Geological Survey Hydrologic Instrumentation Facility (HIF).

The 1998 monitoring involved an In-Situ Inc. data logger with pressure transducers that continuously monitored water levels on the #3 Mine shaft and the alluvial monitoring well MW-18 (Figure 6-1a). The bedrock shale well MW-17 was not monitored during the 1998 study because the 1996/1997 data showed it to mimic the alluvial well MW-18 water levels. The data logger recorded water levels every two hours. AGS leased this equipment to the BOR. In contrast to the 1996-1997 water level study, the #3 Mine and MW-18 never went artesian in 1998. The 1998 monitoring also included the Oro mineshaft water levels and temperatures at three different depths. The Oro Mine shaft was continuously monitored at 12-hour intervals. This was accomplished with a BOR supplied Campbell data logger, pressure transducers, and thermocouples. In addition to the continuous data logging, the 1998 study included manually measured water levels on the mineshafts and all ground-water monitoring wells over a weekly to bimonthly basis. The 1998 monitoring period was from March 24, 1998 to September 2, 1998. The 1998 study was funded through an EPA interagency agreement with the BOR. The BOR contracted AGS to conduct the 1998 monitoring.

Climatic data were integrated with the water level hydrographs. Data sources included:

- U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA) National Weather Service Dillon Weather Station (NOAA, 1996, 1997 and 1998),
- U.S. Department of Agriculture National Resources Conservation Service (NRCS) Water and Climate Center Hoosier Pass snow survey station (NRCS, 1997 and 1998),
- French Creek discharge data from the United States Geological Survey (USGS) gage on French Creek before it enters the Blue River (USGS, 1996, 1997, and 1998); and a
- Snow survey in the vicinity of the Wellington-Oro Mine and Mill site (Brooks, 1998).

Denver Water supplied NOAA weather data for the Dillon weather station at Dillon Reservoir. The Dillon station is the closest daily climatic data available for the study area (Figure 6-1b). This station is at a location approximately 10 miles north of French Gulch and an elevation of approximately 8900 feet. The weather station is over 800 feet lower in elevation than the study area, but was used in this study to approximate the climatic conditions of the study area. This approximation is probably valid for winter storms and spring snowmelt since they tend to be regional events. Summer storm events may be more localized and

could present problems in using the Dillon station data, although multi-day summer wet periods (frontal weather systems) are probably regional events and can be used in a qualitative manner to estimate climatic conditions at the study area. The majority of the W-O site has a southern exposure that may compensate for the elevation difference between the lower Dillon station and the higher expose W-O site.

The Hoosier Pass snow survey station is located approximately 8.5 miles south of the study area and is at an elevation of 11,400 feet, which is over 1,430 feet higher than the study area (Figure 6-1b). The data from this station most likely represents the conditions of snow pack and temperature for the upper French Gulch Basin or headwaters up-valley from the study area. This station may also approximate the more protected and higher elevations along the east-west ridge above the X10U8 site and the Wellington Mine workings. In contrast to the NOAA snow pack data at the Dillon station that records snow depth, the NRCS Hoosier station records water equivalent content of the snow pack. In the winter and spring of 1998 the EPA commissioned a snow survey over the W-O site and the areas that included the east-west ridge above the X10U8 site and the Wellington Mine workings (Brooks, 1998).

6.4 Summary of Results

6.4.1 1996-1997 Monitoring Study Continuous Daily Water Levels

Figures 6-2 through 6-12 are daily water levels for the 1996-1997 monitoring study plotted by month for the mine pool (#3 Mine Shaft), alluvial aquifer (MW-18), and the fractured shale bedrock (MW-17). Included in these figures were climatic data from the Dillon Weather Station (NOAA, 1996 and 1997) and French Creek discharge data from the USGS gage on French Creek before it enters the Blue River (USGS, 1996 and 1997). For consistency, the ground-water levels plotted in Figures 6-2 through 6-12 were derived from midnight readings.

Ground water level monitoring began on July 11, 1996 (Figure 6-2). The steady decline in water levels and French Creek discharge during this period represents the falling limb of the hydrograph after the spring snowmelt. The USGS French Creek gage on July 11 indicated a discharge of 22 cubic feet per second (cfs). The French Creek hydrograph peaked at 80 cfs on May 25, 1996, and again on June 10, 1996 (Figure 6-13).

The water level elevations during July showed that the mine pool, represented by the #3 Mine Shaft, was over one (1) foot higher than the ground water level in the alluvial aquifer at MW-18 (Figure 6-2). It is believed that the foot plus difference in ground-water level elevation between the fractured shale bedrock (MW-17) and alluvial aquifer (MW-18) is largely due to the steep hydraulic gradient of 0.05

to 0.1 ft/ft towards the south at the mine site (Morrissey, 1994). Figure 6-1a displays the ground-water elevations for June 1996 and the steep gradient to the south. This hydraulic gradient can not explain the difference between the mine pool and alluvial and shale aquifers. The differences in ground-water hydraulic head remained fairly consistent from July 1996 through September 1996 (Figures 6-2 through 6-4). This mimicking of water levels for the mine pool, alluvium, and shale suggests that the fractured shale bedrock and alluvial aquifer are acting as one hydraulically connected unit that is communicating with the mine pool. The higher hydraulic head associated with the mine pool implies that the mine pool waters are discharging into the alluvium and fractured shale.

During July and August of 1996 the French Creek discharge, and ground and mine water levels steadily declined. Individual storm events did not appear to affect either the ground and mine water levels, or French Creek discharge. A wet period during the end of August 1996 through September 1996 apparently leveled off the French Creek discharge that stabilized between five- (5) to eight- (8) cfs. Some of these storms were snow events in late September. This wet period did not affect the declining ground-water and mine pool levels in August or September (Figures 6-3 and 6-4).

In October 1996, the mine pool appears to have stabilized at an elevation of 9874 feet while the alluvial and fractured shale aquifers water levels continued to drop (Figure 6-5). Consequently, the head difference between the mine pool and the alluvial aquifer at MW-18 increased to nearly two feet. This apparent increase in head difference was due to a problem with the #3 Mine shaft and does not represent the actual head difference between the W-O mine pool and alluvial aquifer. In mid-November, the mine pool levels rapidly declined and returned to the hydraulic head differences that were observed prior to October 1996 (Figure 6-6).

Subsequent monitoring of the #3 Mine shaft and the relief well (MSRW-3), and purging of the #3 Mine shaft in 1998 indicated that plugging of the #3 Mine shaft is responsible for the increase hydraulic head elevation. The shaft was cased with 4" diameter PVC and staged grouted in 1992. The open-ended PVC casing was apparently open into the #3 Mine drift at 110 feet below ground surface (bgs) by injecting air into the casing while the bottom staged grout was curing. Confirmation of the casing being opened into the drift level was accomplished by monitoring the relief well for air (Figure 6-5a). The purpose of the grout sealing was to prevent the shaft's mine water from communicating with the alluvium. The grouting may have significantly reduced the cased mineshaft's ability to communicate with the drift level and mine pool and resulted in periodic plugging by mine water precipitates. The plugging of the #3 Mine shaft is further discussed in section 7 of this report.

The French Creek discharge in October 1996 slowly declined from 6-cfs to 3-cfs (Figure 6-5). In November 1996 the French Creek hydrograph appears to have

stabilized near baseflow conditions between 2- and 3-cfs (Figure 6-6). The ground water levels in the alluvial and shale monitoring wells were still dropping at a slow rate in November of 1996.

The December 1996 daily water levels included the maximum daily air temperature recorded at the Dillon weather station (Figure 6-7). The snow pack in December began to increase with frequent storm events. The mine pool and ground water levels continued to drop slowly while the French Creek discharge remained fairly constant at 2.5-cfs. A short three-day thaw apparently occurred from December 8 to December 10. The mine pool and ground water levels and French Creek discharge did not appear to be affected by the snowmelt associated with this thaw. In January of 1997, the snow pack was generally increasing throughout the month with no major snowmelt events (Figure 6-8). The mine pool and ground-water levels were continuing to drop very slowly while the French Creek discharge remained at baseflow conditions of around 2-cfs. In February of 1997, storm events were infrequent and the snow pack, French Creek discharge, ground and mine pool water levels remained fairly constant (Figure 6-9).

In March 1997, there was a major thaw at the lower valley elevations (Figure 6-10). Between March 9 and March 20 the snow pack at the Dillon weather station completely melted out. On March 20 the alluvial and shale bedrock monitoring wells began a relatively rapid rise in water levels. Two days later, on March 22, the mine pool water level began to rise. During this initial rise in water levels the head difference between the alluvial aquifer and the mine pool was almost eliminated while the difference between the shale and alluvial monitoring wells remained constant. The elimination of hydraulic elevation head between the #3 Mine and alluvial well was possibly due to partial plugging of the #3 Mine as previously discussed. The French Creek discharges during this snow melt event very gradually increased from baseflow conditions at 1.5-cfs to 3.7-cfs at the end of the month of March. This major snow melt event was not evident at higher elevations above the study area. Figure 6-14 is a plot of the March 1997 daily water levels and French Creek discharge with climatic data from the Hoosier Pass snow survey station (NRCS, 1997). The higher elevation snow pack actually increased slightly during the month of March and there was no evidence for a major snow melt event (Figure 6-14).

The March 1997 snow pack at Hoosier Pass contained approximately 20 inches water equivalent. Prior to the snow melt event at the Dillon station the maximum March snow depth was around 15 inches. A plot of snow depth versus snow water equivalent for different months of the 1996-97 winter season approximated between 3- and 4-inches of snow water equivalent for the 15 inch snow depth at the Dillon station (personal comm., Mike Gillespie, NRCS, 1997). The same plot approximated the depth of the Hoosier Pass 20 inches water equivalent snow pack to be 62 inches or 5.17 feet snow depth.

The storm events in April 1997 added minor snow pack for short periods of time at the Dillon weather station (Figure 6-11). In contrast, the higher elevation Hoosier Pass snow pack was increasing in April (Figure 6-15). During the month of April the French Creek discharge very gradually increased from approximately 3.5-cfs to 5.8-cfs with most of the increase occurring during a warm period from April 17 to April 22 (Figures 6-11 and 6-15). The April 1997 mine pool and ground water elevations leveled off during a cold period from April 10 to April 17. The alluvial and shale monitoring wells began to rise again with the subsequent warm period after April 17. The mine pool stayed level at 9873.8 feet from April 10 to April 28 and abruptly increased to 9875.4 feet on April 29. The hourly data for this date showed that the increase occurred during a two-hour period. As previously discussed, the stable water levels followed by an abrupt rise in the #3 Mine was due to plugging. After April 29, the head differences between the mine pool, alluvial aquifer and shale bedrock at the mine site were very similar to what had been observed prior to the March 1997 rising water elevations (Figures 6-10 and 6-11). It is believed that the rising water levels and possibly increased mine flow in April unplugged the shaft and resulted in the rapid rise in water levels.

In early May 1997, the French Creek discharge, mine pool, alluvial monitoring well MW-18, and shale monitoring well MW-17 began to rise very quickly (Figure 6-12). Most of this rise appears to correspond to the snowmelt associated with the high elevation snow pack at Hoosier Pass (Figure 6-16). The French Creek discharge stopped rising and the Hoosier Pass snow pack stabilized during a cool period from May 22 to May 28. By May 22, the #3 Mine Shaft, MW-17 shale monitoring well, and the MW-18 alluvial monitoring well had water levels in their stand-up casing pipe above ground level. The #3 Mine Shaft appeared to be leaking around its stand-up casing pipe which may explain why its water level stabilized while the alluvial and shale monitoring wells continued to rise in their casing stand-up pipes (Figure 6-12). The automated water level monitoring equipment was dismantled on May 22.

Monitoring of the Oro Mine Shaft in June 1997 indicated that the total mine pool rise from baseline conditions in March was approximately 20 feet. Approximately three feet of this rise occurred in late March and early April that apparently corresponded to the local W-O site snowmelt. The larger rise of over 14 feet occurred from late April to June. This second rise appears to correlate with the high elevation headwater snowmelt. Snowmelt associated with the protected areas and higher elevations above the Wellington workings and the X10U8 site may have also contributed to the rise in late April and May. The French Creek hydrograph peaked at a discharge of 124-cfs on June 5 and had a secondary peak of 89-cfs on June 20 (Figure 6-17). Neither peak on the hydrograph seems to correlate with any storm events at the Dillon weather station. The first peak on June 5 appears to correlate with a rapid decline in the high elevation snow pack at Hoosier Pass (Figure 6-18). The Hoosier Pass snow pack had completely melted by the second French Creek peak on June 20. The second peak may represent a few day bedrock ground-water delayed response to the headwater

snowmelt. The ground-water system subsequently recharges the stream.

6.4.2 1998 Monitoring Study Continuous Daily Water Levels

Figures 6-19 through 6-25 are daily water levels for the 1998 monitoring study plotted by month for the mine pool (#3 Mine shaft and Oro Mine Shaft) and the alluvial aquifer near the #3 Mine (MW-18). These plots also included the weekly to bimonthly water level measurements for the #3 Mine shaft relief well MSRW-3. Similar to the 1996-1997 monthly plots, Figures 6-19 through 6-25 contained the French Creek discharge data and climatic data from either the Dillon Weather station or Hoosier Pass snow survey station (USGS, 1998, NOAA, 1998, and NRCS, 1998). Continuous water level monitoring for the #3 Mine shaft and MW-18 began on March 26, 1998 while monitoring of the Oro Mine shaft began on March 31, 1998 (Figure 6-19). The USGS French Creek gage measurements in the beginning of the month were near baseflow conditions of 2-cfs. Similar to the March 1997 Dillon Reservoir climatic data, there was a major thaw that melted out the snow pack at the lower valley elevations in mid-March. The French Creek discharge nearly doubled during the March thaws. Water level monitoring was not initiated until two weeks after the first major thaw. Consequently, it was not possible to directly observe mine and ground-water level responses to the March 1998 thaw period. A comparison with the March 1997 baseflow elevations suggested that the #3 Mine pool increased in elevation by 0.75 feet and the alluvial well MW-18 by 0.25 feet during March 1998. In contrast, the #3 Mine and MW-18 had nearly a 3 feet rise during late March 1997 (Figures 6-10 and 6-20). The hydraulic head differences between the #3 Mine pool and MW-18 in March 1998 was approximately 1.5 feet compared to 1.0 feet for most of the 1996-1997 monitoring period. The mine pool in the Oro shaft was approximately 0.6 feet higher than the #3 Mine pool.

The March 1998 Dillon snow pack depth appears to be less than half the March 1997 snow pack depth (Figures 6-10 and 6-19). The maximum daily air temperatures recorded at the Dillon station suggest that March 1997 was warmer than March 1998. The average maximum daily air temperature in March 1997 was nearly 5 degrees Fahrenheit higher than the March 1998 average (Table 6-1). There were 27 days of air temperatures greater than freezing in March 1997 compared to 21 days in March 1998. The cooler temperatures in 1998 and less snow pack may have contributed to a minimal March thaw at the W-O mine and mill site compared to the March 1997 thaw. This seems to be supported by mine pool and ground-water levels that appear to have lower water elevation responses during the March 1998 thaw period.

Similar to April 1997, the storm events in April 1998 added minor snow pack for short periods of time at the Dillon weather station (Figure 6-20). The April 1998 water levels in the #3 Mine shaft relief well MSRW-3 and MW-18 gradually increased by approximately two feet while the Oro Mine shaft increased by one foot. The water levels in the #3 Mine shaft remained fairly constant. As

Table 6-1

Monthly Comparison of Maximum Daily Air Temperatures
Dillon Reservoir Weather Station
Hoosier Pass Snow Survey Station

Month/Station	Avg. Max. Daily Air Temp. (°F)	Std. Deviation Avg. Daily Max. Air Temperature	Days Greater than Freezing Temperatures
Mar-97/Dillon	43.9	9.5	27
Mar-98/Dillon	38.9	10.3	21
Apr-97/Dillon	43.3	9.7	26
Apr-98/Dillon	45.1	7.9	30
Apr-97/Hoosier	37.8	9.2	20
Apr-98/Hoosier	40.5	9.0	23
May-97/Hoosier	49.5	7.9	31
May-98/Hoosier	52.5	5.3	31

previously discussed, plugging associated with the grout sealing of the shaft may be responsible for the observed constant water levels in April 1998. It appears that water levels from the relief well are more representative of the #3 Mine pool. The hydraulic head difference of one foot between MSRW-3 and MW-18 is similar to the observed difference between the #3 Mine and MW-18 in the 1996 and 1997 monitoring studies. Apparently, the several #3 Mine shaft purging events associated with the 1996/1997 isotope and water quality sampling and the 1996 and 1997 spring flow that went artesian prevented significant plugging. Although as previously mentioned, plugging of the #3 Mine shaft was observed in October 1996 and April 1997.

It appears that the hydraulic head difference between the Oro Mine shaft pool and the #3 Mine pool was almost eliminated by the end of April. There were no significant changes in French Creek discharges during April 1998. Maximum daily air temperatures at the Dillon weather station and the Hoosier Pass snow station suggested that April 1998 was warmer than experienced in April 1997 (Table 6-1). The high elevation snow pack water equivalent at the Hoosier Pass was increasing in April 1998 (Figure 6-25). As a result, most of the snowmelt during this time period occurred at the lower French Gulch valley elevations. Lower W-O site elevation snowmelt, especially associated with the more exposed and southern facing slopes, was observed during the 1998 snow survey study (Brooks, 1998). This would imply that most of the mine and ground-water level increases in March and April 1998 at the W-O site were due to local snowmelt in the vicinity of the W-O site.

The French Creek discharge increased significantly during the end of May 1998 (Figure 6-21). The high elevation snow pack at Hoosier Pass completely melted by the end of May. The Oro Mine shaft water levels continued to gradually rise in May. The total rise for the month was over 1.5 feet. The #3 Mine pool, as reflected by MSRW-3, increased by approximately 1 feet during the month. As a result, the hydraulic head between the Oro Mine shaft and the #3 mine pool, which was similar at the beginning of May, increased during the month with the Oro having the greater hydraulic head elevation by 0.5 feet at the end of the month.

From June 3 through June 11, 1998, AGS conducted a Mine Pool Characterization study. This study required purging and sampling the #3 Mine shaft on June 8 and removing transducers from the Oro Mine shaft on June 3, June 5, and June 8 through June 11. The elevations for the Oro mine pool in Figure 6-22 are a combination of continuous measurements from the Oro Mine shaft with transducers and hand measurements with a water level meter during this time period. This may explain the erratic nature of the Oro elevations from June 5 through June 11.

It appears that the purging of the #3 Mine shaft unplugged the grout-sealed shaft and recovered water levels to elevations similar to the relief well MSRW-3. Between June 17 and 18, the top of the Oro Shaft mine pool increased in elevation by approximately 0.5 feet. This rise appeared to correspond to a wet period from June 14 through June 18. The French Creek discharge began to increase on June 20. This is the only observation in the 1998 monitoring study where the Dillon precipitation data, Oro Mine shaft pool elevations, and the French Creek discharge appeared to directly correlate. Generally, the Oro Mine shaft elevation data from March 1998 through June 1998 appeared to have minor to no responses to storm events at the Dillon weather station. The minor responses appeared most evident during the April storm events and the June wet period (Figure 6-20). The #3 Mine pool and the alluvial ground-water in MW-18 did not appear to have any direct responses to storm events. French Creek discharge had minor to no responses to storm events and appeared to be driven by snowmelt events, especially the high elevation snowmelt and temperatures at the Hoosier Pass snow station (Figure 6-21). By the end of June 1998 the mine pool water elevations and ground-water elevation in MW-18 had leveled off (Figure 6-22). In contrast, the French Creek discharge peaked in early June at 46 cfs. The total rise in water elevations since early May 1998 for the Oro Mine shaft was approximately 2.5 feet, 1.3 feet for the #3 Mine pool, and 1.5 feet for MW-18. It appears that these water level rises correspond to the high elevation snowmelt. This snowmelt probably included the headwater region of French Gulch and during early May the higher protected elevations along the ridge above the Wellington workings (P. Brooks, 1998).

For the remaining monitoring period in July and August 1998, the Oro Shaft Mine pool, #3 Mine pool, and MW-18 water levels gradually declined (Figures 6-23 and

6-24). Except for a few peaks in the French Creek discharge, which were probably related to large storm events, the French Creek hydrograph also gradually declined. The hydraulic head difference between the Oro Mine shaft pool and the #3 Mine pool was over 1.0 feet while the #3 Mine was 1.3 feet higher than MW-18. By the end of August 1998 the #3 Mine pool elevations were approximately three feet lower than #3 Mine pool elevations at the end of August 1996 (Figure 6-3).

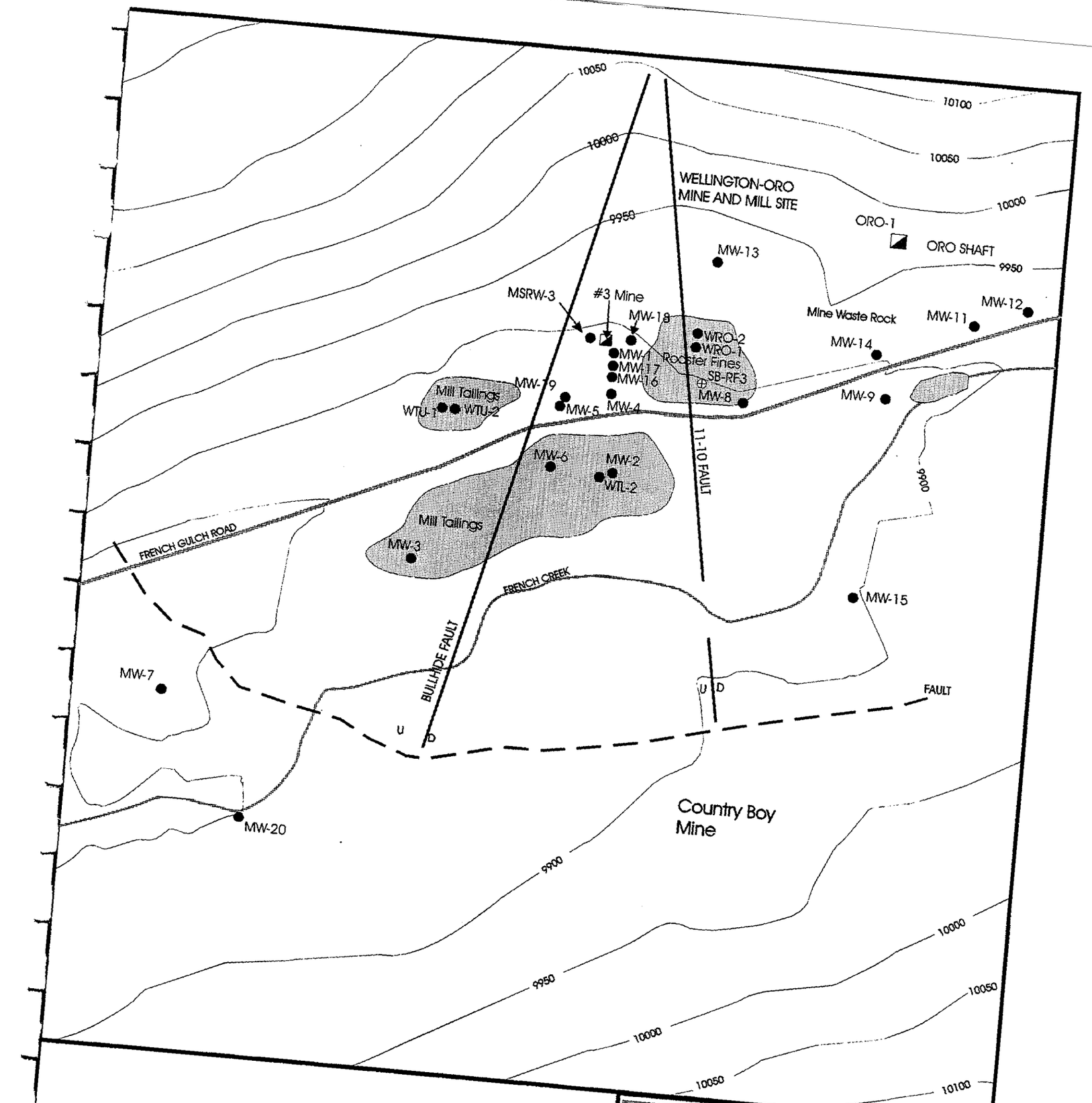
6.4.3 1998 Monitoring Study Weekly to Bi-Monthly Water Levels

From late March 1998 to September 1998, AGS manually recorded ground-water and mine pool water levels from monitoring wells and the #3 and Oro mineshafts with a water level meter (Figure 6-26, Table 6-2, Appendix 6-1). Figures 6-27 through 6-32 are plots of the water elevations. The water elevation plots have been divided by the following groupings:

- **Mine pool** (Oro Mine shaft, #3 Mine shaft, and #3 Mine relief well MSRW-3);
- **Upgradient wells** from the W-O site located north of French Gulch Road (MW-11 and MW-12), A well and soil boring completed in the **roaster fines** (WRO-1 and SBRF-3);
- The **X10U8** site soil boring (EXO-1);
- **Wells located within or downgradient** of the W-O mine and mill site and north of French Gulch Road (MW-1, MW-4, MW-5, MW-8, MW-13, MW-14, MW-16, MW-17, MW-18, and MW-19); and
- **Wells located south of French Gulch Road** (MW-2, MW-3, MW-6, MW-7, MW-9, and MW-20).

The mine pool elevations were very similar to the continuous water level data compiled with the transducers and dataloggers. As previously discussed, it appears that the #3 Mine shaft was partially plugged which explained the hydraulic head elevation difference with the #3 Mine relief well MSRW-3 for most of the monitoring period (Figure 6-27). When the #3 Mine shaft was purged on June 8 and August 10, the hydraulic head differences were eliminated. The hydrographs for the Oro and #3 mine pools appeared to peak from mid-June to early July 1998. From the beginning of monitoring in late March through mid-April the hydraulic head of the Oro Mine shaft was over 0.5 feet higher than MSRW-3. This elevation difference was eliminated from the end of April into early May. At the peak of the hydrographs, the Oro Mine shaft elevations were approximately 1.0 feet higher than the #3 Mine pool. This head difference was slightly reduced by the end of August.

Figure 6-28 is a plot of water elevations for ground-water monitoring wells



N

⊕ SB-RF3 Soil Boring

● MW-15 Monitoring Well (Locations Are Approximated)

◪ ORO-1 Mine Shaft

Scale 1" = 250'

AMERICAN GEOLOGICAL SERVICES, INC.
Environmental, Geological, and Natural Resource Consultants

Figure 6-26
French Gulch Ground Water
Sample Location Map

Project Name: French Gulch
Project Number: CO97DE-056
Date: 10/9/98 | Drawn By: TKS | Reviewed By: AM

Table 6-2

Summary of Ground-water Monitoring Wells

Well	Top Alluvium (ft below surface)	Top Bedrock (ft below surface)	Total Depth (ft below surface)	Screened Intervals (ft below surface)	Comments
MW-1	6	42 (clay) 44 (shale)	50	22-27 (5') 33-43 (10)	contaminated alluvial well at mine site
MW-2	22	41 (porphyry)	47.5	37-47 (10)	contaminated alluvial and porphyry well below mill tailings, downgradient of mine site
MW-3	6	53 (shale)	55	15-25 (10') 45-50 (5')	contaminated alluvial well below mill tailings, downgradient mine site and Bullhide Fault
MW-4	7	55 (clay) 56 (shale)	64	20-30 (10') 46-51 (5') 58-63 (5')	contaminated alluvial and shale bedrock well at mine site
MW-5*	5	52 (shale)	55	20-30 (10') 50-55 (5')	contaminated alluvial and shale bedrock well downgradient of mine site and near Bullhide Fault
MW-6*	25	40 (clay) 42 (shale)	54	34-44 (10') 49-54 (5')	contaminated alluvial and shale bedrock well below mill tailings, downgradient mine site, and near Bullhide Fault
MW-7	12	50 (porphyry)	52	18-23 (5') 38-48 (10')	contaminated alluvial well downgradient mine site and mill tailings
MW-8*	5	43 (shale)	46	15-20 (5') 35-45 (10')	contaminated alluvial well downgradient roaster fines and near 11-10 Fault
MW-9	17	51 (clay) 52 (shale)	54.5	43-53 (10')	clean alluvial well upgradient mine site
MW-11	10	29 (shale)	43	23-28 (5') 38-46 (10')	clean alluvial and shale bedrock well upgradient mine site
MW-12	NP	10 (porphyry)	46	40-45 (5')	clean porphyry bedrock well upgradient mine site
MW-13	13	28 (shale)	47	36-46 (10')	contaminated shale bedrock well below roaster fines and mine waste, near 11-10 Fault

Table 6-2 continued

Well	Top Alluvium (ft below surface)	Top Bedrock (ft below surface)	Total Depth (ft below surface)	Screened Intervals (ft below surface)	Comments
MW-14	2.5	38 (shale) 101 (porphyry)	278	268-278 (10')	clean 11-10 Fault well upgradient mine site
MW-15	3	15 (shale)	46	36-46 (10')	clean shale bedrock well, south side valley, east of Country Boy Mine
MW-16	8	46.5 (porphyry) 70 (shale)	91	71-91 (20')	contaminated shale bedrock well at mine site, observation well during 1994 aquifer tests
MW-17	9	55 (porphyry) 70 (shale)	93	70-90 (20')	contaminated shale bedrock well at mine site, pump well during 1994 aquifer tests
MW-18	7	39 (shale)	43	20-40 (20')	contaminated alluvial well at mine site, pump well during 1994 aquifer tests
MW-19	8	51 (shale)	110	30-110 (80')	contaminated alluvial, Bullhide Fault, and bedrock well
MW-20	0	20 (porphyry)	50	15-25 (10')	clean alluvial well south side valley, downgradient mine site
MSRW-3	0	45 (shale)	110	68-110	relief well for #3 Mine Shaft, open hole completion using washed rock, mine stope or cave-in possible below 97 feet
EXO-1	NP	NA	13.6	7.8-12.8	X10U8 mine waste soil boring
EXO-2	NP	10.2? (shale)	10.2	4.7-9.7	X10U8 mine waste soil boring
WRO-1*	14.5?	NA	18.1	14.1-18.1	contaminated roaster fines/alluvial well
WRO-2*	14.2?	NA	16.6	6.7-11.7	contaminated roaster fines well
WTU-1*	NP	NA	13.5	10.5-13.5	north mill tailings well
WTU-2*	NP	NA	8.0	3.0-8.0	north mill tailings well
WTL-2	NP	NA	19.5	14.1-19.1	contaminated south mill tailings well
SBRF-3*	NP	NA	13	NA	soil boring in roaster fines, 2" PVC pipe open at total depth

NP - not present
NA - not applicable
"*" – plugged and/or abandoned during Fall 1998 surface waste cleanup project

MW-11 and MW-12. MW-12 is a porphyry bedrock well (Table 6-2). MW-11 has a five feet length screen in the alluvium immediately above the shale bedrock and a ten feet length screen nine feet below the top of the bedrock (Table 6-2). For most of the monitoring period, the top of the ground-water level in MW-11 was below the alluvial screen. During peak flow the ground-water level was within the bottom foot of the alluvium screen interval. It is believed that the water levels in MW-11 during this monitoring study were representative of the shale bedrock and not the shallow alluvium.

MW-12 exhibited water level peaks during late March and April 1998 (Figure 6-28). From early May to September 1998 the water levels declined. The peaks in March and April appear to follow warm local snowmelt events (Figures 6-19 and 6-20). After late April there were no significant peaks in the water levels. It is believed that water levels in MW-12 represent a perched water table in the tight fractured porphyry that is recharged by local snowmelt. The lack of water level peaks after late April suggests that the local snow pack had melted by early-May. Similar peak ground-water elevations were also observed in the hydrographs from a monitoring well (WRO-1) and soil boring (SBRF-3) in the roaster fines (Figure 6-29), and from a shallow soil boring (EXO-1) south of the X10U8 waste pile (Figure 6-30). Monitoring well WRO-1 was completed at the base of the roaster fines and top of the alluvium while soil boring SBRF-3 was an open ended 2-inch diameter PCV pipe in the roaster fines (Table 6-2). These hydrographs suggest that the shallow alluvium ground-water table upgradient of the 11-10 Fault and the roaster fines ground-water table is recharged by local site snowmelt (Figure 6-26).

The ground-water hydrograph for MW-11 displayed peak levels from late May to early July 1998 (Figure 6-28). This peak level period is similar to the mine pool, although significantly attenuated (Figure 6-27). MW-11 is relatively clean upgradient shale bedrock well from the W-O mine and mill site. MW-15, the clean upgradient shale bedrock well on the south side of French Creek, also displayed peak ground-water levels from late May to early July 1998 (Figure 6-26, Table 6-2, and Appendix 6-1).

Figure 6-31 are hydrographs from the 1998 monitoring study for ground-water monitoring wells located north of French Gulch Road and downgradient of the 11-10 Fault (Figure 6-26). The anomalies in the plots probably represent errors in manually reading the water level meter. All of the monitoring wells display similar hydrographs and only vary due to hydraulic gradients. These ground-water monitoring wells have peak elevations during similar time periods as the mine pool (Figures 6-27 and 6-31). These ground-water monitoring wells vary in completions from bedrock, alluvium, and faults (Table 6-2). MW-13 and MW-14 ground-water levels are believed to be influenced by flow associated with the 11-10 Fault (Table 6-2). The ground-water elevations within these fault wells are almost identical to the Oro Shaft mine pool elevations (Figure 6-27). The other monitoring wells are contaminated and have lower hydraulic head elevations

than the mine pool and the 11-10 Fault wells. These wells appeared to be influenced by mine water discharge.

Figure 6-32 shows plots of ground-water elevations for monitoring wells located south of French Gulch Road, approximately along the axis of the French Gulch alluvial valley (Figure 6-26). These wells are predominantly completed in the alluvium and are located upgradient (MW-9) and downgradient (WTL-2, MW-2, MW-3, MW-6, MW-7, and MW-20) of the W-O site (Table 6-2, Figure 6-26). Ground-water elevations remained relatively constant throughout the 1998 monitoring period for these wells and their elevations were a function of their hydraulic gradient position along the valley.

6.4.4 1998 Oro Mine Shaft Temperature Monitoring

In addition to monitoring the Oro Mine shaft water levels with pressure transducers, temperatures were recorded by the datalogger from thermocouples within the transducers and a set of separate thermocouples. Figures 6-33 and 6-34 are plots of temperatures measured by the pressure transducers from mid-April 1998 through mid-August 1998 with the mine pool water level elevations. The transducers were set at three different locations in the mine pool: top of the pool at 94 feet below ground surface (bgs), at the 3rd Oro drift level (241 feet bgs), and at 440 feet bgs (Figure 6-35). The 440 feet bgs depth corresponds to the approximate area where Lovering (1934) showed fault splays from the 11-10 fault intersecting the Oro Mine shaft. Figure 6-33 represents the initial rise in the mine pool in April 1998. During the early spring rise of the mine pool the upper two transducer temperature measurements remained relatively constant while the deepest transducer showed a gradual one degree Fahrenheit (F) decrease in temperatures. From early May to mid-June 1998 the three transducers showed increasing temperatures (Figure 6-34). The lowest transducer (440' bgs) displayed the largest increase in temperatures, greater than 1°F, and the most variability. After the peak in mine pool levels in mid-June, the upper two transducers showed a very gradual decrease in temperatures. The lowest transducer immediately indicated a sharp decrease in temperature after the mine pool water level peak followed by a very stable and gradual increase in temperature (Figure 6-34).

6.4.5 1996-1998 Storm Events

Individual storm events, as recorded at the Dillon weather station, did not seem to influence the daily water levels of the monitoring wells and had very minor to no effect on the French Creek discharge (Figures 6-2 through 6-13, 6-17, 6-19 through 6-22, 6-36). Some of the observed storm event impacts on French Creek included a prolonged wet period in August and September 1996 and a multi-day storm event during the spring runoff in 1996. The August and September wet period apparently leveled off the French Creek hydrograph

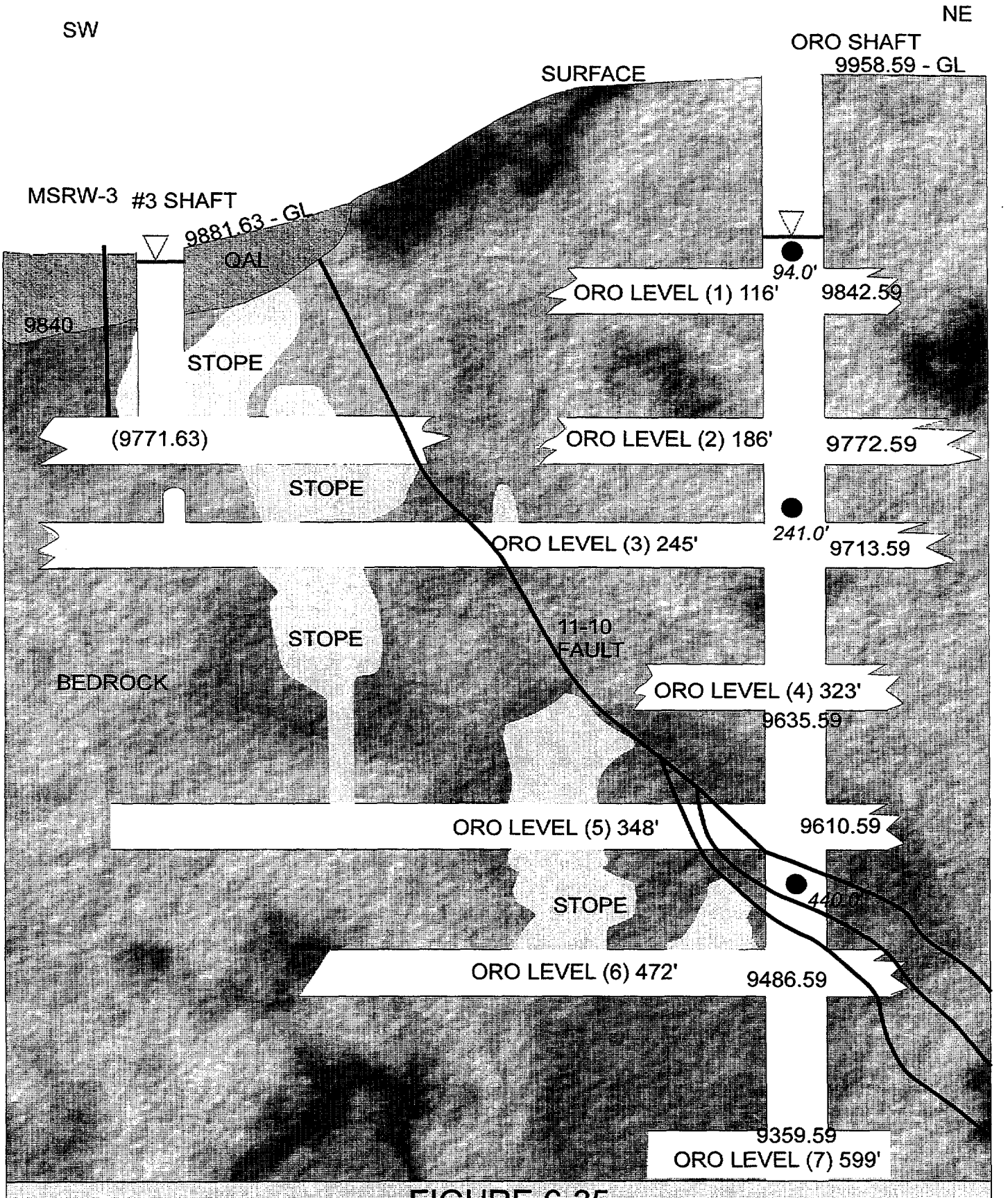


FIGURE 6-35

SCHEMATIC DIAGRAM OF THE ORO SHAFT

WATER LEVEL AND TEMPERATURE MONITORING 1998

● Pressure Transducers and Thermocouples

DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

NOT TO SCALE

(Figures 6-3 and 6-4), and the multi-day storm event during the spring runoff in 1996 probably enhanced the French Creek discharge peak during the end of May (Figure 6-13).

Hourly discharge data was plotted for a storm event in May of 1997 to assess the short-term impact of a storm event on French Creek (Figure 6-37). This storm event occurred during the rising limb of the French Creek hydrograph (Figure 6-36). According to the Dillon weather station data, the subject storm event started during the late evening of May 21, 1997 and continued for over 24 hours into the early morning of May 23. A hydrograph of the rainfall intensity for this storm event was not avialiable. There was minimal rainfall for most of the day and night on May 23 and no rainfall on May 24 to the evening of May 25 at the Dillon station. The discharge peaks during the early morning hours on May 24 and May 25 are not related to storm events but are diurnal cycles associated with snowmelt that originated in the headwaters of French Creek (Figure 6-21). The headwaters are approximately six miles east of the French Creek gage. The lag time from daily maximum snowmelt in the late afternoon to the observed peaks at the gage was observed to be 10 to 12 hours. This corresponds to a stream travel rate of 0.7 to 0.9 feet per second. The instream salt tracer study conducted by the USGS in July of 1996 observed similar travel rates for French Creek in the vicinity of the mine site (Kimball et. al., 1997).

In contrast to the early morning diurnal peaks, the discharge peak of 43 to 44 cfs on May 22 occurred during the afternoon which was at least 5 cfs higher than background (Figure 6-37). This peak is most likely related to the storm event. The May 22 peak represents the accumulated discharge effect at the gage of:

1. early morning runoff associated with rainfall in the headwaters traveling to the gage and
2. local runoff from the day's precipitation.

These types of observations were not evident from the average daily discharge reported by the USGS.

The diurnal cycles can also indicate the influence of snowmelt on stream flows. The background or lower flows during the afternoon hours probably is dominated by ground-water baseflow. The magnitude of the flow peaks associated with headwater snowmelt contributed approximately 3 cfs or 7% of the total flow. This is similar to the stable isotope mixing model calculations of snowmelt contribution to stream flows in the lower reaches of French Creek (RAS, 1996a, 1996b, and 1997b).

Hourly water levels for monitoring wells were also plotted to assess short-term impacts of storm events on the ground-water and mine pool. Two storm events were selected; (1) a summer multi-day storm from August 26 to August 30, 1996 (Figures 6-38 through 6-42a) and (2) a fall snow event from October 15 to

October 19, 1996 with significant melting during the period (Figures 6-43 through 6-47a). Figures 6-42b and 6-47b summarize the storm events. Both storm events had occurred during the falling limb of the ground and mine pool hydrograph and at low flow French Creek conditions.

The Dillon weather station recorded that most of the precipitation associated with the summer storm to have occurred on August 29 (Figure 6-41). The water levels prior to this precipitation were very stable and only dropped 1/10 of an inch every 25 to 40 hours (Figures 6-38 to 6-40). The water levels remained very stable after the precipitation with no change in the rate of water level decline (Figure 6-42a and 6-42b).

For the fall snow event example, the Dillon weather station recorded that most of the precipitation occurred on October 17 (Figure 6-45). The water levels prior to this event were also very stable (Figures 6-43 and 6-44). After the snow event, the water levels remained very stable (Figures 6-45 through 6-47a, and 6-47b).

The hourly water level data compiled during the 1996/1997 study displayed very stable levels over long periods. The 1996 summer storm events recorded at the Dillon weather station were usually short in duration and less than 0.4 inches. Winter snow events and fall/spring mixed precipitation storms tended to be of longer duration and contained more moisture than the summer storms. The mine site is over 800 feet higher than the Dillon station and it is possible that at this higher elevation storm events would be more intense. There were no immediate ground or mine pool water level responses to any storm events observed in the hourly data throughout the monitoring periods, with possibly the one exception previously discussed for the Oro Mine shaft in mid-June, 1998. There had been minor increases in stream discharge observed during some storm events, especially associated with the hourly discharge data.

6.5 Discussion

Important information that was gathered during the ground and mine pool water level monitoring study included the following observations:

- The hydraulic head (water level) of the mine pool was significantly higher than the alluvial aquifer and fractured shale bedrock at the #3 Mine site;
- For most of the 1998 monitoring period the Oro Mine shaft pool had an hydraulic head higher than the #3 Mine pool;
- The hydraulic head difference between the Oro and #3 Mine pool were nearly eliminated in early May 1998;
- The mine pool and ground-water levels began to rise in March and April of 1997 and 1998, almost two months before the French Creek discharge

started its major rise;

- The mine pool and ground-water level initial rise from March to early May in both the 1996/1997 and the 1998 studies appear to correlate with the lower elevation local site snowmelt;
- The major increase in French Creek spring discharge and the rise in the mine pool and ground-water levels during May and June of 1997 and 1998 is apparently associated with high elevation snowmelt;
- Ground-water monitoring wells within the alluvial valley had water levels that remained unchanged between low and high flow conditions;
- Significant increase in temperature of the Oro shaft mine pool appears to be associated with inflow from 11-10 fault splays and correlates with the rising Oro shaft mine pool,
- Individual and multi-day storm events did not affect either the #3 mine pool or ground water levels at the mine site and had minor to no effect on the Oro shaft mine pool,
- Individual and multi-day storm events had minor or no effect on French Creek discharge; and
- Diurnal patterns associated with the spring snowmelt are evident in the hourly French Creek discharge data.

The minimal effect of storm events on the French Creek hydrograph suggests that infiltration of precipitation is much greater than runoff. The nearly instantaneous response of ground-water and mine pool water levels to snowmelt events also suggests that infiltration is much greater than runoff. Brooks (1998) observed that the French Creek discharge responded to snowmelt events in a matter of days. This study referred to regional snowmelt events infiltrating into and recharging the regional ground-water system and ground-water flow being the primary source for spring high flow in French Creek. The stable isotope studies independently arrived at this conclusion (RAS, 1996b and 1997b). The mine pool and ground-water lack of response to storm events indicates that the volume of water associated with these storm events, which is typically less than 0.4 inches of water, is probably very small compared to the volume of water associated with the mine pool, ground-water system, French Creek, and snowmelt events. For comparison, the mine pool probably stores over hundred million gallons of water while a storm event would amount to less than a couple of million gallons of water over the mine workings catchment area, less than 2% of the mine pool volume. The volume of mine water that is discharging into the shale bedrock and alluvial aquifer may also mask any storm responses on the ground-water system. In contrast, spring snow pack can contain over 25 times the water content of an individual storm event. Mine discharge into the alluvial valley and high flow French Creek spring conditions had very small effects on the alluvial valley ground-water elevations. This would suggest that there is significant annual ground-water flow and water storage within the alluvial valley.

The higher hydraulic head elevation for the mine pool at the discharge end of the workings (#3 Mine site) suggests flow is from the mine pool into the alluvium and fractured shale bedrock at the western downgradient portion of the mine workings. The relatively constant hydraulic head difference between the mine pool and the alluvium and fractured bedrock throughout the year in the #3 Mine area implies that the flow rate out of the mine pool is fairly constant from low to high flow conditions. It is possible that the rate of flow from the mine pool into the alluvium, faults, and fractured shale bedrock is buffered by the hydrologic properties of these receiving media. Consequently, the mine pool flow surge associated with spring high flow conditions would have to be accommodated by:

1. increases in the mine water discharge area; and
2. duration of elevated mine water discharge and mine pool elevation levels that are related to storage in the mine pool.

Figure 6-52 schematically shows the increase in discharge area and elevated mine pool elevations. The mine water storage may explain why the mine pool hydrographs have peak elevations that extend past the French Creek peak discharge and last snow melt. This also may explain the prolonged and very gradual falling limb on the mine pool hydrographs.

In summary, the mine pool has a limited draining capacity and water rises in the mine pool during spring high flow because the rate of inflow exceeds its outflow capacity. As a result, this inflow water is dammed up in the mine pool. Eventually, the high flow water drains out of the mine pool, which may take several months, and the mine pool elevation reaches stable baseflow conditions. The comparison of mine pool falling limb hydrographs at the end of August 1996 and 1998 showed the 1996 elevations to be approximately three feet higher. This suggests that there was a greater volume of water in the 1996 high flow that took longer to drain out of the mine.

Figure 6-48 shows the 1998 hydrographs for French Creek and the Oro and #3 mine pools. The lack of correlation between individual stream high flow peaks which are probably enhanced by wet periods in early June, late June, and late-July 1998 with the mine pool hydrographs suggests that French Creek is not a major inflow source to the W-O mine pool. The overall similar timing of mine pool peak elevations and French Creek peak discharge from late-May through June implies that they have similar recharge sources. The broad and smooth character of the mine pool hydrographs can be interpreted to be due to a regional bedrock ground-water source of mine inflow and/or significant water storage capacity in the mine workings. The ground-water source is supported by the isotope studies that concluded the source of recharge water to the mine pool and French Creek is regional bedrock ground-water (see section 5 of this report). Since the hydraulic head difference is not eliminated between the mine pool and alluvium during low flow conditions at the #3 Mine site, mine water continues to flow out of the mine pool at rate similar to ground-water baseflow during the low

flow periods. Most of this baseflow is occurring in large fracture systems and faults in the bedrock.

The higher hydraulic head or mine pool elevations associated with the Oro Mine shaft compared to the #3 Mine pool suggests that:

1. the hydraulic gradient within the mine pool is driving flow within and out of the mine and/or
2. the Oro Mine shaft has limited hydraulic connection to the #3 Mine pool.

It is difficult to assess any flow between the shale bedrock and alluvial aquifer at the #3 Mine site because of the steep hydraulic gradient. Accounting for the hydraulic gradient at the #3 Mine site, the shale bedrock and alluvium should have very similar hydraulic head elevations. The similarity between the shale, alluvial, and mine pool hydrographs for most of the monitoring period would suggest that the shale and alluvium are acting as one hydraulically connected unit that are communicating with the mine pool at the #3 Mine site (Figures 6-49 and 6-50). Aquifer (pumping) tests conducted at the #3 Mine site also showed that the mine, shale and alluvium are hydraulically connected (Morrissey, 1995).

The initial rise in the mine pool and ground-water elevation in March and April at the downgradient mine discharge area (#3 Mine site) correlate with the melt out of the lower elevation Dillon weather station snow pack. This correlation suggests that the March and April source of water to the mine pool and shallow ground-water is related to local site snowmelt (Table 6-3). The Oro shaft mine pool temperatures associated with inflow from the 11-10 Fault showed decreasing temperatures during the initial mine pool rise in April. This also suggests a local snowmelt recharge source.

The May and June 1987 and 1998 rise in the mine pool appears to correlate with a significant melting of the high elevation snow pack at Hoosier Pass. During early May, snowmelt from the higher more protected elevations above the Wellington workings may also contribute to the mine pool rise. The Oro shaft mine pool temperatures during the May and June 1998 water level rise showed increasing temperatures. This would imply that the high elevation snowmelt was recharging the regional ground-water bedrock systems and pushing warmer deep ground-water into the mine pool via the faults and fractured bedrock. French Creek also began significant increases in discharge in mid-May of 1997 and 1998. This would suggest that snowmelt in the headwater region of the upper French Gulch was also responsible for the mid-May and June large increase in French Creek discharge. This snowmelt recharges the regional bedrock ground-water system that subsequently discharges to the down-valley portions of French Creek. The lack of a significant increase in French Creek discharge during the late March to April lower elevation local snow melt is possibly related to a smaller volume of water associated with the lower elevation

snowmelt.

Table 6-3 demonstrates that no linear correlation exists between snow pack, French Creek discharge, and mine pool elevation rises. The 1997 snow pack appeared to be approximately twice the spring 1998 snow pack (Table 6-3). The 1996 and 1997 snow packs were significantly above average, 150% to 200%,

Table 6-3

Comparison of 1997 and 1998 Snow Pack and Mine Pool Rises

Period	Dillon Snow Pack Depth (inches)	Hoosier Pass Snow Pack Water Eq. (inches)	French Creek Peak Discharge (cfs)	Oro Mine Shaft Rise (feet)	#3 Mine Shaft Rise (feet)	% of Total Mine Pool Rise Oro/#3	Comments
1997							
3/5-5/3	15-0	20-28	35	<5.9[1]	5.9	ND/29[1]	local site snowmelt
5/4-6/18	0	28-0	126	>14.1[1]	ND	>71/ND	high elevation site and headwater snowmelt
			Total Rise	20	ND		
1998							
3/4-4/29	8-0	11-18	4	1.1[2]	1.9[2]	29/53	local site snowmelt
4/30-5/17	0	18-10	10	1.3	1.1	34/30	high elevation site and headwater snowmelt
5/18-6/22	0	10-0	46	1.4	0.6	37/17	headwater snowmelt
			Total Rise	3.8	3.6		

ND = Not determined
1 = estimated
2 = rise based on March 1997 baseflow elevations

while the 1998 snow pack were approximately 90% of average (P. Brooks, 1998). The apparent lack of a linear correlation between amount of snow pack and mine pool rises suggest that the mine workings geometry and volume may vary with elevation. Consequently, the water volume associated with a foot rise in the mine pool may vary at different elevations in the mine pool. In addition, variations in snowmelt infiltration, snowmelt runoff, and snow sublimation from

season to season may also contribute to the lack of correlation between snow pack, French Creek discharge, and mine pool rises.

Significant water level rises in the mine pool appear to correlate with the high elevation snowmelt (Table 6-3). Because we do not know the mine workings geometry and volume, it is difficult to assess relative volume contributions from the mine recharge sources. It is believed that peak mine outflow rates correspond to peak mine pool elevations. The peak French Creek discharge and peak mine elevation occur during the high elevation regional snowmelt in late-May and June. Based on this timing, it can be concluded that the mine pool recharge by the regional bedrock ground-water flow associated with the high elevation snowmelt contributed to the majority of spring flow surge in the mine.

The bedrock fracture systems and faults are likely flow pathways to the mine pool and French Creek. Figure 6-51 contains plots of water levels from the 11-10 Fault well MW-14, Oro Mine, and the #3 Mine. The water level elevations of the mine and fault were usually within 1/10 of a foot. This similarity suggests that the fault act as a conduit for ground-water into the mine workings. The temperature monitoring of the Oro Mine shaft in 1998 showed the greatest temperature fluctuations during rising water levels at a mine shaft depth where the 11-10 fault splays intersect the shaft. This suggest that a significant source of water to the rising mine pool water levels may be from the 11-10 Fault. The mine pool temperatures were increasing during the spring flow surge. This implies that warmer bedrock ground-water was the source of recharge water to the mine. The salt tracer work suggested that the 11-10 Fault could also act as a conduit for mine water out of the mine workings (Kimball et. al., 1997). Seasonal flow regimes, different locations along the fault, and hydraulic head fluctuations probably drive this apparent reversal of direction.

6.6 Conclusions

The large volume of water that is associated with melting snow in the vicinity of the mine site and the headwater region recharges the local and regional bedrock ground-water system. This recharge causes the ground-water table to rise. The rising ground-water table and associated flow results in the springtime water fluctuations of the W-O mine pool. A significant portion of the spring surge in regional ground-water flow is driven by high elevation snowmelt. Mine pool elevations rise when inflow to the mine exceed outflow. Consequently, a large portion of this ground-water recharge is stored in the mine by rising water levels. This stored water is gradually drained out of the mine over a several month period. Three major events drive the springtime bedrock ground-water flow surge into the mine pool (Figure 6-52):

(1) Early season (March-April) low elevation local site snowmelt,
(2) Early May high elevation snowmelt above the Wellington mine

workings, and
(3) Mid-May to June headwater snowmelt.

The timing and impact of these snowmelt events on the amount of ground-water inflow to the mine, degree of mine pool elevation rise, and mine water outflow volumes may vary from season to season depending on climatic conditions.

Direct infiltration into the workings from mine openings and possible direct hydrologic connections from the alluvial valley and French Creek apparently are not major recharge pathways and sources to the mine pool. The alluvial ground-water may contribute to recharging the local and regional bedrock ground-water systems upgradient of the W-O site. The lack of mine pool and ground-water level response to storm events at the mine site imply that there are minimal direct flow pathways for surface water above the mine workings to enter the mine pool. This lack of response also suggests that the volume of water associated with storm events is very small compared to the ground-water system, mine pool, and snowmelt. The lack of correlation between individual French Creek peak flows and the mine pool elevation hydrographs supports minimal direct flow pathways for French Creek water to enter the mine pool.

The seasonal similarity between the mine pool, bedrock ground-water, fault monitoring wells, and French Creek hydrographs implies that bedrock fractures and faults are major flow conduits for recharge water to the mine pool and French Creek. The prolonged peak water levels and gradual falling limbs displayed by the mine pool hydrographs suggests that mine water outflow is buffered by the hydraulic properties of the fractured and faulted bedrock. The greater area of upgradient mine workings exposed to the fractured and faulted bedrock ground-water systems probably reduces the bedrock buffering capacity for inflow into the mine (Figure 6-53). Major conduits for regional bedrock ground-water into the W-O mine working probably include the upgradient Great Northern and J-fault systems. Increased mine pool discharge during high flow conditions are probably accommodated by a larger discharge area. The relatively constant hydraulic head elevation differences between the mine pool, alluvial aquifer, and shale bedrock suggests that there is significant flow out of the mine throughout the year.

7.0 Mine Pool Characterization Study

7.1 Abstract

In January of 1997, Radon Abatement Systems (RAS) Inc. conducted geophysical logging and water sampling on the Oro Mine shaft. This work was considered a characterization study of the mine pool during low flow conditions. American Geological Services, Inc. in June of 1998 complemented this study with a high flow evaluation. Geophysical logging involved a Video Log (camera), Water Quality Log (temperature, fluid electrical conductivity, pH and oxidation-reduction potential), Discrete Point Downhole Fluid Sampler, Colloidal Borescope, Hydrophysical flow evaluation technique, and a Heat Pulse Flowmeter. Flow evaluations were also conducted on selected ground-water monitoring wells in January of 1997 and May of 1996.

In the January 1997 study, the Video Log showed potential obstructions in the Oro Mine shaft at 298 feet below surface that prevented an evaluation of the lower portions of the mineshaft. Further evaluation in the June 1998 study resulted in the assessment that these obstructions would not impact the characterization of the lower portion of the Oro mine shaft. The flow evaluations 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 fault block in the vicinity of the #3 Mine shaft. The results from the 1996 USGS salt tracer study indicated that the upper portion of the Oro Mine shaft was not hydraulically connected to the #3 Mine shaft or the downgradient metal-contaminated alluvium or French Creek. The results from the Oro Mine shaft flow evaluation and water quality of the Oro Mine shaft water supported the USGS conclusion.

The mine waters appear to be young, less than 25 years old. The mine pool chemistry is very unstable, highly reactive, and chemical processes are poorly understood. Consequently, the actual source, metal fate, and pathway of mine water to the discharge areas is difficult to assess and any conclusions from chemical data and bench scale testing on mine pool waters may be suspect because they may not be representative of in-situ conditions. Based on temperature logs and flow evaluations, significant flow appears to be occurring below the Oro Mine shaft 2nd drift level. A review of mine maps imply significant mine pool flow could be bypassing the Oro Mine shaft. The characterization studies also suggested that the flow to French Creek is via mine stopes, faults, fractures in the shale bedrock, and the shallow alluvial aquifer.

7.2 Introduction

This section presents the results and findings of a characterization study on the Oro and #3 mine shafts and selected ground-water-monitoring wells. The study was conducted under the direction of the U.S. Environmental Protection Agency (EPA) Region VIII and American Geologic Services, Inc. (AGS) through a combination of funding mechanisms including the EPA Superfund Emergency Response Group, EPA Headwaters Grant, and interagency agreements between the EPA and U.S. Bureau of Reclamation (BOR). The overall objectives of the study were:

(1) To develop an understanding of the hydrochemical and ground-water flow characteristics of the mine pool,
(2) Gain a better understanding of the role of the mine pool water and its relationship to metal loading to French Gulch, and
(3) Evaluate potential flow pathways of mine pool water to French Gulch.

The study took place between January 1997 and June 1998. Various components of the study included:

- A low flow evaluation of Oro Mine shaft inflow using a Heat Pulse Flowmeter;
- Video logging of the Oro Shaft;
- Low flow water quality logging of the Oro Mine shaft using down hole field parameter probes;
- Low flow discrete sampling and chemical analysis of the Oro Mine shaft at various depths;
- Removal of Oro Mine shaft obstructions;
- A high flow evaluation of Oro Mine shaft inflow using a Heat Pulse Flow meter and colloidal borescope;
- High flow down hole field parameter probes and discrete level water sampling; and
- Water quality analysis of the Oro and #3 mine shafts.

Additional work included flow evaluations and water sampling of selected monitoring wells at the Wellington-Oro (W-O) Mine and Mill site during both low and high flow conditions. The following presents a summary of the results including the methodologies used for the various components of this study; a discussion of these results and conclusions based on these results.

7.3 Methodology

Geophysical logging and water sampling of the Oro Mine shaft and selected monitoring wells at the Wellington-Oro (W-O) Mine and Mill site were conducted during low flow winter conditions from January 20 to 22, 1997. In June 1998, geophysical logging and water sampling of the Oro Mine shaft were repeated to characterize high flow spring conditions. The 1998 spring rise in the Oro mine pool was approximately four feet. In contrast, the 1997 spring rise in the Oro mine pool was nearly twenty feet. The low flow study was funded by the U.S. Environmental Protection Agency (EPA) Region VIII Superfund Emergency Response Group. Radon Abatement Systems (RAS) Inc. was subcontracted by URS Operating Services, an EPA Region VIII Superfund prime contractor, to conduct this low flow work. It was originally planned to compliment this study with a similar evaluation during spring 1997 high flow conditions. The EPA postponed the high flow evaluation because of obstructions in the Oro Shaft preventing the evaluation of the lower levels and a decision to wait for further direction from the French Gulch Remediation Opportunities Group (FROG). The EPA decided in the spring of 1998 to removed the obstructions in the Oro Mine shaft and continue with the high flow characterization. AGS was contracted by the U.S. Bureau of Reclamation to conduct the high flow study.

The purpose of the Oro Mine shaft geophysical logging was to evaluate the vertical distribution of water quality and the physical conditions of the mineshaft. The 1997 and 1998 logging included 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. A colloidal borescope, a tool to characterize horizontal flow, was also demonstrated in the Oro Mine shaft and monitoring well MW-3 during the June 1998 high flow study. In the 1997 low flow study, RAS subcontracted the video logging, water quality logging, and downhole fluid sampling to COLOG, Inc. and the water analysis work to Isotope Solutions Inc. and HydroLogic Laboratories. RAS leased the Heat Pulse flowmeter and supporting equipment from COLOG, Inc. and conducted flow evaluations on the Oro Mine shaft and selected monitoring wells. The water analyses in the low flow study included oxygen and hydrogen stable isotopes, metals, and major cations and anions. In addition to these parameters, the high flow 1998 study included tritium analyses on selected depths in the Oro Mine shaft, #3 Mine shaft, and evaluated redox chemistry. The 1998 high flow study also included "Hydrophysical" (Hpl)[1] logging techniques and a colloidal borescope to evaluate flow in the Oro Mine shaft. AGS subcontracted the geophysical logging to COLOG, Inc. and the water analysis to Isotope Solutions Inc. and ACZ Laboratory Services in the 1998 high flow study. Appendix 7-1 contains the RAS report on the "Geophysical Logging, Water Quality Evaluation and Stable Isotope Study of the Oro Shaft and Selected Monitoring Wells at the

[1] HydroPhysical and HpL Logging are trademarks of COLOG, Inc.

Wellington-Oro Mine Complex, French Gulch Colorado" (RAS, 1997a). The RAS appendices to their report are available through the EPA Region VIII records center. Appendix 7-2 contains the June 1998 high flow water chemistry data from Isotope Solutions, Inc. and ACZ Laboratory Services.

The ground-water and Oro shaft mine pool flow evaluation was accomplished with a COLOG, Inc. high resolution Heat Pulse Flowmeter (HPF). This flowmeter is based on detecting the vertical movement of a thermal fluid tracer. The Heat Pulse tool is able to heat or thermally tag the borehole fluid with an electrical heater grid by as much as one degree Fahrenheit. The flow rate is determined by measuring the time from heater grid discharge to the peak of the thermal pulse of water reaching an upper or lower thermistor sensor. As a result, the HPF can only determine the vertical flow direction and rate of vertical flow in a borehole. The tool was calibrated in a six-inch diameter PVC casing under laboratory conditions prior to conducting field measurements. Consequently, all flow rates measured by the tool are based on a six-inch diameter borehole. Measurements conducted on boreholes other than six inches in diameter have to be corrected. The reported range of measurable vertical fluid movement is from 0.01 gpm to 1.5 gpm in a six-inch diameter borehole. For a two-inch diameter borehole the range would be 0.002 gpm to 0.17 gpm.

The HpL logging technique can evaluate both vertical and horizontal flow components in a borehole and is a continuous logging device. In contrast, the Heat Pulse flowmeter is a stationary tool that evaluates the vertical flow components in a borehole at discrete depths. The HpL logging technique is based on borehole logging after the well fluid column has been replaced with environmentally safe deionized (DI) water. DI water has a very low fluid electrical conductivity (FEC). The DI water provides a distinct FEC contrast with the naturally high FEC ground-water. After the well fluid column has been replaced with DI water by a combination of DI water injection and well pumping, multiple FEC measurements are taken with a fluid conductivity logging tool over time and analyzed to identify where high FEC ground-water is entering or exiting the borehole. The rate of change of FEC in the borehole is used to quantify vertical and horizontal flow rates. The evaluation and quantification of hydrologic parameters are accomplished by using computer modeling and interpretation techniques.

Colloidal borescope technology was demonstrated in monitoring well MW-3 and the 5th Level of the Oro Mine shaft. COLOG subcontracted this work to AquaVISION. The colloidal borescope consists of a camera, compass, optical magnification lens, and a light source, which are contained in stainless steel housing. The compass orientates the borescope. As colloidal size particles in the ground-water pass beneath the lens, the light source illuminates the particles similar to a conventional microscope with a light stage. The borescope transmits an electronic image of the particles that is magnified 140X to a PC computer at the surface. A software package compares digitized video frames of the colloidal

particles. By tracking the movement of the particles between video frames with a one-second frequency, the colloidal particle velocity and direction of flow can be determined. The borescope can only track and quantify the horizontal movement of the colloidal particles. Appendix 7-3 consists of a letter report from AquaVISION to COLOG. This report describes the colloidal borescope and presents the French Gulch results.

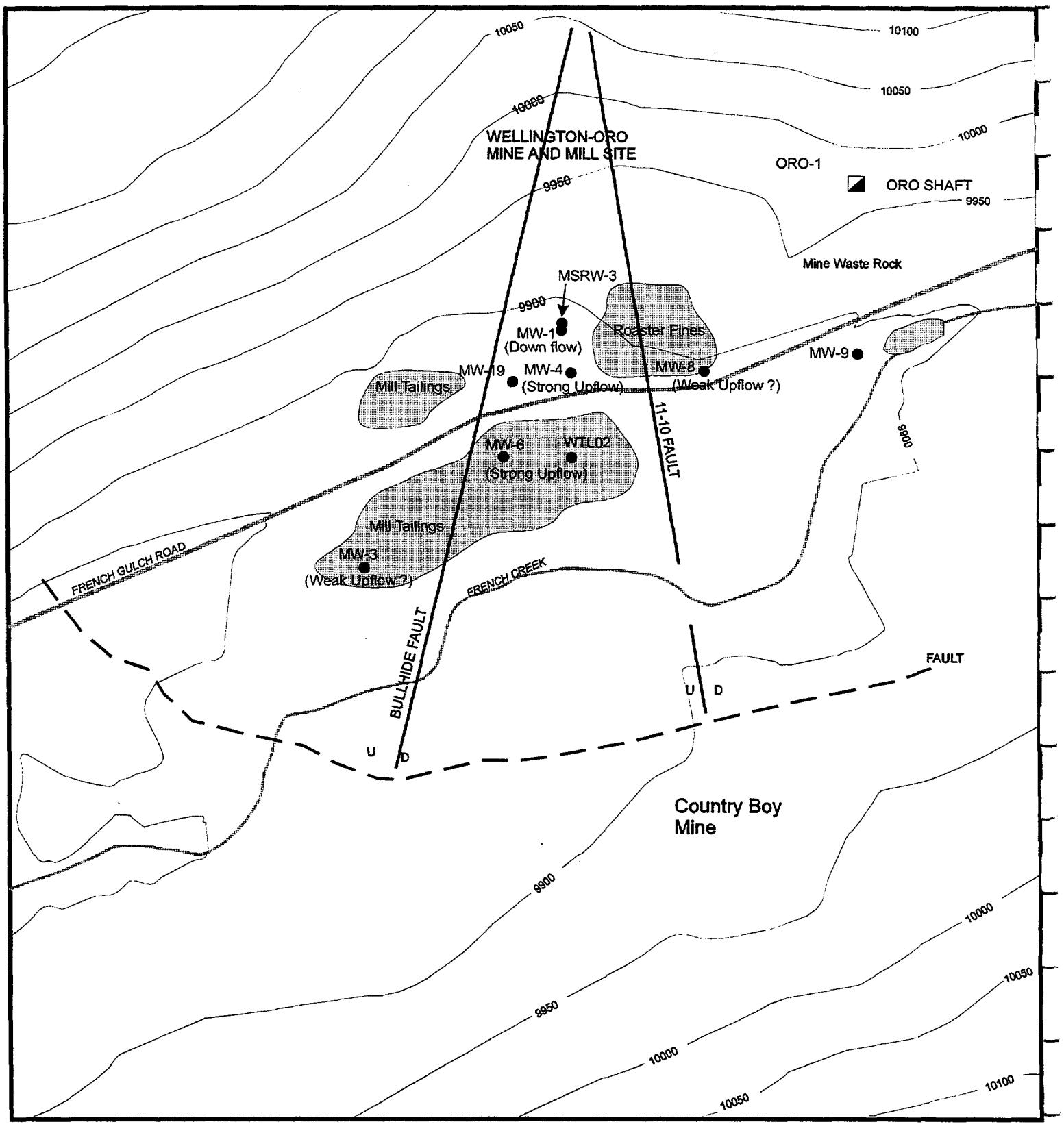
7.4 Summary of Results

7.4.1 January 1997 Flow Evaluation

The ground-water and Oro shaft mine pool flow evaluations were accomplished with a COLOG, Inc. high resolution Heat Pulse Flowmeter (HPF) and "HydroPhysical" (HpL) logging techniques. The HPF flow measurements were conducted on six ground-water-monitoring wells near the W-O Mine and Mill site. These wells were selected for this study because of their multiple screened completion intervals (MW-1, MW-3, MW-4, MW-6, and MW-8) or large continuous screened interval (MW-19), high metal ground-water contamination, and locations which bracket the Bullhide and 11-10 faults near the W-O site (Figure 7-1, Table 7-1). MW-19 was the only six-inch diameter well evaluated in this study. The other monitoring wells were two inches in diameter. The original RAS (1997a) report did not correct the HPF flow measurements performed in the two-inch diameter wells. The flow in monitoring well MW-19 was also evaluated during spring high flow conditions in May of 1996 using "HydroPhysical" (HpL) logging techniques. COLOG, INC. under a State of Colorado Division of Minerals and Geology (DMG) contract conducted the "HydroPhysical" flow evaluation. The DMG funding originated from an EPA Region VIII Headwaters Grant.

Table 7-2 summarizes the Heat Pulse flowmeter results for the selected monitoring wells and the Oro Mine shaft. This table includes corrected flow results for the two-inch diameter wells. The Oro Mine shaft is over 600 feet deep and has seven drift levels (Figure 7-2). According to Lovering (1934), the Oro Shaft was connected to the #3 Mine shaft by the 3rd, 5th, and 6th Oro levels via stopes and faults. A Video Log (camera) was run in the Oro Mine shaft prior to the Heat Pulse flowmeter and other logging tools to assess the physical conditions of the mineshaft and determine the feasibility of logging with other geophysical tools. Conduit (?) cable debris was observed in the mineshaft at 298 feet below surface. RAS decided it was too risky to lower the Video tool and other geophysical tools below the cable debris. The cable debris was between the 3rd and 4th Oro drift levels (Figure 7-2). The Heat Pulse flowmeter did not detect vertical flow in the 1st through 3rd Oro levels or above the cable debris (Table 7-2).

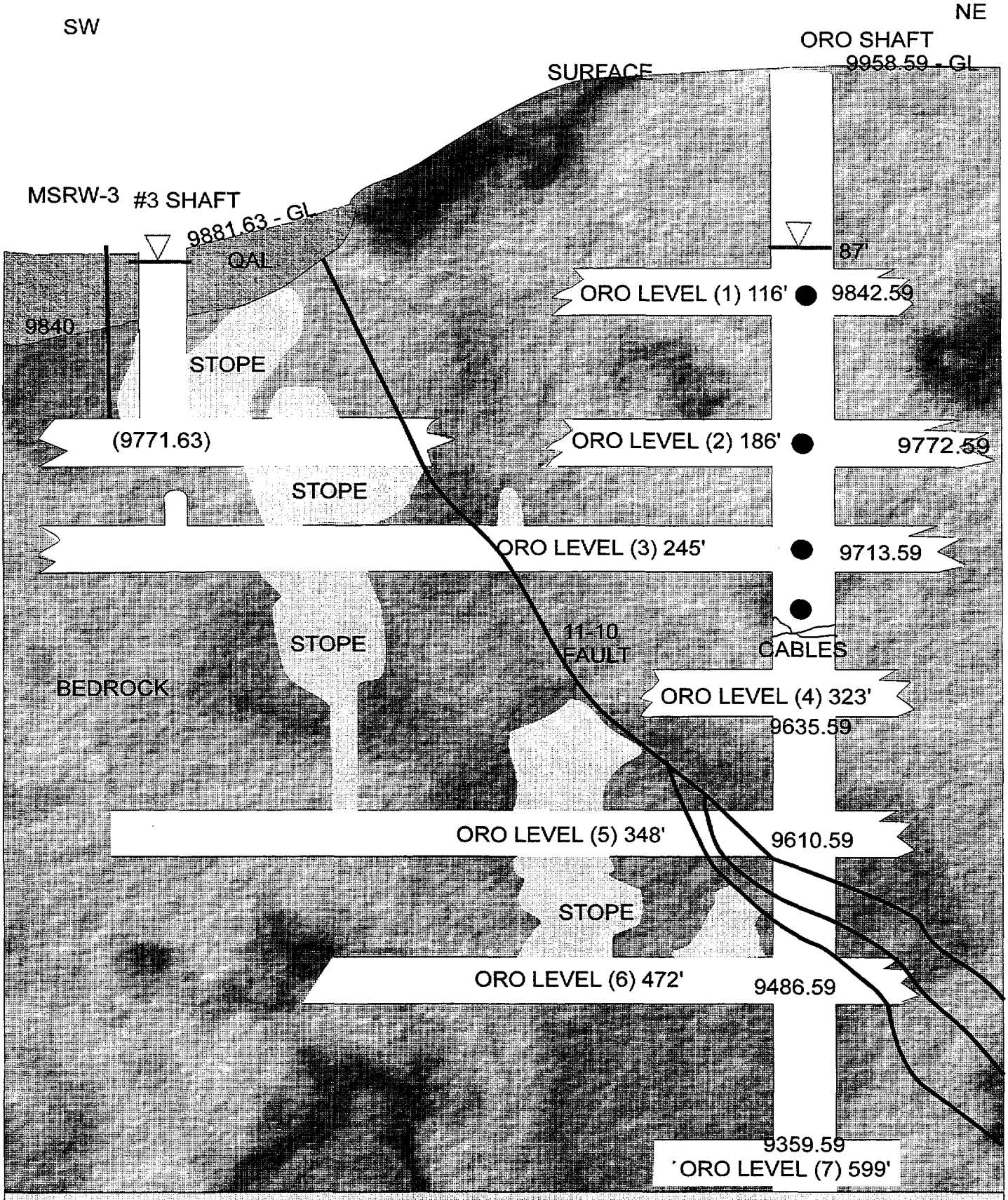
The Video Log was also used to qualitatively examine fluid flow in the Oro Mine



scale 1" = 250'

LOCATION MAP FOR HEAT PULSE FLOWMETER WELLS LOW FLOW CONDITIONS, JANUARY 1997

Figure 7-1



Low Flow January 1997

SCHEMATIC DIAGRAM OF THE ORO SHAFT

● Sample Locations
NOT TO SCALE

DEPTH MEASURED FROM ORO SURFACE
DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

Figure 7-2

Table 7-1

Multiple Screen Wells for Heat Pulse Flowmeter Borehole Logging from RAS, 1997

Monitoring Well	Screen Intervals*	Comments
MW-1 TD- 50'	22'-27' (upper Qal) 33'-43' (lower Qal)	Contaminated Qal well at mine site. Flow data for mine discharge.
MW-3 TD- 55'	15'-25' (upper Qal) 45'-50' (lower Qal)	Contaminated Qal well downgradient mine site and mill tailings. Flow data for bedrock and Bullhide Fault discharge.
MW-4 TD- 64'	20'-30' (upper Qal) 46'-51' (lower Qal) 58'-63' (Sh bedrock)	Contaminated Qal and shale well downgradient mine site. Flow data for mine and bedrock discharge.
MW-6 TD- 54'	34'-44' lower Qal/top sh bedrock) 49'-54' (sh bedrock)	Contaminated Qal and shale well below mill tailings. Flow data for bedrock discharge and Bullhide Fault.
MW-8 TD- 46'	15'-20' (upper Qal) 35'-45' (lower Qal)	Contaminated Qal well immediately downgradient roaster fines. Flow data for roaster fines and bedrock discharge
MW-19 TD- 110'	30'-110 (Qal/Shale bedrock)	Contaminated Qal and shale well. New 1996 well w/continuous slotted screen in Qal, Bullhide fault and Shale bedrock. Flow data for fault and bedrock discharge.

*-depth measured from ground surface
Qal - Alluvial aquifer
TD- Total Depth

shaft. A piece of colored yarn was attached to the end of the Video tool. The tool was placed in a stationary mode between the mine drift levels for the purpose of observing any movement of the colored yarn due to fluid flow. No movement of the yarn was observed suggesting that flow in the Oro 1st through 3rd levels and above the 4th Oro level was minimal.

Monitoring well MW-19 had significant upward vertical flow, up to 1.44 gallons per minute (gpm), as measured by the Heat Pulse flowmeter in January of 1997 (Table 7-2). This well has been inferred to penetrate the Bullhide Fault based on Lovering (1934) mapping of the fault and the observed surface expression of the fault relative to the MW-19 well location (Figure 7-1). The strong vertical upward flow apparently is driven by Bullhide Fault seepage, fractured shale bedrock and porphyry, and flow associated with the base of the alluvium (Figures 7-3). Monitoring wells MW-4 and MW-6 had a limited range of measured upward flow between 0.11 gpm to 0.16 gpm, approximately 1/10th the flow measured in the MW-19 Bullhide Fault well. This flow was near the upper detection limit of the heatpulse tool for two-inch diameter wells. The upflow in MW-6 appeared to be due to inflow to the borehole from the fractured shale bedrock (Figure 7-4). The upflow in MW-4 appeared to be driven by flow along the base of the alluvium (Figure 7-5). Monitoring wells MW-4 and MW-19 were discharging into the upper

Table 7-2

January 1997 Heat Pulse Flowmeter Results
from RAS, 1997

Monitoring Well	Test Depths*-results	Comments
Oro Mine Shaft	116.00'- no vertical flow 116.00'- no vertical flow 116.00'- no vertical flow 186.00'- no vertical flow 186.00'- no vertical flow 186.00'- no vertical flow 245.00'- no vertical flow 245.00'- no vertical flow 245.00'- no vertical flow 288.00'- no vertical flow 288.00'- no vertical flow 288.00'- no vertical flow	-water level 87.5' bgs 1st Oro Level 116' 2nd Oro Level 186' 3rd Oro Level 245' Total Depth Oro Shaft Logging 290'
MW-1	18.00'- no vertical flow 18.00'- no vertical flow 30.00'- no vertical flow 30.00'- no vertical flow 32.00'- no vertical flow 32.00'- no vertical flow 45.61'-0.08 gpm downflow 45.61'-0.08 gpm downflow	-water level 11.65' bgs -downward flow below lower screen
MW-3	30.00'- 0.04 gpm upflow 30.00'- 0.03 gpm upflow 30.00'- 0.02 gpm upflow 30.00'- 0.05 gpm upflow 30.00'- 0.02 gpm upflow 35.00'- 0.04 gpm upflow 35.00'- 0.03 gpm upflow 35.00'- 0.03 gpm upflow 35.00'- 0.02 gpm upflow 35.00'- 0.02 gpm upflow 52.00'- no vertical flow	-water level 14.99' bgs (top of upper screen) -poor repeatability and tool response for flow data -measurements near lower detection limit of tool, results questionable
MW-4	16.00'- no vertical flow 16.00'- no vertical flow 16.00'- no vertical flow 35.00'- 0.13 gpm upflow 37.00'- 0.13 gpm upflow 39.00'- 0.15 gpm upflow 39.00'- 0.15 gpm upflow 43.00'- 0.14 gpm upflow 43.00'- 0.14 gpm upflow 53.00'- no vertical flow 55.00'- no vertical flow 56.00'- no vertical flow	-water level 9.91' bgs -good tool response and data repeatability -upward flow between lower and upper Qal screens -no flow between shale bedrock and lower Qal screens

Table 7-2 (cont.)

Monitoring Well	Test Depths*-results	Comments
MW-6	24.99'- no vertical flow 24.99'- no vertical flow 40.01'- no vertical flow 40.01'- no vertical flow 46.00'- 0.16 gpm upflow 46.00'- 0.15 gpm upflow 46.00'- 0.13 gpm upflow 46.00'- 0.13 gpm upflow 48.00'- 0.14 gpm upflow 48.00'- 0.12 gpm upflow 48.00'- 0.11 gpm upflow	-water level 16.82' bgs -good tool response and data repeatability -upward flow between lower Qal/top shale bedrock and shale bedrock screens
MW-8	13.50'- no vertical flow 13.50'- no vertical flow 13.50'- no vertical flow 28.00'- 0.03 gpm upflow 30.01'- 0.03 gpm upflow 32.00'- 0.02 gpm upflow 32.00'- 0.05 gpm upflow	-water level 12.13' bgs -poor tool response and flow data repeatability -measurements near lower detection limit of tool, results questionable
MW-19	25.00'- no flow 25.00'- no flow 40.00'- 1.186 gpm upflow 40.00'- 1.168 gpm upflow 45.00'- 1.442 gpm upflow 45.00'- 1.442 gpm upflow 50.00'- 0.587 gpm upflow 50.00'- 0.578 gpm upflow 55.00'- no vertical flow 55.00'- no vertical flow 60.00'- 0.244 gpm downflow 60.00'- 0.567 gpm downflow 60.00'- 0.393 gpm downflow 60.00'- 0.370 gpm downflow 70.00'- 0.399 gpm upflow 70.00'- 0.528 gpm upflow 70.00'- 0.499 gpm upflow 85.00'- 0.602 gpm upflow 85.00'- 0.674 gpm upflow 85.00'- 0.633 gpm upflow 100.0'- 0.349 gpm upflow 100.0'- 0.358 gpm upflow	-water level 9.89' bgs -good tool response and data repeatability -upward flow above Bullhide Fault(?) @ 55' -downward flow below Bullhide Fault(?) -upward flow between 70' to 100'

*-depth measured from ground surface
Qal - Alluvial aquifer
gpm - gallons per minute

alluvium. Monitoring well MW-6 was discharging at the top of the shale bedrock and/or base of the alluvium. The January 1997 Heat Pulse flow measurements for MW-19 also showed downward flow immediately below the inferred depth of the Bullhide Fault (Table 7-2, Figure 7-3). This downward flow was exiting the borehole between 60 and 70 feet below ground surface. Below 70 feet in MW-19

the flowmeter detected upward flow. The other downward flow detected by the Heat Pulse flowmeter in January of 1997 was in MW-1 (Figure 7-6). The HPF showed inflow to the MW-1 borehole from the base of the alluvium. This flow was discharging into the underlying shale bedrock.

The May 1996 high flow evaluation on MW-19 by HydroPhysical Logging (HpL) showed major water entry at approximately (55) feet (Bullhide Fault) with an upward flow rate above this entry of 0.63 gpm (Figure 7-7, Table 7-3). This evaluation did not detect any downward flow in the MW-19 borehole. Similar to the January 1997 HPF low flow evaluation, the high flow HpL evaluation showed water was exiting the borehole into the upper alluvium at 35 feet. The RAS (1997a) report stated that the upward flow of 0.63 gpm in the high flow evaluation was less than the comparable interval in January 1997 that had a HPF measurement of 1.44 gpm. The 1.44 gpm upflow in January 1997 was actually above the water entry associated with the base of the alluvium (Figure 7-3, Table 7-3). The upward flow rate immediately above the Bullhide Fault averaged 0.58 gpm for the January 1997 HPF measurements. This rate was very similar to the HpL calculations of 0.63 gpm in May of 1996, although the low flow evaluation showed that a major component of the inflow associated with the Bullhide Fault had downward flow that averaged 0.39 gpm. Consequently, the combined upward and downward flow that brackets the Bullhide Fault in the MW-19 borehole low flow evaluation averaged 0.97 gpm. Apparently, the high flow evaluation by HydroPhysical methods only detected inflow associated with the Bullhide Fault while the low flow Heat Pulse flowmeter evaluation detected major inflow associated with the both the Bullhide Fault and the base of the alluvium.

Table 7-3

MW-19
Comparison of May 1996 HydroPhysical Logging (HpL) Flow Evaluation
With
January 1997 Heat Pulse Flowmeter (HPF) Evaluation

Depth (feet bgs)	Comments	January 1997 HPF Low Flow	May 1996 HpL High Flow
45	above base alluvium	1.44 gpm upflow	0.63 gpm upflow
45-50	above top of shale bedrock (51 feet bgs)	0.86 gpm inflow*	minimal inflow
50	above Bullhide Fault	0.58 gpm upflow	0.63 gpm upflow
55	Bullhide Fault	no vertical flow 0.97 gpm inflow*	0.63 gpm inflow
60	below Bullhide Fault shale bedrock	0.39 gpm downflow	minimal flow
100	base of borehole	0.35 gpm upflow	minimal upflow

bgs - below ground surface
gpm - gallons per minute
* calculated from vertical flow measurements

The flows measured in MW-19 during low and high flow conditions were driven by hydraulic head differences between the alluvium, Bullhide Fault, and bedrock. The higher flow measurements for MW-19 during low flow January conditions do not imply that the mine pool has corresponding higher discharge rates in January. The higher flow measurements in January 1997 suggests that the head differentials were increased between the alluvium, Bullhide Fault, and bedrock in low flow conditions compared to high flow conditions in May 1996.

The Heat Pulse flowmeter in January of 1997 measured significantly lower upward vertical flow, 0.02 gpm to 0.05 gpm, between the alluvial screened intervals in monitoring wells MW-3 and MW-8 compared to the other wells. MW-3 and MW-8 are outside of the Bullhide and 11-10 fault block (Figures 7-1, 7-8, and 7-9, Table 7-2). The HPF data from these wells were of poor repeatability and tool response and it could be interpreted that there was negligible vertical flow associated with MW-3 and MW-8 (RAS, 1997a). A possible explanation for the poor data quality could be that these wells are highly contaminated with metals and have low pH borehole fluids that are thermally unstable. These wells are located in the vicinity of the roaster fines and mill tailings. Mapping of ground-water temperatures have shown high temperature anomalies associated with monitoring wells MW-3 and MW-8 (Morrissey, 1995).

7.4.2 January 1997 Oro Mine Shaft Video Log

As previously discussed, the purpose of obtaining a Video Log (camera) on the Oro Mine shaft was to observe the physical conditions of the mine shaft, determine the feasibility of logging the shaft with other geophysical tools, and to qualitatively evaluate fluid flow in the shaft. A copy of the standard VCR formatted tape for this logging is available through URS Operating Services and the BOR. No flow or mine drifts were observed in the video. In addition to the cable debris at 298 feet below ground surface (bgs), observations included:

- timbers across the mine shaft at the top of the mine pool at 87.5 feet bgs (possibly floating on top of the mine pool),
- scattered fine suspended debris, and
- a large (possibly greater than five feet diameter) mineshaft (Figure 7-2).

7.4.3 January 1997 Oro Mine Shaft Water Quality Log

The Water Quality Log (WQL) involves continuous measurements of temperature, fluid electrical conductivity, pH and oxidation-reduction potential (ORP). The logging interval in the Oro Mine shaft was from the top of the mine pool at 88 feet bgs to a depth of 290 feet bgs, which was above the cable debris. This interval included the 1st through 3rd Oro Mine levels (Figure 7-2). Plate 2

contains a copy of the log. Table 7-4 is a summary of the Water Quality Log. There appear to be discontinuities in the water quality data at depths of 113 feet, 140 feet, 186 feet, and 242 feet below ground surface (Plate 2, Table 7-4). Between 113 feet to 119 feet bgs the ORP (Eh) abruptly decreased from approximately +185 mV to +120 mV. This interval corresponded to the 1st Oro level (Figure 7-2). The other water quality parameters did not display any abrupt changes at the 1st Oro level. At 140 feet bgs, the Eh, pH, and fluid electrical conductivity (FEC) had abrupt changes over a one-foot interval. The pH increased from approximately 6.3 to 6.8 standard units (s.u.) while the Eh decreased from +110 mV to +90 mV. The 140 feet bgs depth also corresponded to a change in the rate that the FEC was increasing with depth. Between 88 feet bgs and 140 feet bgs the FEC was increasing at a rapid rate from 1000 μS/cm to 3250 μS/cm. Below 140 feet bgs, the FEC increase with depth was very gradual. The 140 feet depth is between the 1st and 2nd Oro levels (Figure 7-2). There was an abrupt increase in FEC at 242 feet bgs from 3700 to 3775 microS/cm. This depth corresponds to the 3rd Oro Mine level (Figure 7-2).

Table 7-4

Summary of January 1997
Oro Mine Shaft
Water Quality Log (WQL)

Depth (feet bgs)	Temperature (^{0}C)	FEC (uS/cm)	pH (s.u.)	ORP (mV)
113 (1st Oro Level)	>>7.2	>>2,140	=6.3	<<185 to 120 (113'-119' bgs)
140	>>8.4	>3,220 (rate of FEC increase changes)	> 6.3-6.8 (abruptly increases by 0.5 s.u.)	<<110 to 90 (abruptly decreases by 10 mV)
186 2nd Oro Level)	=9.0 (temperature stabilizes)	>3,460	=6.9	<72
242 3rd Oro Level)	<9.0 (temperature starts to decrease)	>3625 (abruptly increases by 75 uS/cm)	=6.9	<64

> slight increasing trend with depth
>> moderate increasing trend with depth
< slight decreasing trend with depth
<<moderate decreasing trend with depth
= constant value

From 88 feet bgs to 186 feet bgs, the temperature increased from 6^0 C to 9^0 C. At 186 feet bgs, the temperature of the mine pool water stabilized at 9^0 C. The 186

feet bgs depth corresponds to the 2nd Oro Mine level. From 186 feet bgs to 241 feet bgs, the mine pool temperature remained at 9^0 C. Below 241 feet bgs, the mine pool temperature slightly decreased by 0.2^0 C.

7.4.4 January 1997 Oro Mine Shaft Fluid Sampling

Two-liter volume mine pool water samples were collected with the discrete point downhole fluid sampler from four depths in the Oro Mine shaft: 116 feet bgs, 186 feet bgs, 245 feet bgs, and 288 feet bgs. These depths corresponded to the 1st through 3rd Oro levels and the bottom of the logged interval (Figure 7-2). The fluid samples were analyzed for dissolved and total recoverable metals, oxygen and hydrogen stable isotopes, and major cations and anions. Field measurements of pH, temperature, dissolved oxygen, and fluid electrical conductivity (FEC) were taken at the surface after the fluid samples were removed from the sampler. In addition to the Oro Mine shaft samples, RAS also sampled the recently drilled U.S. Bureau of Reclamation lower mill tailings well (WTL02) which is located south of French Gulch Road near monitoring well MW-2 (Figure 7-1). Tables 7-5, 7-6 and 7-7 summarize the water quality data.

A comparison of field measurements with the water quality log on the Oro Mine shaft was made in Table 7-5. The purpose of this comparison was to determine if surface field measurements could approximate in-situ conditions and be a data quality control mechanism. The fluid sample field temperatures were not reliable. These temperatures were measured in a field container after the samples were released from the fluid sampler. Air temperatures were below freezing which resulted in the measured fluid sample temperatures being lower than the in-situ water quality log temperatures. It is also possible that the sample temperatures were changing in the discrete point sampler. The fluid samples remained in the sampler for over 10 to 15 minutes, the time required to bring the sampler to the surface and prepare for fluid transfer. The dissolved oxygen field readings for the Oro Mine shaft fluid samples were also not reliable. These measurements were taken at the surface in the field container. It was observed that the Oro Mine shaft fluid samples were degassing when removed from the downhole fluid sampler. The degassing was probably related to the decrease of pressure when the samples were raised from their sample depths and removed from the sampler. The surface field measurements of pH for the Oro Mine shaftfluid samples were different from the water quality log pH readings (Table 7-5). The WQL pH measurements appeared to be consistently higher than the surface field measurements. The WQL and surface field measurements of fluid electrical conductivity (FEC) displayed similar increasing trends with depth. Although the FEC measurements exhibited similar trends with depth, the surface FEC measurements and the water quality log FEC absolute values were significantly different. The in-situ FEC values were greater than the field measurements, especially with increasing depth.

Table 7-5

January 1997
Comparison Water Quality Log (WQL)
with
Fluid Sample Field Parameters
after RAS, 1997

Sample No.	Sample Description	Depth to Water	pH*	pH WQL	Temp.*	Temp. WQL	DO*	FEC*	FEC WQL
		(ft)	(s.u.)	(s.u.)	(^{0}C)	(^{0}C)	(%)	(uS/cm)	(uS/cm)
FG0053	Oro Shaft 116 ft level	87.5	5.71	6.0	4.9	7.8	64.4	2,420	2,530
FG0052	Oro Shaft 186 ft level	87.5	6.26	6.9	6.2	9.0	74.1	2,700	3,460
FG0051	Oro Shaft 245 ft level	87.5	6.28	6.9	4.7	8.9	77.2	2,750	3,700
FG0050	Oro Shaft 288 ft level	87.5	6.28	6.9	4.1	8.8	72.5	2,860	3,820
FG0054	Mill Tailings Well	12.02	6.59	N.A.	4.4	N.A.	1.8**	2,330	N.A.

*readings measured at surface
**reading measured in-situ (surface reading 16%)
N.A. - not applicable

Table 7-6

Summary of January 1997 Water Quality Data
from RAS, 1997

Sample #	***FG0050***	***FG0051***	***FG0052***	***FG0053***	***FG0054***
***Water Quality* Data**	**Oro Shaft 288 ft level**	**Oro Shaft 245 ft level**	**Oro Shaft 186 ft level**	**Oro Shaft 116 ft level**	**Mill Tailings Well WTL02**
Hardness as $CaCO_3$ (mg/L)	1456	1382	1374	1080	1151
Alk (mg/L)	30	40	40	20	100
Calc. TDS (mg/L)	2,609	2,589	2,542	2,304	2,226
TSS (mg/L)	155	132	124	14	14
Cl (mg/L)	3.3	ND	3.3	6.95	3.3
SO_4 (mg/L)	1700	1720	1700	1560	1480
Ca-d (mg/L)	382	357	354	273	305
K-d (mg/L)	3.07	2.15	3.36	1.81	2
Mg-d (mg/L)	122	119	119	96.6	94.6
Na-d (mg/L)	14.2	19	15.1	11.4	9.13
Al-t/d (ug/L)	6020/ND	1080/ND	447/ND	1810/884	ND/ND
Mn-t/d (mg/L)	43.2/44.4	40.5/41.4	36.9/39.1	36.7/36.5	42.7/44.3
Ni-t/d (ug/L)	155/125	147/127	115/121	123/127	115/122
Zn-t/d (mg/L)	191/203	177/190	170/174	186/187	141/148
Cd-t/d (ug/L)	200/184	183/178	176/185	384/387	5.09/7.55
Cu-t/d (ug/L)	15.4/ND	ND/ND	ND/ND	65.1/47.7	ND/ND
Fe-t/d (mg/L)	153/119	142/117	137/110	125/118	79.9/79.6
As-t/d (ug/L)	9.9/ND	11/ND	ND/ND	ND/ND	28/30
Pb-t/d (ug/L)	210/ND	240/ND	180/ND	470/250	30/4.2

"ND" = Sample Concentration not detected above method report limit
"t" = Total Recoverable
"d" = Dissolved

Table 7-7

Summary of January 1997 Stable Isotope Data
from RAS, Inc.

Sample #	***FG0050***	***FG0051***	***FG0052***	***FG0053***	***FG0054***
***Stable* Isotopes**	**Oro Shaft 288 ft level**	**Oro Shaft 245 ft level**	**Oro Shaft 186 ft level**	**Oro Shaft 116 ft level**	**Mill Tailings Well WTL02**
Oxygen: Delta O18 (‰)	-19.2	-19.4	-19.2	-19.0	-18.9
Hydrogen: Delta D (‰)	-146	-146	-146	-143	-141

The water quality analyses for the different Oro Mine shaft levels suggest that the mine pool is not homogenous (Table 7-6). There were generally three trends in water quality parameters in the Oro Mine shaft:

1. increasing concentrations with depth (total suspended solids, calculated total dissolved solids, calcium, total recoverable and dissolved Ni, and total recoverable Fe);
2. high concentrations associated with the 1st Oro level (Cl, Cd, Cu, and Pb); and
3. relatively minor changes in concentrations with depth (alkalinity, SO_4, Mg, Mn, and Zn).

The mill tailing ground-water concentrations for zinc, cadmium, iron, and lead were lower compared to the Oro Mine shaft samples. In particular, cadmium and zinc concentrations were significantly lower while arsenic and alkalinity mill tailing ground-water concentrations were higher (Table 7-6).

Section 5.0 of this report reviewed the basic concepts and theory behind using stable isotopes of oxygen and hydrogen as natural tracers in ground and surface water studies. RAS, Inc. conducted stable isotope studies for the State of Colorado Division of Minerals and Geology at French Gulch in 1996 and 1997 (RAS, 1996a, 1996b, and 1997b). These studies have demonstrated that the French Creek surface waters and associated alluvial ground-water, and the Wellington-Oro mine water at the #3 Mine shaft had a restricted range of isotopic compositions. The oxygen isotopic compositions ranged from -19.0‰ to -17.4‰. This limited range has been interpreted to be due to the dominance of regional bedrock ground-water discharge which influences the mine pool at the #3 Mine shaft, French Creek, and the alluvial aquifer. These studies have also shown that the isotopic composition of snowmelt water in the 1996 and 1997 winter seasons was ^{18}O depleted compared to the mine, surface, and ground waters in French Gulch. The oxygen isotope composition of water from the March 1996 snow pack in the vicinity of the mine site was (-27.2‰). The March 1997 snowmelt water at the mine site had isotopic compositions of (-23.6‰). Although all the waters in French Gulch had a restricted range of isotopic compositions, there were two statistically distinct groups: (1) mine water and (2) French Creek/ground-water (Figures 7-10 and 7-11). Figures 7-10 and 7-11 are stable isotope low flow results in March of 1996 and 1997 with the January 1997 stable isotope results from the Oro Mine shaft and the WTL02 mill tailings well. The mill tailings and 1st Oro level (ORO-116) isotopic results plot within the mine water isotopic composition that was observed at the #3 Mine shaft. The Oro Mine shaft samples from the 2nd level (ORO-186), 3rd level (ORO-245), and at 288 feet bgs (ORO-288) plot at lower oxygen and hydrogen isotope compositions than the #3 Mine shaft water (Figures 7-10 and 7-11).

7.4.5 June 1998 Obstruction Removal

AGS subcontracted KK Pump Systems and Golden Drilling Inc. to remove the obstructions in the Oro Mine shaft. In addition to the obstruction removal operations, a larger hole was made in the Oro Mine shaft concrete pad to improve access. The top of the Oro mine pool was measured at 83.95 feet bgs. After removal of the protective concrete pad, attempts were made to remove floating timbers with a modified 55-gallon drum containing a metal screen on the bottom. A large hook was also used unsuccessfully to snag the floating timbers. The fishing with the 55-gallon drum resulted in limited success. A couple of small timbers were removed, but two large timbers remained. There was concern that if the large timbers were not removed they may become jammed against the shaft walls during subsequent fishing attempts for the lower cable debris at 298 feet bgs. After the fishing attempts for the floating timbers, the 55-gallon drum was lowered to 500 feet bgs and raised without encountering obstructions or problems. Prior to the obstruction removal operations, cables associated with pressure transducers and thermocouples were removed from the shaft. Portions of these cables were below the 298 feet bgs cable obstructions. There were also no problems encountered during their removal. Based on the lack of problems with lowering and raising the 55-gallon drum and transducers, it was decided not to attempt to remove the lower cables at 298 bgs.

7.4.6 June 1998 Flow Evaluation

A video log (camera) was run in the Oro Mine shaft prior to the other geophysical tools to assess the physical conditions of the mineshaft and determine the feasibility of further evaluations. The radius of view for the video camera appeared to be two to three feet. The conduit (?) cable observed in the January 1997 study was not encountered. A fine silt material was near the bottom of the shaft at approximately 590 feet bgs. COLOG measured the bottom of the shaft at 597 feet bgs. A loose timber (?) was observed to be protruding from the side of the shaft at approximately 348 feet bgs (5th Oro Level), but did not obstruct the logging. No other obstructions were encountered during the video logging.

A colored piece of flagging tape was also attached to the end of the Video tool to qualitatively examine fluid flow in the mineshaft. The tool was placed in a stationary mode at and between mine drift levels. No movement of the colored tape was observed. Because of the large size of the mineshaft, only very high flow rates in the mineshaft would move the color taped.

The COLOG high resolution Heat Pulse Flowmeter (HFP) was used to detect vertical movement of mine water in the shaft. Prior to the flow testing, the Heat Pulse tool was evaluated for its applicability in a large mine shaft environment. The tool was fired in the mine pool immediately below the top of the mine water. Once fired, the tool was physically moved vertically upward and downward to

observe if the tool's thermistors could detect the heat generated by the tool. The thermally tagged mine pool was detected by the thermistors indicating that the mine pool did not totally disperse the heat. It was concluded that the Heat Pulse tool could be used to detect and evaluate vertical flow in the mineshaft. Table 7-8 summarizes the HpL results. The HFP results were also plotted on COLOG's Water Quality Log (Plate 3). The HFP tool is calibrated for flow (i.e. gallon per minute) in a six-inch borehole. Due to the large size of the Oro Mine shaft, the flow results were converted to a velocity in feet per minute (ft/min) which is a measurement independent of the size or volume of the Oro Mine shaft. The results of the HFP flow evaluation showed no detected vertical flow above the 5th Oro Level and upward flow of 0.0034 ft/min below the 5th Level. An U.S. Bureau of Mines (1971) report stated that the Oro Mine shaft was 5 feet by 10 feet in size. Converting the measured velocity to flow for the 5 feet by 10 feet mineshaft

Table 7-8

Oro Mine Shaft
June 1998 Heat Pulse Flowmeter Results

Test Depths*-results (feet/minute)	Comments**
186'- no vertical flow	-water level 83.84' bgs
245'- no vertical flow	1st Oro Level 116' 2nd Oro Level 186'
332'- no vertical flow	3rd Oro Level 245' 4th Oro Level 323'
348' - 0.0034 ft/m upflow	5th Oro Level 348' 11-10 Fault near 444'
444' - 0.0034 ft/m upflow	6th Oro Level 472' 7th Oro Level 590'
570' - 0.0034 ft/m upflow	Total Depth Oro Shaft Logging 597'

* - depth measured from top of concrete pad
** - Level and fault depths from Lovering (1934)

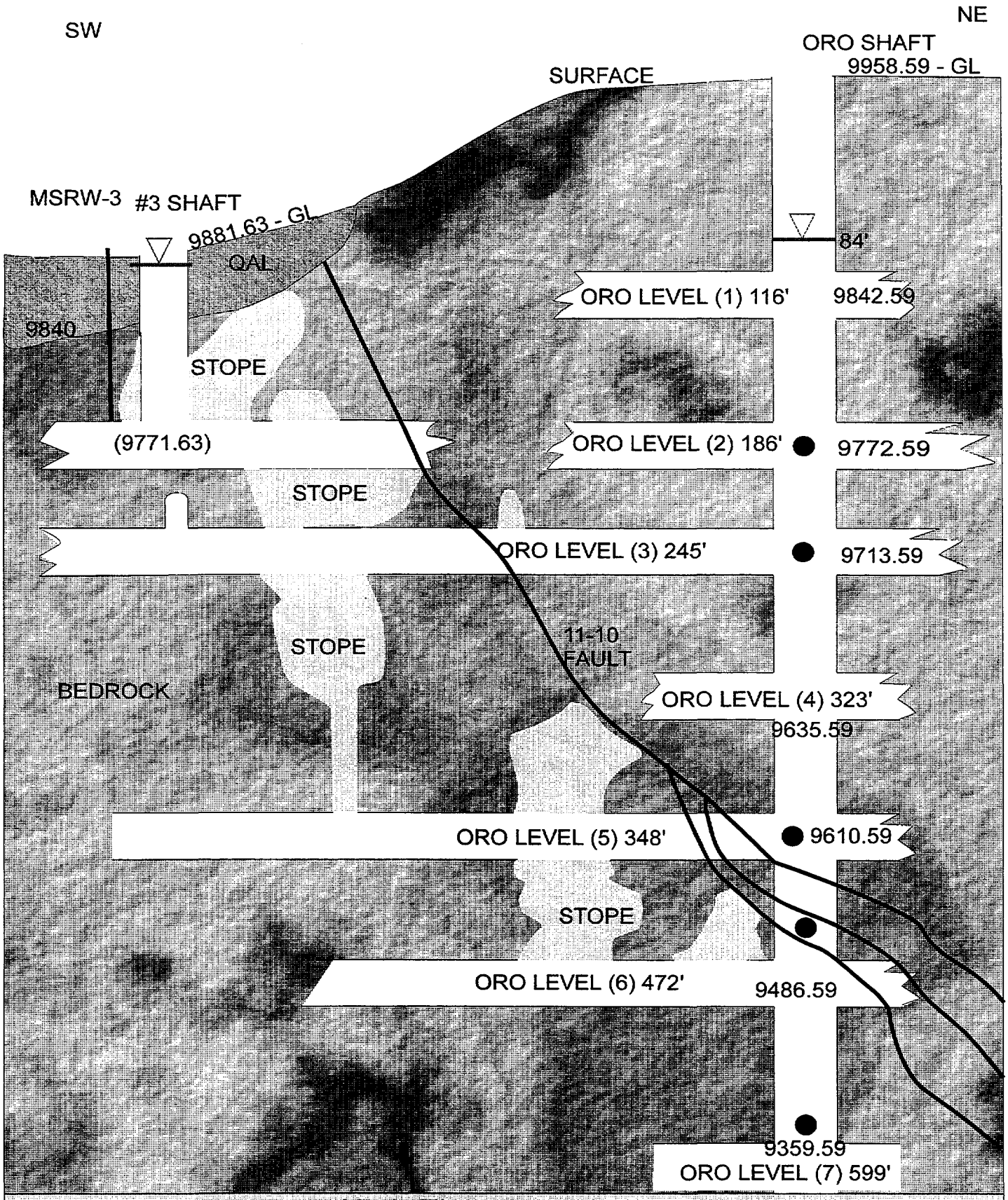
volume yields 1.31 gallons per minute. This measurement probably represents the lower detection limit of the HFP in the large shaft environment.

Colloidal borescope technology was demonstrated in monitoring well MW-3 and the 5th Level of the Oro Mine shaft. In monitoring well MW-3, a zone with significant horizontal flow was detected by the colloidal borescope in the middle of the upper alluvial-screened interval, which is 15 to 25 feet below ground surface. The particle flow direction was in a westerly direction consistent with the down valley gradient. The measured velocity values averaged 460 feet per day. According to AquaVISION, these colloidal velocities were the highest ever measured by the borescope and represent the upper limits for the equipment. The lower alluvial screen in MW-3 did not have any measurable ground-water

flow. The letter report erroneously referred to this interval to be completed in the shale bedrock. This interval most likely represents clayey fine-grained material at the base of the alluvium and on top of the shale bedrock. It is also possible that the lower screened interval could be plugged.

The colloidal borescope flow measurements were also performed on the Oro Mine shaft. This demonstration was concentrated on the 5th Oro Level due to time constraints. It has been inferred from dewatering activities associated with the Oro Mine shaft in the early 1970's that major water entry occurred at and below the 5th Level (Woodward-Clyde Consultants, 1975). This source of water entry was also supported by the vertical flow evaluations, which showed upward heatpulse flow measurements below the 5th Level and no detectable vertical flow above the 5th level. This suggests that mine water was moving from the deeper shaft to the 5th drift level. The first two colloidal borescope flow measurement depths were at 348 feet bgs, Lovering (1934) reported depth for the 5th Level, and at a depth of 345 feet bgs. Both of these depth measurements resulted in swirling flow suggesting minimal hydraulic connection with the 5th drift level. The third depth zone at 340 feet bgs showed significant directional flow. There was generally a westerly flow towards the downgradient stream valley, but the flow did vary between a southwest to northwest direction. The Lovering (1934) underground mine maps showed the 5th level to intersect the Oro Mine shaft in a northwest orientation. The predominant orientation of the 5th Level, outside the local area of the Oro Mine shaft, is a southwest direction. Flow velocity was measured at 150 feet per day. It is possible that Lovering's 1934 reported depth for the 5th Oro Level was 5 to 10 feet low. The depth discrepancy could be due to ground surface alterations around the Oro Mine shaft since Lovering's work. The present ground in the vicinity of the Oro Mine shaft appears to have been excavated in the past.

A modified HpL technique was also attempted on the Oro Mine shaft. Appendix 7-4 contains a letter report from COLOG to AGS summarizing the modified HpL technique and discusses the results. The HpL technique is based on replacing the formation fluid in a borehole with low fluid electrical conductivity DI water to provide a distinct contrast with the high formation fluid conductivity formation water. For the Oro Mine shaft it was decided to inject low fluid electrical conductivity, 70 to 100 μs, upstream creek water instead of DI water to contrast with the mine pool water fluid conductivity of 2,000 μs to over 3,000 μs. COLOG's injection system had the capacity to pump at an average of 20 gallons per minute. The total injection volume per test depth was approximately 800 gallons, the capacity of the water truck. Consequently, it required around 45 minutes of pumping to inject the 800 gallons of creek water per test depth. The first depth for injection was at 585 feet bgs, immediately above the lowest drift level (7th) in the Oro Mine shaft (Figure 7-12). The COLOG HpL logging (fluid electrical conductivity) did not detect the low conductivity creek water slug after the 45 minutes of injection. The initial interpretation of this test was that



High Flow June 1998

SCHEMATIC DIAGRAM OF THE ORO SHAFT

● Sample Locations
NOT TO SCALE

DEPTH MEASURED FROM ORO SURFACE
DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

Figure 7-12

horizontal flow at the 7th Oro Level was at least 20 gpm. The next injection depth was 523 feet bgs, between the 6th and 7th Oro drift levels. A slightly lower conductivity slug, approximately 100 μs less than the conductivity measured below the injection point was detected by HpL logging (Figure 7-13). Similar results were observed in subsequent injection depths of 418 feet bgs, 334 feet bgs, and 240 feet bgs. Although there was a slight decrease in fluid conductivity at the point of injection, the overall fluid conductivity of the mine pool did not significantly change after injection compared to the pre-injection fluid conductivity (Appendix 7-4, Figure 7-14). According to modeling results, if the low conductivity creek water was conservative there should have been a much lower mine pool fluid conductivity than observed at the point of injection (Appendix 7-4). It is suspected that the lack of a low conductivity creek water injection slug was due to mobilization and dissolution of metal and possibly non-metal species, and other geochemical processes as a result of mixing the creek water with the mine pool. Consequently, it was not possible to model the HpL data for flow evaluation.

7.4.7 June 1998 Oro Mine Shaft Water Quality Log

The water quality logging interval in the Oro Mine shaft during the 1998 high flow evaluation was from the top of the mine pool at 83.84 feet bgs to the tagged bottom of the shaft at 597 feet bgs. The water quality logging was conducted several days after the obstruction removal attempts and prior to the flow evaluations. This interval included the 1st through the 7th Oro Mine drift levels (Figure 7-12). The COLOG Water Quality Log (WQL) included continuous measurements of temperature, fluid electrical conductivity (FEC), pH and oxidation-reduction potential (ORP). Plate 3 contains a copy of the WQL. Table 7-9 summarizes the Oro mineshaft June 1998 Water Quality Log. There appear to be discontinuities in the water quality data near the top of the mine pool, 113 feet bgs, 136 feet bgs, 170 feet bgs, 190 feet bgs, 205 feet bgs. 244 feet bgs, 410 feet bgs, and 440 feet bgs (Table 7-9). The following significant changes occur in pH, ORP or Eh, and FEC within the upper ten feet of the mine pool:

1. ORP abruptly decreases from approximately +260 mV to +160 mV,
2. pH increases from 4.2 standard units (s.u.) to 6.1 s.u., and
3. FEC increased from 1,540 μS to 2,400 μS.

The next significant physical change in the mine pool occurs around the 2nd Oro drift Level. The temperature gradient, which was increasing with depth, stabilizes at the 2nd Oro Level at a temperature of 9^0C. Below the 3rd Oro Level the temperature gradient actually reverses with a 0.2^0C temperature decrease. A similar temperature decrease was observed in the January 1997 logging (Table 7-4). The temperature appears to return to a normal increasing gradient below the 5th Oro Level and the 11-10 Fault splays. The deepest discontinuity in the

water quality logging occurred in the vicinity of where Lovering (1934) indicated 11-10 Fault splays intersect the Oro mineshaft. At 440 feet bgs, the ORP

Table 7-9

Summary of June 1998
Oro Mine Shaft
Water Quality Log (WQL)

Depth (feet bgs)	Temperature (^{0}C)	FEC (uS/cm)	pH (s.u.)	ORP (mV)
86 (top of mine pool)	=6.5	>>1,540	>>4.2-6.1 (abrupt increase 86'-95' bgs)	<<260-160 (abrupt decrease 86'-95' bgs)
113 (1st Oro level)	>7.3	=2,400	=6.1	<150
136 (below 1st Oro level)	>8.0	>2,470	>6.2	<128
170 (above 2nd Oro Level)	>8.7	>2,740	=6.7	<94
190 (below 2nd Oro Level)	=9.0 (temperature stabilizes)	=2,800	=6.7	<88
205 (below 2nd Oro Level)	=9.0	=2,800	=6.7	<82
244 (3rd oro Level)	<9.0 (temperature begins to decrease)	>2,830 (FEC starts slight increase)	=6.7	=76 (ORP stabilizes)
410 (near 11-10 Fault)	<8.8 (temperature starts to increase again)	>3,010	=6.7	=68
440 (near 11-10 Fault)	<9.0	>3,070	=6.7	<<52-8 (ORP abruptly decreases 440'-450' bgs)

> slight increasing trend with depth
>> moderate increasing trend with depth
< slight decreasing trend with depth
<<moderate decreasing trend with depth
= constant value

abruptly decreases by 44 mV to 8 mV over a ten feet interval. Below 490 feet bgs to the bottom of the shaft the ORP stabilized at +52 mV (Plate 3).

The temperature and ORP profiles between the June 1998 and January 1997 logging were very similar (Tables 7-4 and 7-9). There were differences for FEC and pH. Although the FEC increased with depth in both the June 1998 and January 1997 logging, the overall low flow January FEC values were higher. The pH values were slightly higher in January 1997. It is possible that low ("clean") FEC ground-water that was recharging the mine pool during high flow conditions in June 1998 diluted the high FEC mine water resulting in lower FEC mine water compared to low flow conditions in January 1997. The rising mine pool levels during high flow conditions probably generated metal-bearing acid solutions by reacting with sulfide minerals in the presence of oxygen. The greater oxidizing conditions and acid generation in June 1998 is supported by high ORP values and low pH values at the top of the mine pool (Table 7-9).

7.4.8 June 1998 Oro and #3 Mine Shaft Fluid Sampling

Approximately two-liter volume mine pool water samples were collected with COLOG's discrete point downhole fluid sampler from five depths in the Oro Mine shaft; 186 feet bgs, 245 feet bgs, 348 feet bgs, 444 feet bgs, and 570 feet bgs. In addition, the #3 Mine shaft and soil boring EXO-2 were sampled. Fluid samples from the mineshafts were analyzed for dissolved and total metals, oxygen and hydrogen stable isotopes, tritium, and major cations and anions. Field measurements on the mine pool samples included pH, temperature, fluid conductivity, ferrous iron, alkalinity, and sulfite. The U.S. Bureau of Reclamation in 1996 drilled the EXO-2 soil boring. This boring is located immediately south of the X10U8 waste pile. The boring was only sampled for stable isotope analysis because there was less than a foot of water in the 2-inch diameter PCV casing and it had never been developed. Tables 7-10, 7-11, and 7-12 summarize the water quality data. Appendix 7-5 is a compilation of all the mine water quality results since sampling was initiated on the mine pool in 1996.

Comparisons of field and laboratory measurements with the COLOG's water quality log on the Oro Mine shaft were made in Table 7-10. According to COLOG, the pH and FEC probes on their water quality log were calibrated prior to the Oro Mine shaft work. Consequently, it is assumed that the water quality log represents in-situ measurements. Dissolved oxygen (DO) measurements were not included in the June 1998 program due to unreliable surface measurements and the possibility that high sulfide concentrations in the mine pool would damage any in-situ DO probe. Similar to the January 1997 temperature measurements, the surface fluid sample field temperatures were not reliable. The warm air temperatures resulted in the surface measured fluid sample temperatures to be higher than the water quality log temperatures. The

Table 7-10

June 1998
Comparison Water Quality Log (WQL)
with
Fluid Sample Field Parameters and Laboratory Measurements

Sample No.	Sample Description	Depth to Water (ft)	Lab pH (s.u.)	Field pH* (s.u.)	WQL pH (s.u.)	Field Temp.* (°C)	WQL Temp. (°C)	Lab FEC (µS/cm)	Field FEC* (µS/cm)	WQL FEC (µS/cm)
0007	Oro Shaft 186 ft level	83.81	4.8	5.8	6.7	15.7	8.9	2,280	2,190	2,800
0006	Oro Shaft 245 ft level	83.81	4.7	5.69	6.7	11.8	9.0	2,230	2,150	2,830
0005	Oro Shaft 348 ft level	83.84	5.0	5.87	6.7	8.9	8.7	2,310	1,830	2,950
0004	Oro Shaft 444 ft level	83.84	5.3	5.65	6.7	13.8	9.1	2,420	2,180	3,040
0003	Oro Shaft 570 ft level	83.84	5.8	5.9	6.7	15.4	9.6	2,930	2,780	3,130
0001	#3 Mine	11.06	5.1	5.85	N.A.	11.7	N.A.	2,780	2,300	N.A.
0009	EXO-2	9.11	n.d.	n.d.	N.A.	n.d.	N.A.	N.A.	3,300	N.A.

*readings measured at surface
n.d. - not determined
N.A. - not applicable

Table 7-11

Summary of June 1998 Water Quality Data

Sample #	***0003***	***0004***	***0005***	***0006***	***0007***	***0001***	***0002***	***0001/0002***
Water Quality **Data**	**Oro Shaft 570 ft level**	**Oro Shaft 444 ft level**	**Oro Shaft 348 ft level**	**Oro Shaft 245 ft level**	**Oro Shaft 186 ft level**	**#3 Mine Shaft**	**#3 Mine Shaft Duplicate**	**#3 Mine Shaft RPD**
Hardness as $CaCO_3$ (mg/L)	1638	1150	1114	1111	1209	1415	1416	0.1
Carbon, total organic TOC (mg/L)	2	2	2	2	2	2	2	0.0
Field Alkalinity (mg/L)	145	65	85	55	45	70	70	NA
Lab Alkalinity (mg/L)	78	16	74	<2 (ND)	3	45	78	**200**
Filterable TDS (mg/L)	3,440	2,710	2,760	2,530	2,570	3,200	3,190	0.3
Calculated. TDS (mg/L)	3,097	2,414	2,476	2,322	2,276	2,889	2,865 (0.8)	0.8
Non-Filterable TSS (mg/L)	32	50	46	48	46	600	400	**40**
Cl (mg/L)	1	2	2	2	2	1	1	0.0
Sulfate SO_4 (mg/L)	2,090	1,650	1,680	1,590	1,490	1,970	1,940	1.5
Sulfide as S (mg/L)	<0.02 (ND)	<0.02 (ND)	<0.02 (ND)	<0.02 (ND)	<0.02 (ND)	0.07	0.09	20
Lab Sulfite SO_3 (mg/L)	<2 (ND)	<2 (ND)	<2 (ND)	<2 (ND)	<2 (ND)	2	<2 (ND)	NA
Field Sulfite SO_3 (mg/L)	<0.64 (ND)	<0.64 (ND)	<0.64 (ND)	<0.64 (ND)	<0.64 (ND)	<0.64 (ND)	<0.64 (ND)	NA
Ammonia NH_3 (mg/L)	0.54	0.44	0.47	0.41	0.53	0.6	0.8	**28.6**
Nitrite NO_3 as N (mg/L)	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	<0.01 (ND)	NA
Nitrate NO_2 as N (mg/L)	0.07	0.16	0.09	0.05	0.06	0.13	0.06	**73.7**
Ca-d (mg/L)	435	299	291	289	316	367	369	0.5
K-d (mg/L)	3.4	2.8	3.0	3.1	2.8	3.0	3.0	0.0
Mg-d (mg/L)	134	99	94	94.6	102	121	120	0.8

Table 7-11 (continued)

Sample #	***0003***	***0004***	***0005***	***0006***	***0007***	***0001***	***0002***	***0001/0002***
Water Quality **Data**	**Oro Shaft 570 ft level**	**Oro Shaft 444 ft level**	**Oro Shaft 348 ft level**	**Oro Shaft 245 ft level**	**Oro Shaft 186 ft level**	**#3 Mine Shaft**	**#3 Mine Shaft Duplicate**	**#3 Mine Shaft RPD**
Na-d (mg/L)	14.9	11.1	11.8	12.2	11.6	13.8	13.6	1.5
Ag-t/d (ug/L)	<0.5/<0.5 (ND)	<0.5/<0.5 (ND)	<0.5/<0.5 (ND)	<0.5/<0.2 (ND)	<0.5/<0.2 (ND)	5.0/<0.5(ND)	4.9/<0.5(ND)	2.0/NA
Al-t/d (ug/L)	100/100	830/710	970/830	900/800	1,020/850	15,300/160	15,000/170	2.0/3.0
As-t/d (ug/L)	14/12	11/9	10/8	11/11	11/14	63/<5(ND)	67/6	6.2/NA
Cd-t/d (ug/L)	16/9	205/234	249/268	232/294	265/226	166/64	153/62	8.2/3.2
Cr-t/d (ug/L)	7/<2(ND)	<1/<2 (ND)	<1/<2 (ND)	<1/<0.4 (ND)	<1/<0.4 (ND)	3/<2(ND)	3/<2(ND)	0.0/NA
Cu-t/d (ug/L)	40/35	88/84	112/91	108/133	130/100	474/37	499/38	5.1/2.7
Field Ferrous Fe^{+2}-t (mg/L)	180	130	140	140	130	165	nd	NA
Lab Ferrous Fe^{+2}-t (mg/L)	142	116	101	123	125	145	nd	NA
Fe-t/d (mg/L)	143/142	121/123	114/122	119/118	110/134	173/131	170/132	1.7/0.8
Mn-t/d (mg/L)	40.8/43.3	36.4/37.5	34.5/36.5	35.6/36.2	33.4/37.7	42.8/44.2	43/44.2	0.5/0.0
Mo-t (ug/L)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	2	2	0.0
Ni-t/d (ug/L)	150/150	120/110	110/110	110/110	200/110	130/130	130/120	0/8.0
Pb-t/d (ug/L)	<80/<40 (ND)	240/200	300/260	280/280	340/200	4,600/260	4,700/240	2.2/8.0
Sb-t (ug/L)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	4	4	0.0
Se-t (ug/L)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	NA
U-t (ug/L)	1.6	1.3	1.4	1.3	1.3	8.4	8.6	2.4
V-t (ug/L)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	<1 (ND)	5	6	18.2
Zn-t/d (mg/L)	137/148	160/172	159/172	162/171	159/177	197/196	194/195	1.5/0.5

"ND" = Sample Concentration not detected above method report limit
"t" = Total Recoverable
"d" = Dissolved
"NA" = Not Applicable
"RPD" = Relative Percent Difference (EPA acceptance criteria <20%)

Table 7-12

Summary of June 1998 Stable Isotope and Tritium Data

Sample #	***0009***	***0010***	***0003***	***0004***	***0005***	***0006***	***0007***	***0001***	***0002***
	EXO-2 X10U8 Tailings	**FG-0 SNOW**	**Oro Shaft 570 ft level**	**Oro Shaft 444 ft level**	**Oro Shaft 348 ft level**	**Oro Shaft 245 ft level**	**Oro Shaft 186 ft level**	**#3 Mine Shaft**	**#3 Mine Shaft Duplicate**
Tritium Total (TU)	n.d.	n.d.	n.d.	22	n.d.	n.d.	20	18	n.d.
Oxygen: Delta O18 (‰)	-18.1	-19.3	-18.7	-18.6	-18.6	-18.4	-18.6	-18.6	-18.8
Hydrogen: Delta D (‰)	-137	-144	-145	-139	-143	-141	-138	-140	-141

"n.d." = not determined

field pH measurements were also consistently lower, approximately 1 s.u., than the water quality log readings. The laboratory-measured pHs on raw unpreserved samples was even lower than the field measured pH (Table 7-10). Field and laboratory measured fluid electrical conductivity (FEC) were significantly lower than the in-situ water quality log readings. The laboratory FEC was usually slightly higher than field measured FEC. The laboratory and water quality log FEC measurements were increasing with sample depth. Section 7.4 of this report discusses possible explanations for these observations.

In contrast to the January 1997 sampling, because of budgeting constraints the June 1998 sampling of the Oro Mine shaft did not include the top of the mine pool. Therefore, trends in water quality parameters for the 1998 results are from the 186 feet depth (2nd Oro Level) and deeper. The increasing concentrations with depth trend observed in the January 1997 results for total suspended solids and calcium were not evident in the June 1998 data. For the June 1998 results, calculated total dissolved solids and sulfate concentrations increased with depth, except for the 444 feet depth (11-10 Fault?). With the exception of the June 1998 348 feet depth (5th Oro Level), field-measured alkalinity and total recoverable iron concentrations increased with depth (Table 11). The lowest sample depth in June 1998 (570 feet) showed the greatest variation from the other Oro Mine shaft samples. This depth had significantly higher concentrations for hardness, field-measured alkalinity, measured filterable TDS, calculated TDS, sulfate, Ca, Mg, Na, Cr, ferrous iron, and total recoverable and dissolved Fe. This depth also had significantly lower concentrations for Al, Cd, Cu, and Pb and slightly lower concentrations of TSS and Zn. For most of the water quality parameters, the #3 Mine shaft concentrations were between the Oro 570 feet depth and the other Oro depth samples (Table 11). The major exceptions for the #3 Mine shaft June 1998 water quality parameters occurred with significantly higher total recoverable Al, As, Cu, Pb, and TSS compared to the Oro Mine shaft samples.

Results for the oxygen and hydrogen stable isotope results are presented in Table 7-12. In addition to the mine pool samples from the Oro and #3 mine shafts, isotope samples were collected from the soil boring (EXO-2) due south of the X10U8 mine waste tailings and from snow (FG-0) located approximately 3.5 miles up valley from the W-O site. It was originally planned to collect snow samples from the ridge above the Wellington workings and the X10U8 waste piles. Snow pack could not be found in this area during the June 1998 study. Therefore, snow was collected from a small snow pile protected by dense trees immediately adjacent to French Gulch Road in the upper portions of French Gulch valley. The high elevation snow pack was nearly melted out during the June 1998 study. Figure 7-15 is a plot of all the French Gulch isotope data since 1996 showing three groupings; snow melt, mine water, and French Creek/ground-water. The Oro and #3 mine shaft samples plot within the mine water group (Tables 7-7 and 7-12, Figures 7-15 and 7-16). The EXO-2 sample

plots predominantly in the French Creek/ground-water group while the FG-0 snow sample plots between the snowmelt and mine water groupings.

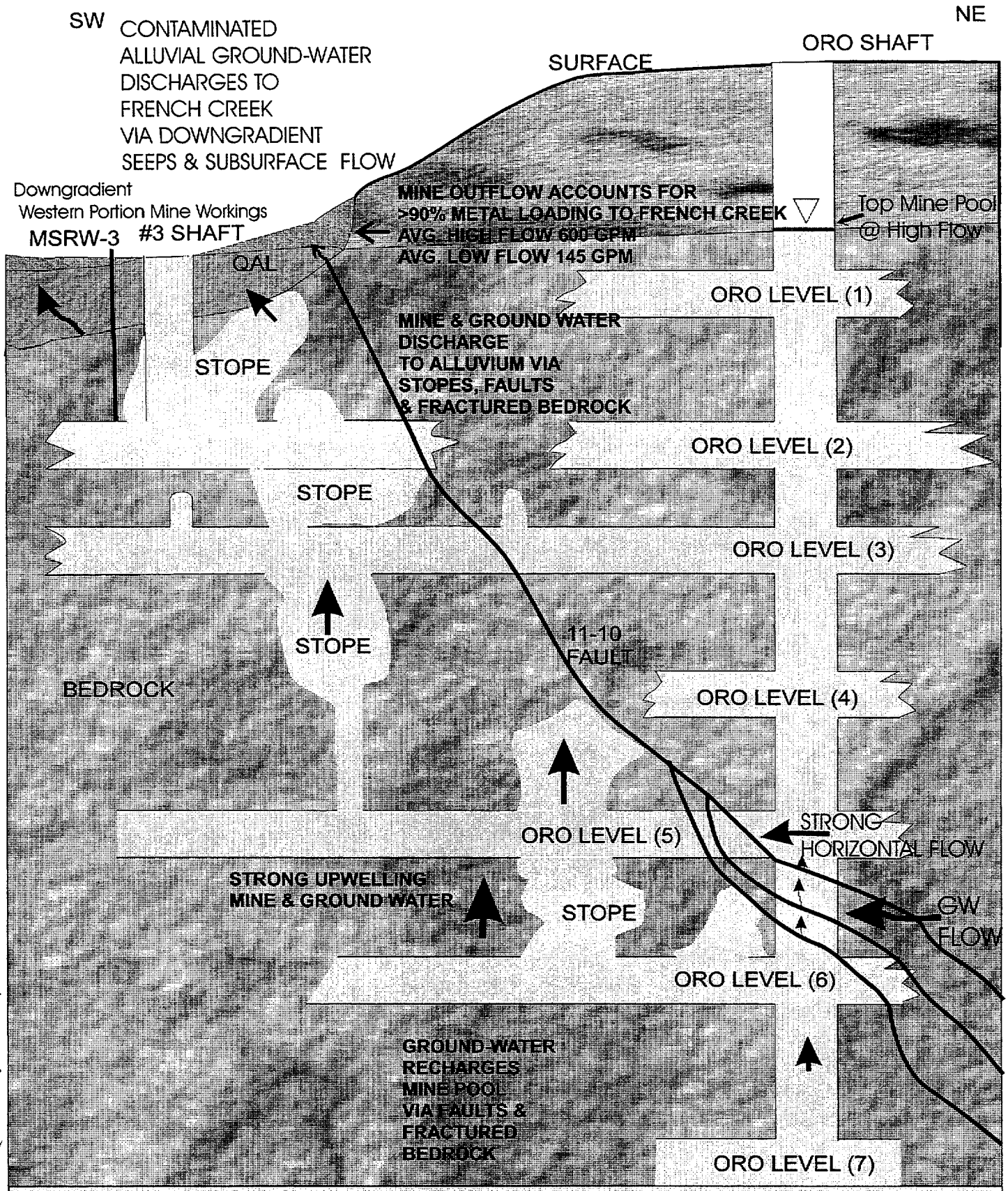
The three tritium samples from the Oro and #3 mine shafts had a limited range of values from 18 to 22 tritium units (Table 7-12). These results are within the error of +/- 3 TU for the analytical methods. The following section discusses the significance of the tritium data.

7.4 Discussion

The January 1997 results of the flow evaluation on selected metal contaminated monitoring wells in the vicinity of the Wellington-Oro Mine and Mill complex suggest that a significant portion of mine water discharge has been occurring within the fault block between the Bullhide and 11-10 faults (Figure 7-1). It has been inferred from flow data at MW-19 that the Bullhide Fault is a major conduit for mine water. The upward vertical flow in MW-19 was measured to be as high as 1.44 gpm or 0.003 cfs. This flow is very similar to the vertical upward flow measured below the 5th Level in the Oro Mine shaft in the June 1998 study. The upward vertical flow within the shale bedrock in MW-19 and MW-6 suggests that fractures may also be conduits for mine water. The downward flow from the base of the alluvium into the shale bedrock in MW-1 and the significant flow associated with the base of the alluvium in MW-19 and MW-4, has been interpreted to be due to mine water discharging directly into the base of the alluvium in the vicinity of the #3 Mine site. The pathway for this direct mine discharge to the alluvium could be from underground mine stoping up to the base of the alluvium and bedrock fault and fracture seepage into the base of the alluvium (Figure 7-12a).

The observed flow rates in the monitoring wells are a function of the hydraulic head differences between the mine pool, Bullhide Fault, fractured shale bedrock, and alluvium. The slightly lower measured flow rates in MW-19 during high flow conditions suggest that the increased mine discharge in the spring high flow is accommodated by an increase in discharge area and storage in the mine pool and not by increase flow rates within the mine discharge areas. For further explanation, see the previous discussion on the faulted and fractured bedrock buffering the mine outflow in section 6 of this report.

Limited evaluation of horizontal flow in the Oro Mine shaft 5th drift level showed flow in a westerly direction, up to 150 feet per day. Assuming a 5 feet by 7 feet drift, this flow velocity can approximate a discharge rate of 25 gallons per minute. According to Lovering (1934) mine maps, the 3rd and 5th Oro levels are the only drifts that pass through the Oro Mine shaft, the other drift levels either terminate into the shaft or connect the drift level to the shaft with a crosscut. Consequently, evaluation of horizontal flow for the other drift levels in the Oro Mine shaft may not be representative of their flow outside of the shaft.



SCHEMATIC MINE WATER OUTFLOW MODEL
WELLINGTON-ORO

DRAFTED BY AMERICAN GEOLOGICAL SERVICES, INC
AFTER LOVERING (1934)

NOT TO SCALE

FIGURE 7-12a

The Oro Mine shaft January 1997 low flow characterization study was conducted to a mine depth of 298 feet bgs. This depth was between the 3rd and 4th Oro levels and only represented the upper half of the shaft (Figure 7-2). The June 1998 high flow characterization covered the entire mine shaft that included the 1st through 7th Oro levels (Figure 7-12). Figure 7-17 is a plot comparing the January 1997 and June 1998 mine pool isotope data. The data suggest that the mine water shifted during the June 1998 high flow towards the relatively $\delta^{18}O$-rich Group #2 which is characteristic of regional bedrock ground-water, French Creek, and the alluvial ground-water (see section 5 of this report). Similar shifts during high flow conditions were observed in the 1996 and 1997 isotope data from the #3 mine pool and wells and seeps influenced by mine water discharge (Figures 7-18 and 7-19). These shifts would imply that direct infiltration of $\delta^{18}O$-poor snowmelt into the mine pool was not responsible for the spring recharge of the mine. One possible explanation for these shifts is that French Creek and/or the alluvial ground-water is responsible for the spring mine pool recharge. Individual discharge peaks on the French Creek hydrograph were not evident in mine pool elevation hydrographs. This would suggest that there are not direct pathways for French Creek and alluvial ground-water to recharge the mine pool. A second possible explanation for these shifts, which is supported by previously discussed characterization studies, is that spring snowmelt initially recharges the relatively $\delta^{18}O$-rich ground-water. The recharge results in a nearly instantaneous pressure response on the ground-water system and French Creek (see Brooks, 1998, Appendix 7-6). The ground-water pressure response from the snowmelt appears to be responsible for the high flow ground-water recharge of the mine pool and the initial increase in the $\delta^{18}O$ composition of the mine water. The low flow $\delta^{18}O$-poor mine waters may represent the time it requires for the previous season's high flow $\delta^{18}O$-poor snow melt influenced ground-water to physically reach the mine pool. This explanation would imply that there is ground-water baseflow into the mine during low flow conditions and the ground-water is very young in age. The tritium data suggest that the #3 and Oro Mine pool water can be bracketed in age between the early 1970's to present (pers. comm. B.M. Smith, Isotope Solutions, 1998).

Figure 7-20 is a plot of isotope data for all the snow samples since 1996. The snow samples were consistently $\delta^{18}O$-poor compared to mine, ground-water, and stream samples (Figure 7-15). March snow samples appear to be more $\delta^{18}O$-poor than spring snow pack sampled in May and June. Possible explanations for the seasonal difference are that spring snowstorms are from a different origin than winter storms and are associated with higher temperatures of precipitation. In addition, the spring snow pack may have been contaminated with rain events that tend to be $\delta^{18}O$-rich compared to snow events.

The January 1997 and June 1998 water quality from the upper Oro Mine pool appears to be different from the water in the #3 Mine shaft, especially the 1st Oro level. Figures 7-21, 7-22, and 7-23 are plots of selected total recoverable metal

concentrations (Zn, Cd, and Fe) from the four January 1997 sampled depths in the Oro Mine shaft, the #3 Mine Shaft relief well (MSRW-3), the downgradient mine seep (FG-6C), and monitoring well MW-3. Seep FG-6C and well MW-3 appears to be influenced by mine water discharge. The stable isotope data supports the mine water influence (Figures 7-10 and 7-11). Figures 7-24, 7-25, and 7-26 are plots of total recoverable Zn, Cd, and Fe concentrations for the five June 1998 sample depths in the Oro Mine shaft and the #3 Mine shaft. The following discussion compares the January 1997 and June 1998 selected metal results for the Oro shaft and the downgradient mine water.

The January 1997 Zn concentrations tended to be higher in the upper Oro Mine shaft than the downgradient mine waters and the #3 Mine concentrations in January 1997 (Figure 7-21). In contrast, the June 1998 Oro Mine shaft Zn concentrations were lower than the #3 Mine shaft concentrations (Figure 7-24). It appears that the June 1998 high Zn concentrations decreased in the Oro Mine shaft while the #3 Mine Zn concentrations increased relative to low flow conditions.

A comparison of Cd concentrations between high and low flow conditions showed an opposite trend than Zn concentrations. The 1st Oro level January 1997 Cd concentrations were more than double the downgradient mine water and the #3 Mine concentrations (Figure 7-22). The other January 1997 Oro depths Cd concentrations were similar to the downgradient mine water concentrations. With the exception of the 570 feet level, June 1998 Cd concentrations in the Oro Mine shaft were consistently higher than the #3 Mine shaft (Figure 7-25).

The January 1997 Fe concentrations in the Oro Mine shaft gradually increased from 125 mg/L at the 116 feet bgs 1st Oro level (ORO-116) to 153 mg/L between the 3rd and 4th Oro levels at 288 feet bgs (Figure 7-23). This increase in Fe concentrations with depth correlates to the fluid electrical conductivity (FEC) increase on the water quality log (Plate 2). The #3 Mine and the downgradient mine water Fe concentrations tended to be higher than the Oro Mine shaft concentrations (Figures 7-23 and 7-26). The June 1998 Fe concentrations also displayed a general increase with depth in the Oro Mine shaft (Figure 7-26).

Measured ferrous Fe concentrations of the mine pool waters were very similar to total recoverable Fe concentrations in the June 1998 study (Appendix 7-5). This suggests that the Oro and #3 Mine shafts mine pool waters were in a predominantly reducing environment. A plot of the Oro Mine shaft's ORP (Eh) and pH from COLOG's January 1997 and June 1998 water quality logs suggest that the mine pool is slightly reducing (Figure 7-27). Figure 7-28 is a more detailed Eh-pH plot of the Oro mine pool for the January 1997 and June 1998 studies. Generally, below the 116 feet depth the mine pool waters are nearly neutral and more reducing than the upper mine pool waters. The upper few feet of the mine pool in June 1998 (see Plate 3) was more acidic (pH 4.4) and less

reducing than the other samples. The top of the mine pool and the 186 feet depth showed the greatest variation between high and low flow conditions. The 186 feet level displayed a shift towards more oxidizing conditions during the June 1998 high flow study (Figure 7-28). It has been inferred from a Bureau of Mines (1971) report that the 186 drift level may have been developed with additional adits and stoping in the early 1970's via the Main Tunnel west of the Oro shaft. This area may be a significant ARD source.

A comparison of field (at surface) and in-situ (COLOG's water quality log) measurements of water quality parameters suggest significant chemical changes of the mine pool samples were taking place during the sampling process (Appendix 7-5). As a result, any inferences made from the laboratory analyses and bench scale testing of the mine waters are suspect because they may not represent in-situ conditions. Sample pH readings decrease significantly from near neutral in-situ conditions to a pH that ranges for surface readings from 5.5 to 6.3 s.u. and laboratory measurements from 4.2 to 5.8 s.u. Significant decreases in fluid electrical conductivity and alkalinity also occurred between in-situ conditions, surface readings, and laboratory measurements. There was also a consistent slight decrease in ferrous Fe concentrations between field and laboratory measurements. These changes suggest that chemical species were precipitating, oxidizing and producing acidic conditions during the sampling process. This may include precipitation of carbonate species, Fe and other metals, and oxidation of Fe and sulfur species to generate acid.

It was common that dissolved Zn and Mn concentrations were slightly higher than total recoverable metals (Tables 7-6 and 7-7). This could be due to two different sample preparation methods. "Dissolved Metals" are operationally defined as metals that pass through a 0.45 micron filter. "Total Recoverable Metals" means the concentration of metals in an unfiltered sample following digestion with hot mineral acid. Incomplete digestion and possibly precipitation of Zn and Mn species may be responsible for the lower total metal concentrations. The Zn metal ICP analysis of dissolved versus total recoverable may also be complicated by interference with Fe ICP peaks.

There is concern about the sampling of the #3 Mine shaft in the June 1998 study. The shaft was cased with 4" diameter PVC and grouted in 1992. The casing was open into the #3 Mine drift level at 110 feet bgs by injecting air into the casing while the grout was curing. During initial purging of the cased mineshaft in the June 1998 study using a pump rate of approximately three to five gallons per minute, the water level dropped a couple of feet and the submersible purge pump went dry. The pump was subsequently lowered and the purged mine water became highly turbid with abundant iron-rich appearing sediment. Purging proceeded for over one and a half-hours with an estimated volume of over 300 gallons and a reduction of most of the turbidity. Prior to sampling, the water level recovered to over a foot higher than prior to purging. This higher water level corresponded to the levels measured in the #3 Mine relief well. It was suspected

that the #3 Mine shaft was partially plugged prior to purging. The stress on the #3 Mine shaft well caused by the pumping apparently unplugged the shaft. It is believed that the unplugging resulted in large amounts of suspended clay which was reflected in the water analysis by high total suspended solids (TSS) and total recoverable aluminum (Table 7-7 and Appendix 7-5). A comparison with previous #3 Mine water analyses from the relief well MSRW-3 showed significantly higher total recoverable As, Cu, and Pb in the June 1998 samples. It is not known if these higher concentrations are related to the unplugging of the shaft.

The USGS salt tracer study in July of 1996 injected lithium chloride into the top of the Oro Mine pool. This injection increased the chloride concentration of the upper Oro Mine pool from approximately 2.5 mg/L prior to injection to over 60 mg/L after injection. The January 1997 Oro Mine shaft sampling showed the 1st Oro level to have a chloride concentration of nearly 7 mg/L, more than twice the natural background and the concentration at the 2nd and 3rd Oro levels (Figure 7-29). Lithium was never detected in the downgradient French Creek stream sampling locations, monitoring wells (MW-3), seeps (FG-6C), or mine water samples at MSRW-3 (Kimball et. al., 1997). The June 1998 study did not sample the top of the Oro Mine shaft. Consequently, it could not be determined if the Cl concentrations were still elevated. The elevated levels of tracer in the upper mineshaft months after injection further support the USGS conclusion that this area of the shaft was not communicating with the downgradient mine discharge areas (Kimball et. al., 1997).

The following information supports the conclusion that the upper Oro shaft mine water is poorly mixed with the W-O mine pool:

- elevated tracer concentrations at the 1st Oro level months after injection;
- the lack of lithium tracer in the downgradient monitoring sites and the #3 Mine;
- the lack of flow in the upper Oro Mine shaft; and
- the water quality contrast of the upper Oro Mine pool compared to the downgradient mine waters and #3 Mine pool water.

It was inferred in the salt tracer study and by the RAS study that the lower portions of the mine pool, below the 3rd Oro level, are the source of mine water discharging in the area of the #3 Mine shaft and the Bullhide and 11-10 fault block (Kimball et. al., 1997, and RAS, 1997a). Due to the complex chemistry of the mine pool and potential for significant mine water flow bypassing the Oro Mine shaft, it is presumptuous to infer that the lower portions of the Oro Mine shaft are the sole source of mine water in the #3 Mine shaft area. The June 1998 temperature log showed a significant decrease in temperature from the 186 feet 2nd Oro drift level to below the 348 feet 5th Oro Level (Figure 7-30). This would suggest flow in this area of the mine. The pathway for the mine water

could be stopes between mine levels and faults that cut the mine workings, many of which may bypass the Oro mineshaft (Figure 7-12a). The HPF evaluation suggests that mine water discharge at the Oro Mine shaft, the #3 Mine shaft, and the Bullhide 11-10 fault block was apparently driven by a strong upward vertical ground-water flow during both low flow conditions in January of 1997 and high flow in June of 1998. Significant horizontal flow is associated with at least the 5th Oro drift level.

The stable isotope data for the mill tailings well south of French Gulch Road suggest that W-O mine water is discharging into the mill tailings. The flow evaluation of selected monitoring wells also suggests that the flow pathway to the mill tailings has a strong vertical upward component. This pathway may include mine water flow through faults, fractured shale bedrock, and the alluvial aquifer before it discharges into the mill tailings. It is believed that most of the metal contamination in the mill tailing ground-water originated from the mine pool. Some of the contamination could be from leaching of the mill tailings. The significantly lower metal concentrations in this well compared to the mine water suggests that many of the metals have been attenuated and/or diluted along the flow pathway to the mill tailings.

The stable isotope data from soil boring EXO-2 suggest that the source of contaminated ground-water in the area south of the X10U8 tailings was not underground W-O mine water but leachate from the tailings. Water level monitoring of this area in 1998 showed that the shallow aquifer had its highest water levels in late April and early May, suggesting that this area is influenced by local snowmelt and may have a perched alluvial ground-water table. Development and fluid sampling of the soil borings in this area should be conducted during this time of season when there is sufficient fluid in the soil borings.

7.5 Conclusions

Flow evaluations of selected ground-water monitoring wells in the vicinity the Wellington-Oro Mine and Mill site suggest that a significant amount of metal contaminated mine water has been upwelling into the French Gulch valley from the Bullhide and 11-10 faults and their associated fault block. The direction of flow and the major fluid entry at the base of the alluvium in the monitoring wells implies that there has been direct mine water discharge into the alluvium, possibly from mine stopes and fault seepage. The results from the USGS tracer study, flow evaluation of the Oro Mine shaft, and water quality data suggest that the upper portions of the Oro Mine pool were not the main source of metal contaminated water observed at the #3 Mine or in downgradient seeps and monitoring wells. This study has inferred that the source of metal contaminated water, including the ground-water contamination associated with the mill tailings, could be from below the 2nd Oro drift level. The flow pathway for mine water to French Gulch is probably the mine stopes, faults, fractures in the shale bedrock,

and the shallow alluvial aquifer. There is the possibility of numerous areas in the mine where flow has been cutoff (i.e. the upper Oro mineshaft).

Considerable chemical changes occur in the mine waters during the sampling process. Any conclusions based on laboratory chemical analysis or "bench scale" testing of samples collected from the #3 Mine, Oro Mine shaft, or downgradient mine seeps have to be suspect because the samples may not represent in-situ conditions. Consequently, these samples may not be representative of the mine water in an ex-situ or in-situ treatment scenario. Flow pathways for mine waters and potential complex chemical processes in the mine pool are not fully understood. It appears that the mine waters are relatively young in age. The tritium data brackets the age of the mine water to be less than 25 years. Isotope and chemical data imply that the resonance time of the snow melt waters to reach the mine pool and solute transport out of the mine is possibly less than a year. This would suggest substantial annual flow in the mine pool. Significant horizontal flow of 150 feet per day was measured at the 5th Oro drift level and upflow was measured below the 5th level of nearly 5 feet per day in the June 1998 study. There is probably some retardation of solutes in the mine pool and along the ground-water pathways out of the mine pool. A substantial portion of mine water flow may be bypassing the Oro Mine shaft and discharging into the downgradient alluvium by way of faults, the fractured bedrock, and other mine workings (Figure 7-31).

The conclusions from the mine pool characterization studies are:

- direct infiltration or percolation of local snowmelt above the mine workings is not responsible for the spring recharge of the mine
- regional bedrock ground-water pressure response from the high elevation snowmelt drives the spring recharge of the mine
- mine water discharge is occurring between the Bullhide and 11-10 faults
- the faults are major conduits for mine water
- fractures in the bedrock can also transport mine water
- the mine pool waters are young in age
- the mine pool is predominantly in a reducing environment
- more oxidizing conditions and acid generation are occurring at the top of the mine pool while major flow is associated with the deeper levels
- more oxidation may be occurring at the 186 feet drift level during spring high flow(2nd Oro level), this maybe an area of significant ARD generation
- temperature data suggests that horizontal flow is occurring between the 2nd and 5th Oro drift levels
- significant horizontal flow at the 5th Oro level
- horizontal flow measurements within the Oro Mine shaft may not be representative of flow outside the shaft

- significant mine flow may be bypassing the Oro Mine shaft
- significant vertical upflow in the Oro Mine shaft occurs below the 5th Oro level
- mine water quality data may not be representative of in-situ conditions in the mine pool
- the upper portion of the Oro Mine shaft (above the 2nd Oro Level) has limited hydraulic connection to the mine discharge areas

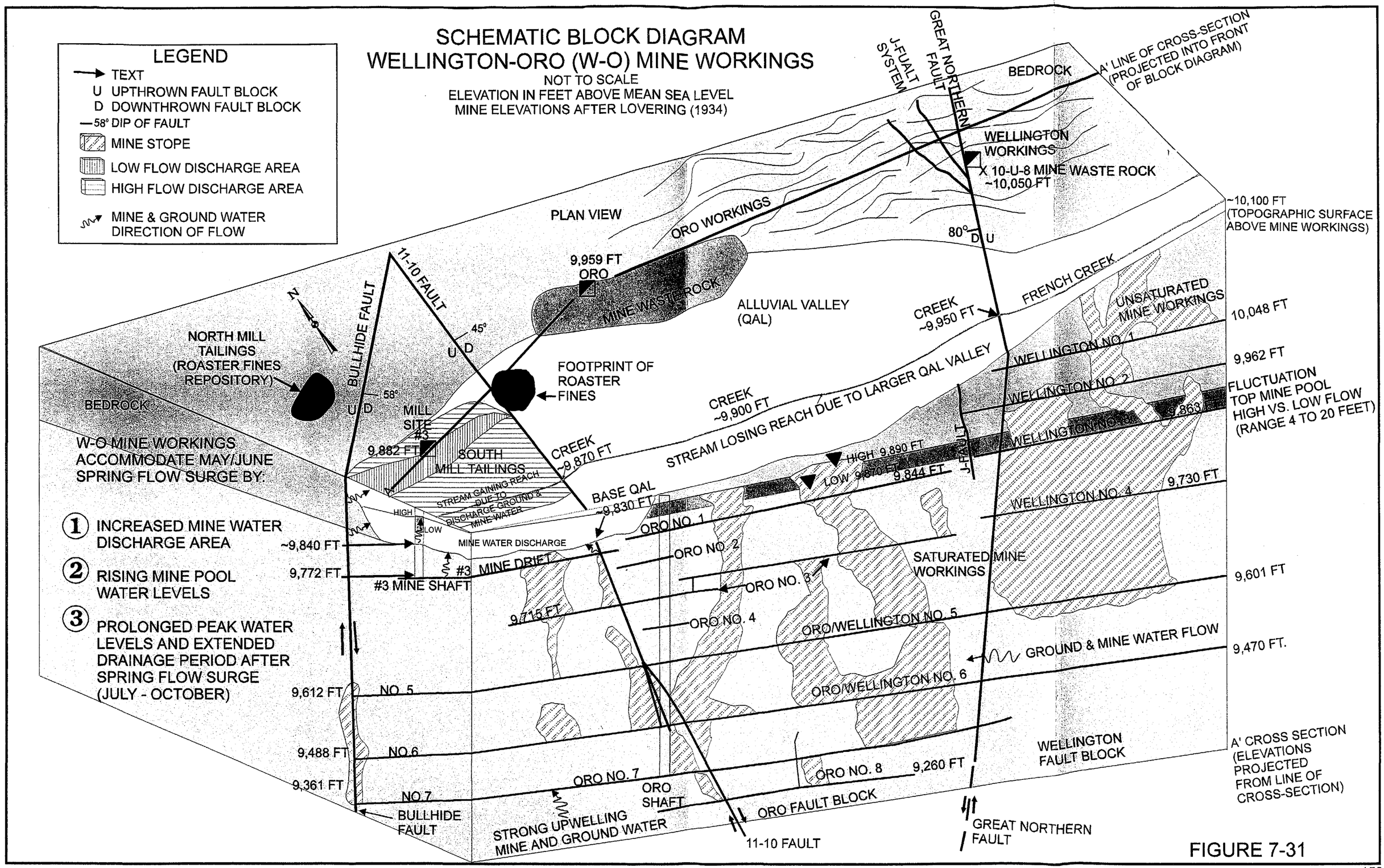

SCHEMATIC BLOCK DIAGRAM
WELLINGTON-ORO (W-O) MINE WORKINGS
NOT TO SCALE
ELEVATION IN FEET ABOVE MEAN SEA LEVEL
MINE ELEVATIONS AFTER LOVERING (1934)
LEGEND
TEXT
U UPTHROWN FAULT BLOCK
D DOWNTHROWN FAULT BLOCK
58° DIP OF FAULT
MINE STOPE
LOW FLOW DISCHARGE AREA
HIGH FLOW DISCHARGE AREA
MINE & GROUND WATER DIRECTION OF FLOW
PLAN VIEW
J-FUALT SYSTEM
GREAT NORTHERN FAULT
BEDROCK
A' LINE OF CROSS-SECTION (PROJECTED INTO FRONT OF BLOCK DIAGRAM)
WELLINGTON WORKINGS
X 10-U-8 MINE WASTE ROCK ~10,050 FT
~10,100 FT (TOPOGRAPHIC SURFACE ABOVE MINE WORKINGS)
ORO WORKINGS
80°
D U
9,959 FT ORO
MINE WASTE ROCK
ALLUVIAL VALLEY (QAL)
FRENCH CREEK
CREEK ~9,950 FT
UNSATURATED MINE WORKINGS
10,048 FT
11-10 FAULT
BULLHIDE FAULT
N
45°
U D
NORTH MILL TAILINGS (ROASTER FINES REPOSITORY)
FOOTPRINT OF ROASTER FINES
WELLINGTON NO. 1
9,962 FT
WELLINGTON NO. 2
FLUCTUATION TOP MINE POOL HIGH VS. LOW FLOW (RANGE 4 TO 20 FEET)
BEDROCK
58°
U D
MILL SITE #3
CREEK ~9,900 FT
STREAM LOSING REACH DUE TO LARGER QAL VALLEY
9,863
WELLINGTON NO. 3
W-O MINE WORKINGS ACCOMMODATE MAY/JUNE SPRING FLOW SURGE BY:
9,882 FT
SOUTH MILL TAILINGS
CREEK ~9,870 FT
HIGH 9,890 FT
LOW 9,870 FT
9,844 FT
J-FAULT
9,730 FT
WELLINGTON NO. 4
STREAM GAINING REACH DUE TO DISCHARGE GROUND & MINE WATER
BASE QAL ~9,830 FT
HIGH
LOW
MINE WATER DISCHARGE
ORO NO. 1
1 INCREASED MINE WATER DISCHARGE AREA
~9,840 FT
ORO NO. 2
2 RISING MINE POOL WATER LEVELS
9,772 FT
#3 MINE DRIFT
#3 MINE SHAFT
SATURATED MINE WORKINGS
ORO NO. 3
9,601 FT
9,715 FT
ORO NO. 4
3 PROLONGED PEAK WATER LEVELS AND EXTENDED DRAINAGE PERIOD AFTER SPRING FLOW SURGE (JULY - OCTOBER)
ORO/WELLINGTON NO. 5
GROUND & MINE WATER FLOW
9,470 FT.
9,612 FT
NO. 5
ORO/WELLINGTON NO. 6
9,488 FT
NO.6
WELLINGTON FAULT BLOCK
A' CROSS SECTION (ELEVATIONS PROJECTED FROM LINE OF CROSS-SECTION)
9,361 FT
ORO NO. 7
ORO SHAFT
ORO NO. 8
9,260 FT
NO.7
BULLHIDE FAULT
STRONG UPWELLING MINE AND GROUND WATER
ORO FAULT BLOCK
11-10 FAULT
GREAT NORTHERN FAULT

FIGURE 7-31

8.0 Surface Waste Characterization

8.1 Abstract

During 1996 and 1997, the U.S. Bureau of Reclamation and URS Operating Services Inc. performed investigations on the geology, mineralogy, and materials and metals testing of the waste spoils exposed at the surface in the vicinity of the Wellington-Oro Mine and Mill site. These studies were contracted by the U.S. Environmental Protection Agency Emergency Response Branch. The characterization included volumetric analysis of the spoil piles and particle size distributions, field X-ray fluorescence, X-ray diffraction, Total Characteristic Leaching Procedure, and laboratory measured total metals for the roaster fines, mill tailings, and waste rock. The results suggested that the roaster fines contain the highest metal concentrations while the waste rock at the Extentuate site has the lowest metal concentrations. Ground-water quality and saturated paste extract results suggested that the roaster fines have the highest metal leaching potential, orders of magnitude greater than the mill tailings and waste rock.

An U.S. Environmental Protection Agency Headwater Mining Waste Initiative Program grant funded a study to evaluate surface waste remediation alternatives at the Wellington-Oro site. This study included estimates of potential metal loading to French Creek from the Wellington-Oro mine pool, the Country Boy mine pool, and from the roaster fines, mill tailings and waste rock at the Wellington-Oro site. Based on the estimated metal loading, it can be inferred that the Wellington-Oro mine pool has been contributing over 90% of the metals to French Creek. The combined estimated metal loading potential from the various sources at the Wellington-Oro site were significantly greater than the observed metal loading in French Creek downstream from the mine site. It has been suggested that the difference in metal loading from various sources and the observed loading in French Creek were due to:

1. *attenuation of the contaminants by geochemical processes along the transport pathways to French Creek,*
2. *substantial metal transport associated with ground-water flow in the alluvium and placer dredge piles, and*
3. *transient storage in the stream gravels downgradient from the mine site.*

8.2 Introduction

There were four investigations conducted in the vicinity of the Wellington-Oro (W-O) Mine and Mill complex during 1996 and 1997 that addressed surface mine wastes. These investigations included two studies on the geology, mineralogy, and materials and metals testing of the mine waste, roaster fines, and mill tailings (U.S. Bureau of Reclamation, 1997a and URS Operating Services Inc., 1997). The U.S. Bureau of Reclamation (BOR) also performed a cost study for various surface waste cleanup options (BOR, 1997b). The BOR and URS Operating Services (UOS) studies were contracted by the U.S. Environmental Protection Agency (EPA) Emergency Response Branch. The fourth study was funded by an EPA Rocky Mountain Headwater Mining Waste Initiative program grant to the Northwest Colorado Council of Governments (Richard, 1997). This study evaluated the proposed surface waste remediation alternatives from the BOR cost study based on criteria approved by the French Gulch Remediation Opportunities Group (FROG). The criteria included; the degree of reduction in metal loading in French Creek and the Blue River, impacts to historical mining structures and features, non-water related exposure risks, and cost effectiveness. This review of the above mentioned surface waste characterization investigations only involved surface and ground water hydrogeologic implications on metal loading. Please refer to the individual reports for other aspects of these studies.

8.3 Summary of Surface Waste Characterization Studies

8.3.1 Introduction

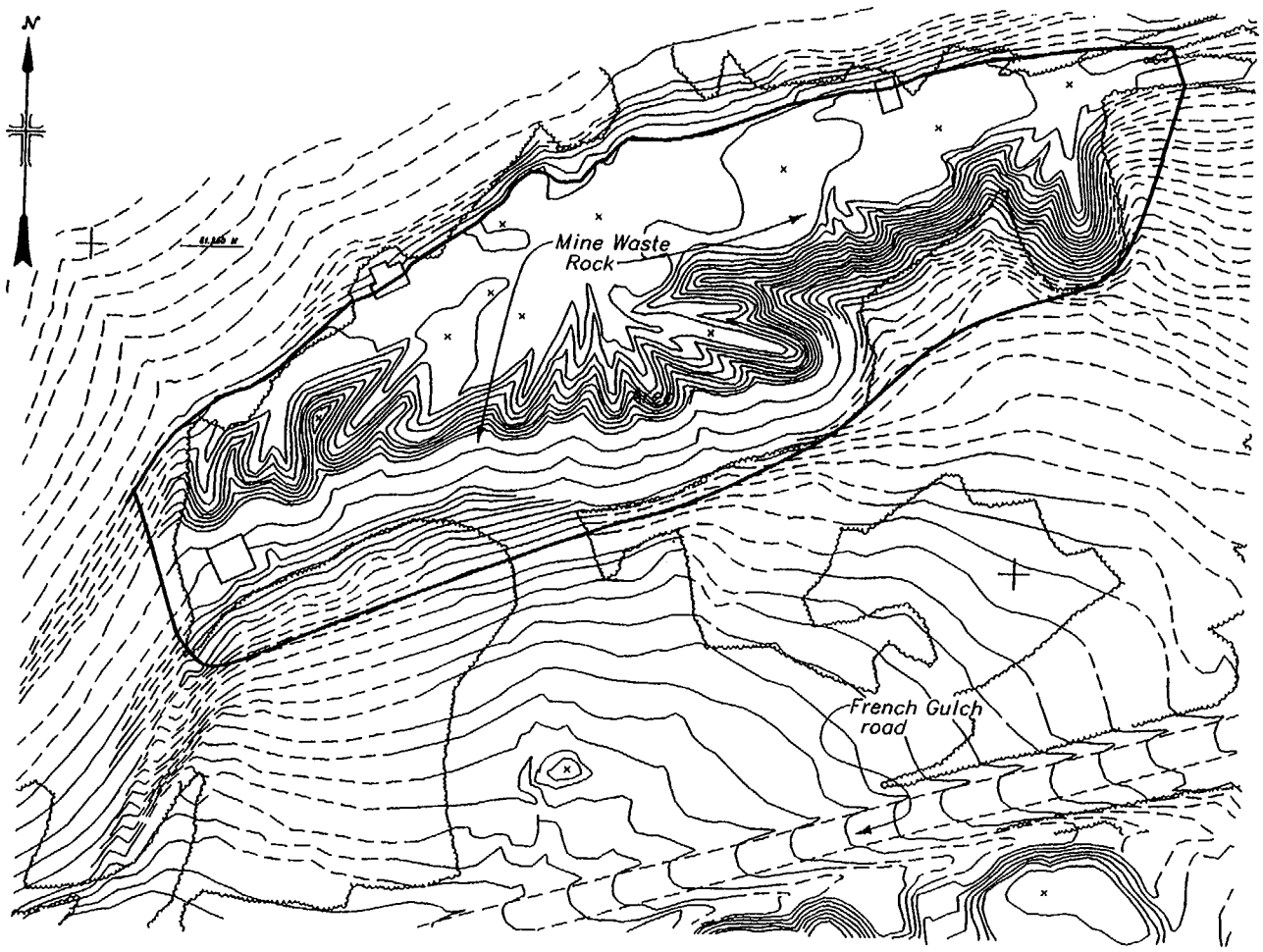
The surface spoils of concern in the characterization studies were the roaster fines, mill tailings and waste rock piles in the vicinity of the W-O site (Figure 8-1) and mine waste rock at the X.10.U.8 (Extenuate) portal (Figure 8-2). The Union mill tailings west of the W-O site were also characterized, but are believed to be a minor source of metal loading to French Creek and the Blue River. The Extenuate area is approximately one quarter of a mile east of the W-O site. The BOR drilled ground-water-monitoring wells in the north and south mill tailings area and the roaster fines in 1996 (BOR, 1997a). The BOR and UOS studies also collected surface and soil boring samples from the spoil piles (BOR, 1997a and UOS, 1997). Materials volumes were estimated by the BOR to be 43,000 cubic yards of roaster fines, 13,000 cubic yards of north mill tailings and 42,000 cubic yards of south mill tailings (BOR, 1997b). The volume of waste rock is unknown. The fall of 1998 roaster fines characterization study by Adrian Brown Consultants, Inc. and clean-up work on the roaster fines suggested that the original BOR volume estimates were too high. Approximately 6,000 cubic yards of roaster fines were removed during surface clean-up (L.F. Brown, 1998). An unknown quantity of roaster fines may be buried under the waste rock at the W-O site. The total metals content, particle size, mineralogy and degree of saturation

Surface Waste Wellington - Oro Mine and Mill Site

From USBR, 1997b

Figure 8-1

Surface Waste X.10.U.8 (Extenuate) Portal Site



1 inch = 77 feet

From USBR, 1997b

Figure 8-2

vary within the different surface spoils. These factors affect the surface spoils metal leaching potential (BOR, 1997b).

8.3.2 Analysis of Surface Spoil Materials

The analysis 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 for the different spoil materials were also available from the State of Colorado Division of Minerals and Geology (DMG, 1994). Mill tailings, roaster fines, and waste rock all had elevated levels of Pb, Zn, and other metals compared to background samples. In general, total Fe concentrations were highest in the roaster fines and mill tailings, up to 20 percent. Total Pb concentrations were highest in the waste rock and mill tailings, up to 2 percent. Zn concentrations for the spoil materials ranged from one to several thousand parts per million (ppm). One roaster fines sample had up to 2% total Zn. Cd concentrations ranged from a few ppm to over 1,000 ppm for a roaster fines sample. Mn concentrations for the spoil materials ranged from less than 1,000 ppm to thousands of ppm. The average metals concentrations were highest in the roaster fines. Cd, Fe, and Zn concentrations in the roaster fines were approximately twice the average mill tailing concentrations (Figure 8-3). The Cd, Fe, and Zn roaster fines concentrations were nearly four times the concentrations observed in the Wellington Mine waste material. The Extenuate mine waste material had the lowest Cd, Fe, Mn, and Zn average metal concentrations (Figure 8-3). The highest metal concentrations within the roaster fines and mill tailings piles appeared to be immediately above the ground-water table (Figures 8-4 and 8-5).

The processed material (roaster fines and mill tailings) had smaller grain sizes and better sorting than the mine waste material. Most of the roaster fines and mill tailings samples were classified as silty sands (BOR, 1997a). There was some gravel material described in the roaster fines and mill tailings, although the gravels may be related to the alluvial valley and placer material. The median grain size for the roaster fines and mill tailings varied from less than 0.075 to 0.33 millimeters (mm). The waste rock from the Wellington and Extenuate areas was very poorly sorted in grain sizes. The grain classification of these materials was mostly clayey gravels with abundant silt and sand. Grain sizes ranged from 0.037 to 16.719 mm.

The mill tailings and roasters fines were processed by-products of the W-O mill. This processing included grinding the ore material to fine grain sizes. The roaster fines were subjected to heat under oxidizing conditions to decrease the sulfur content for easier smelting. The roasting process should produce raw metals, metal oxides, and sulfate mineral assemblages (UOS, 1997). The XRD data suggests that the roaster fines and mill tailings contain Fe, Pb and Zn sulfate minerals (jarosite, angelsite, and $ZnSO_4$), metal oxides (hematite), and

metal hydroxides (goethite). Although, sulfur forms analysis conducted for the BOR by Barringer Laboratories (1996) indicated that most of the sulfur in the roaster fines was in the sulfide form (i.e. pyrite), which implies that the roasting process was not complete. The waste rock apparently also has Fe, Pb and Zn in sulfide mineral assemblages (pyrite, galena and sphalerite). The XRD results showed that the waste rock and mill tailings had significant amounts of illite/mica and kaolinite clays.

TCLP is an aggressive leaching test that uses acid. Because of the aggressive nature of this test, leaching results are probably higher than one would expect under site conditions (UOS, 1997). The TCLP indicated that Zn was more leachable in the processed material than in the waste rock. This may be due to Zn being in the sulfate form (UOS, 1997). Leachable Zn for the spoil materials ranged from 1,560 mg/L to 9.25 mg/L. Pb appears to be more leachable in the waste rock compared to the roaster fines and mill tailings. This may be due to the lead sulfate forms (jarosite and angelsite) in the processed material being less soluble than the sulfide forms associated with the waste rock (UOS, 1997). The levels of Pb in the TCLP leachate ranged from 53.2 mg/L to 4.08 mg/L. Except for a shale waste rock sample, all samples exceeded the TCLP standard for Pb (UOS, 1997). The TCLP results did not indicate significant overall metal leaching potential differences or trends between the roaster fines, mill tailings or waste rock (Table 8-1).

The saturated paste extract method uses a less aggressive leaching procedure than TCLP. This method is based on a 24-hour leach test using water. Saturated paste extract results also showed the spoil materials to be highly leachable with Pb levels as high as 0.72 mg/L, Zn as high as 235 mg/L, and Cd as high as 9.73 mg/L (Table 8-2). In contrast to the TCLP results, the paste extract results for the roaster fines showed Fe, Pb, Zn, and Cd leachate levels to be orders of magnitude greater than the mill tailings and waste rock.

The observed ground-water metal concentrations were highest in the saturated portion of the roaster fines, by orders of magnitude compared to the mill tailings (Figure 8-6). There were no ground-water wells in the waste rock to determine its associated ground-water quality. A seep during high flow conditions was sampled at the base of the main waste pile (WP-1) near the roaster fines in 1996(EPA, 1996a). The Zn and Cd concentrations of this seep were very similar to the roaster fines ground-water (Figure 8-6). The Pb and Mn concentrations of the seep were significantly higher while Fe concentrations were lower than the roaster fines ground-water. The TCLP results indicated that Pb might be more leachable in the waste rock, which may explain the higher Pb concentrations. The similarity in overall water quality, especially Cd and Zn concentrations, suggest that this seep may be a mixture of roaster fines and waste rock leachate. The saturated paste extract results suggested that the roaster fines metal leachable potentials are orders of magnitude greater than the waste rock (Table

Table 8-1

Surface Spoils
Total Metals and TCLP Results for Cadmium, Lead, and Zinc
from BOR (1997a) and UOS (1997)

Sample	Description	Cadmium		Lead		Zinc	
concentration		Total (ppm)	TCLP (mg/L)	Total (ppm)	TCLP (mg/L)	Total (ppm)	TCLP (mg/L)
WOWR01	Roaster Fines	3.7	0.82	30500.0	11.40	2070.0	16.60
WOOPO6	gray waste west roaster fines	1470.0	7.41	72700.0	43.30	304000.0	1,560
WOOP06	green waste northeast portion roaster fines	3.1	0.07	24100.0	25.60	1760.0	9.25
WOOP10A	Mill Tailings	11.5	0.29	25000.0	21.30	5520.0	45.10
WODD03	Mill Tailings	70.6	1.02	3360.0	29.50	12500.0	128.00
WOWTL02	Waste Rock	78.0	0.39	7230.0	32.10	14700.0	59.20
WOWTL04	Waste Rock	85.5	0.48	10900.0	42.7	17600.0	83.90
WOWWR01	sand waste in Waste Rock	187.0	0.81	10600.0	53.2	34300.0	145.00
WOWWR03	shale in Waste Rock	79.0	0.29	2930.0	4.08	14300.0	26.70

TCLP Maximum Regulatory Levels: Cd (1.0 mg/L); Pb (5.0 mg/L); and Zn (no limit)

8-2). Accordingly, the major contributor to this contaminated seep water appears to be leachate from the roaster fines.

The total metal concentrations and TCLP results did not display the orders of magnitude differences between the roaster fines and mill tailings as observed in their associated ground-water quality. As previously mentioned, the saturated paste extracts did display the orders of magnitude difference in leachate metal concentrations between the roaster fines and the other spoils. A possible explanation for the differences in ground-water quality is that the roaster fines have greater leachable metals due to its acid generation potential, greater leachable sulfur forms, mineralogy, and physical characteristics. The limited sampling and analysis associated with the BOR and UOS surface waste studies were not able to characterize the differences between the roaster fines and mill tailings. Whereas the saturated paste extract results did suggest a greater leaching potential associated with the roaster fines.

Table 8-2

Surface Spoils
Saturated Paste Extract Results
for Cadmium, Lead, Manganese , Iron and Zinc
from DMG (1994)

Sample	Description	Cd (mg/L)	Pb (mg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)
RF-1-2	Roaster Fines	2.30	0.22	142.34	15.55	192.34
RF-3-2	Roaster Fines	9.73	0.61	582.45	14.34	711.32
RF-3-3	Roaster Fines	2.63	0.24	157.11	21.93	235.07
RF-3-4	Roaster Fines	2.69	0.33	241.85	14.36	171.74
RF-4-2	Roaster Fines	0.24	0.72	712.22	10.60	198.97
RF-5-2	Roaster Fines	0.59	0.49	553.36	3.56	85.78
RF-4-1	Roaster Fines	2.75	0.32	293.75	3.95	145.53
MW-1-1	Mill Tailings	0.19	0.58	828.60	1.34	9.41
MW-1-4	Mill Tailings	0.11	0.14	2.41	7.65	13.26
MW-3-2	Mill Tailings	<0.01	<0.05	0.03	0.26	0.03
MW-3-3	Mill Tailings	<0.01	<0.05	0.04	0.03	0.04
MW-2-2	Mill Tailings	0.12	0.38	388.56	7.49	7.51
MW-2-4	Mill Tailings	0.17	<0.05	0.08	7.13	11.01
MW-1-3	Mill Tailings	0.05	0.07	54.71	1.72	5.68
DP-1-1	Waste Rock	0.06	0.08	0.05	1.75	1.66
DP-1-2	Waste Rock	0.03	0.15	16.51	23.26	22.86
DP-1-3	Waste Rock	0.15	0.12	0.32	15.99	10.67
DP-1-4	Waste Rock	0.02	0.07	0.07	12.37	10.09

A possible contributing factor for the higher roaster fines ground-water metal contamination compared to the mill tailings is annual water table fluctuations (Table 8-3). The water table variation between low flow and high flow conditions for the roaster fines ranged from approximately 4.5 feet to over 6 feet. It is possible that the roaster fines near the 11-10 Fault had annual water fluctuations as high as 20 feet. Water level monitoring suggested that the ground-water table in the roaster fines area may have been perched above the original ground surface and the alluvial material (see section 6 of this report for further discussion). In contrast, ground-water monitoring wells in the vicinity of the south mill tailings showed yearly fluctuations from less than 2 feet to approximately 4.5 feet. The recent BOR north mill tailing ground-water wells were dry during both low and high flow conditions. The larger water level fluctuations in the roaster fines may result in greater oxidation and acid generation. The acid generation was evident by field measured pH that ranged from 2.2 to 4.12 standard units (s.u.) in the roaster fines ground-water. In contrast, the recent BOR south mill tailings ground-water monitoring well (WTL02) had field measured pH that ranged from 6.44 to 6.59 s.u.. The much higher metal concentrations in the TCLP leachate compared to the paste extract results was an example of how much additional leaching potential results from acidic waters (Tables 8-1 and 8-

Table 8-3

Water Level Fluctuations for Roaster Fines and South Mill Tailings Areas

Monitoring Well	Type	Water Elevation (ft)	Annual Fluctuation (ft)
MW-13	Shale Bedrock & 11-10 Fault Monitoring Well in Roaster Fines		
	High Flow 5/97	9889.58	18.85
	Low Flow 3/97	9870.73	
SBRF-3	Roaster Fines Soil Boring		
	High Flow 5/97	9881.62	4.56
	Low Flow 3.97	9877.06	
WRO-1	Roaster Fines Monitoring Well		
	High Flow 5/97	9883.03	>5.81
	Low Flow 3/97	<9877.22	
WTL-02	South Mill Tailings Monitoring Well		
	High Flow 5/97	9857.95	4.3
	Low Flow 3/97	9853.65	
MW-3	Alluvial Monitoring Well in South Mill Tailings		
	High Flow 5/97	9847.26	1.8
	Low Flow 3/97	9845.46	
	High Flow 6/96	9847.46	2.19
	Low Flow 3/96	9845.27	

2). Another contributing factor for lower metal concentrations in the mill tailings ground-water are clays that may be scavenging metals, possibly by adsorption and other geochemical processes.

8.3.3 Metal Loading from Surface Spoils

The Richard (1997) study modeled potential metal loading from the W-O mine pool and surface wastes. The surface waste evaluation included loading associated with ground-water flow and surface runoff. The surface loading was based on the assumption that most metals were transported to French Creek as metals adsorbed to sediment particles. Thus, the surface runoff metal loading estimates were based on sediment yield or soil loss approximations using the Universal Soil Loss Equation (USLE). The USLE method incorporates climatic, soil characteristic (physical and chemical), vegetation, and topographic data. Soil and topographic characteristics of the surface wastes were inferred from BOR (1997a) data. Metal loading estimates were determined by multiplying sediment yield approximations by the average content of metals in the surface waste. The metal content data were also derived from the BOR (1997a) study. The results of metal loading associated with surface runoff have been summarized in Table 8-4. Metal loading from runoff associated with the mine waste was not possible using the USLE method because of its median gravel grain size. The USLE method is only applicable up to a median sand size.

Table 8-4

Potential Metal Loading from Surface Runoff based on Soil Loss Estimations (Richard, 1997)

Surface Spoil	Cd (kg/yr)	Fe (kg/yr)	Mn (kg/yr)	Zn (kg/yr)
Roaster Fines	3 - 8	676 - 1,777	13 - 35	648 - 1,703
Mill Tailings	1	1,459	62	115

Estimating surface runoff metal loading from the dissolved phase was not possible because of the lack of water quality data of runoff during storm events. TCLP or saturated paste extracts results were not used in the Richard (1997) study to estimate metal loading associated with the dissolved phase of surface runoff. A rough estimate by AGS of metal loading associated with the dissolved phase in the surface runoff was made based on the saturated paste extract results and the Dillon weather station climatic data. This analysis suggested a similar magnitude of metal loading from the dissolved phase versus the USLE calculation.

Metal loading estimates associated with the mine pool and surface waste piles ground-water flow were calculated by multiplying the metal content of the associated ground or mine water by estimated discharge rates (Richard, 1997). The metal content data of the ground-water associated with the roaster fines, south mill tailings, and the mine pool water were based on numerous water quality studies (CDPHE, 1989;. EPA, 1992, 1993a, 1993b, 1994, 1996a and 1996b; NAWQA, 1997a; and RAS, 1996a, 1996b, 1997a and 1997b). The metal content of the ground-water associated with the mine waste was inferred from the water quality of a seep at the base of the main waste pile (WP-1). As previously discussed, it is possible that the major contributor to this seep was leachate from the roaster fines. Consequently, the ground-water metal loading analysis of the mine waste rock is suspect.

The ground-water discharge rates for the surface spoils were derived from estimates of fluid hydraulic conductivity, cross sectional area, and hydraulic gradients of the individual surface waste piles using Darcy's ground-water flow equation (Darcy, 1856). The fluid hydraulic conductivity for the individual waste piles were made by Tom Brown (BOR) based on grain size distribution from the BOR (1997a) study. The BOR (1997b) performed volume estimates for the waste piles based on data the BOR and DMG collected. The Richard (1997) study determined cross sectional areas of the individual waste piles from BOR (1997b) cross sectional profiles of the waste piles, DMG and BOR surface mapping (BOR, 1997a), and AGS supplied estimated average saturated thickness based on historic water levels from nearby monitoring wells. AGS also

Table 8-5

Potential Metal Loading from Surface Spoils Ground-water Discharge (Richard, 1997)

Surface Spoil	Cd (kg/yr)	Fe (kg/yr)	Mn (kg/yr)	Zn (kg/yr)
Mine Waste*	71	2,629	4,007	11,104
Roaster Fines	31.9	9,752	554.5	6,889
Mill Tailings	0.1	2.1	1.1	3.75

* results suspect due to unknown source of seep used for mine waste ground-water quality

provided estimates of the hydraulic gradients from the historic water levels of monitoring wells. Table 8-5 summarizes the metal loading associated with ground-water discharge for surface spoils. The original spoil pile volumes applied in the Richard (1997) study, specifically the roaster fines, may have been too high (L.F. Brown, 1998). Consequently, the roaster fines results presented in Table 8-5 may also be several orders of magnitude too high.

8.3.4 Wellington-Oro Mine Discharge Model

The W-O mine pool discharge rates were originally calculated by extrapolating observed mine water discharge rates associated with the 11-10 and Bullhide faults and quantifying mine discharge from observed head differences in the alluvium in the vicinity of the #3 Mine Shaft and the Bullhide Fault. Fault seepage was quantified from data presented in the stream tracer and borehole flowmeter studies (Kimball and others, 1997 and RAS, 1997a). Based on this analysis, AGS supplied the Richard (1997) study with mine discharge rates of 1.5 cfs (670 gpm) for low flow conditions and 3.5 cfs (1570 gpm) for high flow conditions.

Since the original mine discharge estimates, AGS modified the method by generating a range of possible mine discharge. Appendix 8-5 summarizes the calculations and assumptions for the modified mine discharge model based on observed ground-water flow rates and discharge areas in the vicinity of the W-O mine site. This analysis resulted in a low flow range of mine discharge of 0.94 cfs (420 gpm) to 1.5 cfs (655 gpm) and a high flow range from 1.8 cfs (800 gpm) to 3.2 cfs (1,440 gpm).

The original and modified mine discharge model based on extrapolating observed fault and ground-water flow rates contains numerous assumptions and may not be representative of average precipitation years. Flow measurements

were conducted during two consecutive above average snow seasons (1995-1996 and 1996-1997), possibly as much as 150% to 200% above average. The spring mine flow surge during these seasons had associated water level rises of approximately 14 feet and 20 feet, respectively. Ground-water monitoring wells in the vicinity of the #3 Mine site went artesian during the spring flow surge in 1996 and 1997. In contrast, the 1997-1998 snow season was nearly 90% of normal (Brooks, 1998) and the corresponding mine pool water level rise was only 4 feet. None of the monitoring wells flowed to the surface in the spring of 1998.

Ground-water baseflow and spring high flow conditions may have been significantly influenced by the above average snow years. The July 1997 stream salt tracer study observed mine water discharge via faults as they crossed French Creek (Kimball and others, 1997). AGS applied this observation in the mine discharge models to extrapolate high flow mine discharge areas (Appendix 8-5). The discharge areas and ground-water flow rates used in the mine discharge flow models may not be typical for normal snow years. As a result, the original and modified estimates of mine discharge rates might only represent conditions for significantly above normal snow seasons.

AGS has produced sulfate chemical mass balance flow models to independently derive mine discharge rates. It is believed that sulfate is the most conservative chemical constituent in the geochemical system and may better represent average seasonal fluctuations of mine discharge. The mass balance approach is based on modeling the surface and ground-water sulfate flux at stream station FG-9 (USGS gage before French Creek enters the Blue River), estimating sulfate sources, and back calculating associated sulfate production and discharge from the W-O underground mine complex.

A series of spreadsheet models were developed that incorporated a range of ground-water discharge rates, streambed transient flow, stream flow and sulfate concentration data (Appendix 8-6). In the stream salt tracer study discussed in section 4 of this report transient flow was shown to be as high as 30% of measured stream flow (Kimball et. al., 1997). Surface water quality and flow data was readily available from CDPHE (1989), the EPA (1992, 1993a, 1993b, 1994, 1996a, and 1996b), the USGS NAWQA (1997a), and the USGS gage station (1996 and 1997) at the FG-9 stream site. Ground-water flow and associated flux at FG-9 had to be modeled.

The ground-water sulfate concentration was assumed to be similar to the surface water concentration because studies indicated that stream flow is dominated by ground-water. The ground-water discharge rates had to be estimated based on Darcy's flow equation. The variables for this equation are hydraulic gradient (I), discharge area (A), and the hydraulic conductivity (K). The area and hydraulic gradient can be derived from observations of ground-water levels and known dimensions of the alluvial valley. The horizontal hydraulic conductivity for the alluvial valley material has been calculated from pumping tests (Morrissey, 1995)

and alluvial ground-water flow measurements. The hydraulic conductivity derived from pumping tests ranged from 0.002 cm/sec to 0.029 cm/sec with an average of 0.011 cm/sec. The low conductivity value of 0.002 cm/sec was calculated from drawdown data associated with the pumping well while the higher values were from observation well data. Morrissey (1995) stated that the observation well data with the higher hydraulic conductivity values were probably more representative of the alluvial material. The observation wells were located in undisturbed alluvial material in the vicinity of the #3 Mine (Figure 8-7).

In June 1998, a colloidal borescope was used to measure ground-water horizontal flow in the alluvial monitoring well MW-3. This well is located in the placer dredge tailings area (Figure 8-7). This technique measured a preferential high flow zone of 460 feet/day. This seepage velocity would correspond to a hydraulic conductivity of 0.162 cm/day. According to the developers of the colloidal borescope, a correction factor of as high as four for highly heterogeneous aquifers should be used to determine average seepage velocities. Using a correction factor of four to reduce ground-water velocity to an

Table 8-6

French Gulch Alluvial Hydraulic Conductivities and Associated Discharge

Hydraulic Conductivity (K) (cm/sec)	Hydraulic Conductivity (K) (ft/sec)	Hydraulic Gradient[1] (i)	Discharge Area[2] (A) (ft^2)	Ground-water Discharge[3] (Q) (ft^3/sec)	Associated Unconsolidated Sediments[4]
0.002	0.000076	0.03	40,000	0.09	Silty sands, fine sands, well-sorted sands, glacial outwash
0.011	0.00036	0.03	40,000	0.43	Well-sorted sands, glacial outwash, well-sorted gravel
0.029	0.00095	0.03	40,000	1.14	Well-sorted sands, glacial outwash, well-sorted gravel
0.041	0.0013	0.03	40,000	1.56	Well-sorted sands, glacial outwash, well-sorted gravel
0.162	0.0053	0.03	40,000	6.36	well-sorted gravel

[1] Observed gradient between alluvial ground-water wells MW-3 and MW-7 (AGS, 1998a).
[2] Volume based on an average width of 1000 feet and saturated thickness of 40 feet for the alluvial valley.
[3] Calculation based on Darcey's Flow equation Q = -K A i.
[4] Fetter (1988).

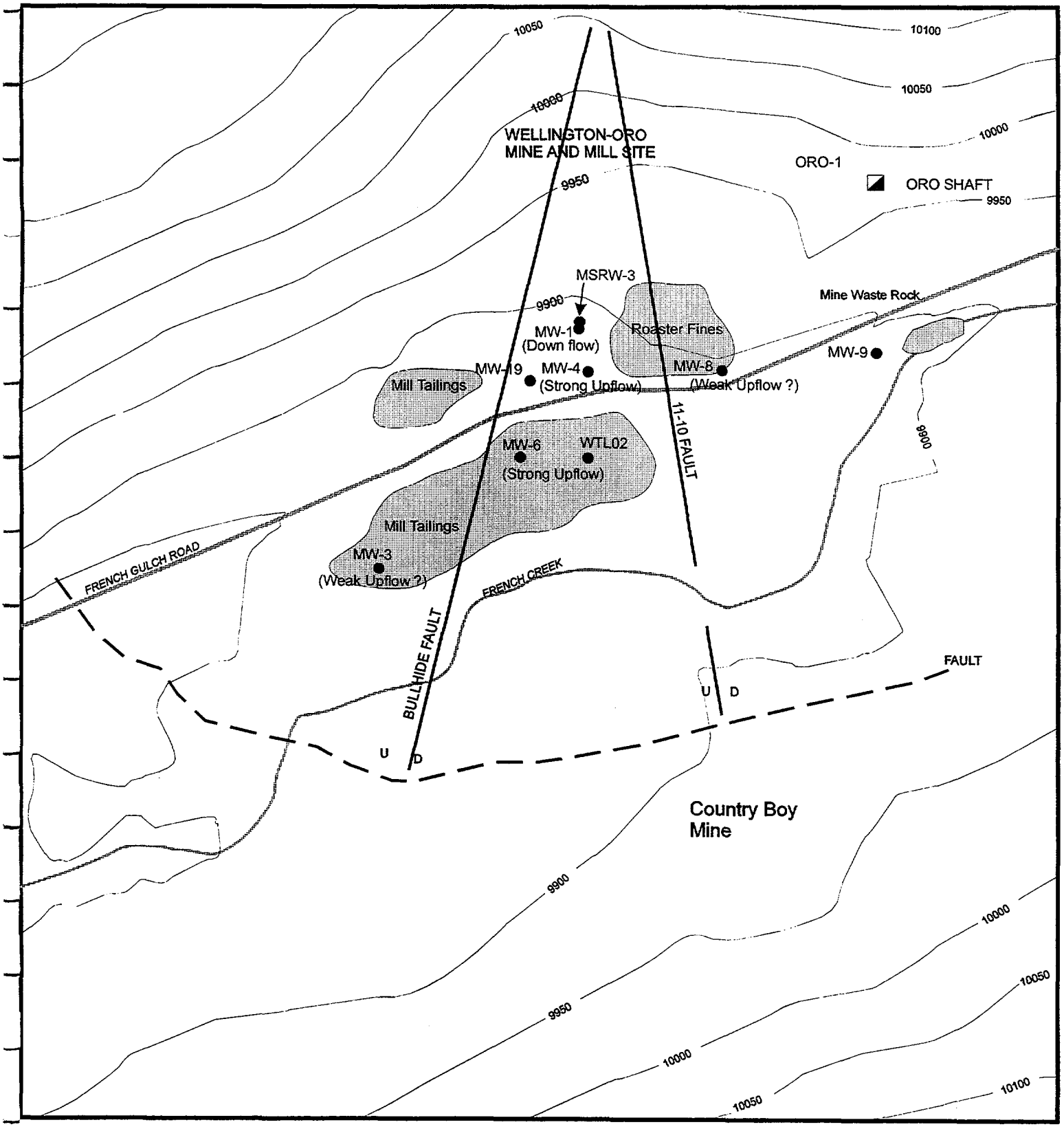
average seepage velocity of 115 feet/day, the associated average hydraulic conductivity for the alluvial valley material would be 0.041 cm/sec.

Table 8-6 summarizes the limits of alluvial ground-water discharge that is associated with the range of calculated hydraulic conductivity for the alluvial valley material. The spreadsheet sulfate flow models incorporated a range of potential ground-water discharge from 0.1 cfs to 6 cfs and transient flow from 10% to 30% of measured stream flow (Appendix 8-6). The sulfate mass flux models assumed that the W-O mine pool contributed over 90% of the total flux to French Gulch, similar to what has been estimated for the mine pool's metal contribution (see section 8.3.5). This assumption was based on sulfate and metal flux from the W-O mine pool being coupled. A review of sulfate ground and surface water background concentrations suggests that the mine pool sulfate flux may not be coupled with metal fluxes and is less than 90% of the total French Gulch production.

A probable ground-water model was integrated into a most likely sulfate mass flux and mine flow model (Appendix 8-6). The probable ground-water model used a ground-water discharge of 5 cfs and a transient flow of 20% of measured stream flow. The higher calculated alluvium ground-water discharge was used in the most likely model because it is believed that it represents the disturbed alluvium and placer materials that cover most of the valley floor. The pumping tests were conducted in the vicinity of the #3 Mine site in an area outside the placer dredge tailings. The low hydraulic conductivity values from these tests were calculated from the pump well data that is not representative of the alluvial material. The higher ground-water flow is also supported by ground-water discharge observed in the salt tracer study and discussed in section 4 of this report. Based on the salt tracer observations and ground-water water level monitoring, AGS suspects that ground-water flow through the dredge tailings may be higher than 5 cfs. Further characterization of ground-water flow through the alluvium and placer tailings is needed to refine hydraulic conductivity and discharge associated with these materials. The most likely sulfate mass flux and mine flow model has a peak mine flow in May of 605 gpm and a low flow of 143 gpm in February. It is believed that these mine flows probably represent average snow years. During consecutive above normal snow years (i.e. 200%), the mine flows may be twice as much as the normal years.

8.3.5 Metal Production from the Various Sources

Mine water metal loading from the W-O pool and the Country Boy pool is summarized in Table 8-7. The Country Boy mine is located across from the W-O site on the south side of the French Gulch valley (Figure 8-7). The loading estimates for the Country Boy were based on water quality and discharge measurements on a discrete adit discharge (EPA, 1996a). This discharge is fairly constant year around and is the only known discharge associated with the



scale 1" = 250'

LOCATION MAP FOR HEAT PULSE FLOWMETER WELLS LOW FLOW CONDITIONS, JANUARY 1997

Figure 8-7

Country Boy Mine (pers. comm. Doug Tomlison, 1996). The limited mine water discharge and metal loading for the Country Boy Mine is possibly due to most of the workings being above the ground-water table. The W-O metal production was based on the original estimated mine discharge rates. Applying the mine discharge rates from the sulfate production models for normal snow years would probably decrease the W-O metal production by at least one-half what was estimated in the Richard (1997) study.

A comparison of Richard (1997) metal loading from the various sources with observed loading on French Creek above the mine site (FG-5) and below the mine site (FG-7, FG-8, and FG-9) is summarized in Table 8-8. As previously discussed, the W-O metal production is based on the original estimated mine discharge rates and actual production for normal snow years could be at least half of Richard (1997) estimates. The upstream site FG-5 was used as a metal loading background site. The stream site metal production in Table 8-8 only includes surface flows. AGS conducted a Zn production model for FG-9 that incorporated ground and surface water production (Appendix 8-7). The AGS FG-9 flux models calculated production of 66,700 lbs Zn/year from surface flow, 43,522 lbs Zn/year from ground-water and transient flow, and a combined ground, transient, and surface flow production of 110,243 lbs Zn/year.

Table 8-7

Potential Metal Loading from Underground Mine Pools
(Richard, 1997)

Mine Pool	Cd (kg/yr)	Fe (kg/yr)	Mn (kg/yr)	Zn (kg/yr)
W-O	1,213	341,003	96,435	418,530
Country Boy	0.8	297	242	815

The metal loading associated with the surface spoils includes both ground-water discharge and surface runoff estimates from the Richard (1997) study. The reported loading from the mine waste is suspect due to unknown source of the seep used for mine waste ground-water quality. As previously discussed, the loading associated for ground-water discharge in the roaster fines is high because of the overestimation of volume. This overestimation probably doubled the calculated total metal production associated the roaster fines. Accounting for the overestimation of mine discharge and roaster fines volume, the relative contribution of metal from the W-O mine pool remains over 90% compared to the surface spoils.

Table 8-8

Comparison of Potential Metal Loading from Various Sources
with
Observed Metal Loading in French Creek
(Richard, 1997)

	Cd (kg/yr)	Fe (kg/yr)	Mn (kg/yr)	Zn (kg/yr)
Underground Mine Pools				
W-O Mine	1,213	341,003	96,435	418,530
Country Boy Mine	0.8	297	242	815
Surface Spoil Piles				
Roaster Fines	40	11,529	590	8,592
Mine Waste*	71	2,629	4,007	11,104
Mill Tailings	1.1	1,461	63	119
French Creek				
FG-5	0.1	2,014	217.9	266
FG-7 + FG-8	80	5,629	7,219	29,561
FG-9	79	2,797	3,500	26,038

* results suspect due to unknown source of seep used for mine waste ground-water quality

The potential metal loading estimates presented in this report were based on the absolute estimates of loading from the Richard (1997) study (Table 8-8). Richard (1997) also presented metal loading estimates that were proportioned to the observed loading at the combined FG-7 and FG-8 sampling sites. The absolute estimates for metal production imply that the metal loading from the various sources at the W-O site is significantly greater than observed loading in the downstream French Creek sampling sites. Accounting for ground-water and transient flow associated with French Creek, the zinc production from the W-O mine appears to be attenuated by up to 60%. A comparison of the most likely mine discharge model from the sulfate mass flux method with the mine zinc production model suggested that zinc was attenuated up to 40% during low flow conditions and 60% during high flow conditions (Appendix 8-8). This attenuation could be due to metal adsorption to sediments, geochemical processes such as oxidation in the alluvial aquifer that results in precipitation of metals, and the presence of Fe and other metal hydroxides that can adsorb metals.

8.4 Conclusions

The recent studies performed by the U.S. Bureau of Reclamation and URS Operating Services characterized the roaster fines, mill tailings, and waste rock in the vicinity of the Wellington-Oro Mine and Mill complex (BOR 1997a and UOS, 1997). The Richard (1997) study applied data from these studies with

additional information supplied by American Geological Services, Inc. to estimate metal loading potentials from the various sources at the W-O site. Based on the estimated metals loading, it can be inferred that the Wellington-Oro mine pool was contributing over 90% of the metals to French Creek. The mill tailings and the Country Boy mine were estimated to contribute less than 1% of metals to French Creek. The remaining source of metal loading was from surface runoff and ground-water discharge associated with the roaster fines and waste rock. Due to the lack of data on ground-water quality associated with the waste rock, estimated metal loading potentials for the waste rock in the Richard study (1997) are suspect. The combined estimated metal potential from various sources at the W-O site were significantly greater than the metal loading observed in French Creek downstream from the mine site. It is believed that this difference may be the result of natural attenuation along the contaminant pathways to French Creek, possibly adsorption of metals to sediments.

The observed metal loading in French Creek may only be a portion of the overall metal loading in the valley downgradient from the mine site. Significant metal transport is probably occurring by ground-water flow through the alluvial material and placer dredge piles and transient flow within the streambed cobbles and gravels. The geochemical processes responsible for natural attenuation of metals and the magnitude of ground-water flow downgradient of the mine site are not well understood at this time.

9.0 Hydrogeologic Model

The role of ground-water and its influence on the mine pool and French Creek were demonstrated in the characterization studies. Results from the stable isotope, mine pool and ground water level monitoring, and mine pool characterization studies implied that ground-water was the major source of recharge water to the W-O mine pool. The integration of the characterization studies with climatic data suggested that W-O site and headwaters region spring snowmelt was recharging the ground-water system. The spring rise in the ground-water table subsequently provides inflow into the mine pool via the faults and fractured bedrock. A significant portion of this inflow is probably associated with the upgradient portions of the mine workings and the Great Northern/J-fault system.

The majority of mine pool and ground-water table rise in the spring is driven by snowmelt associated with the upgradient headwaters region and the more protected higher elevations above the W-O mine workings. The rate of mine inflow and outflow is controlled by the hydraulic properties of the faults and fractured bedrock. The mine pool water level rises and mine water storage increases during the spring flow surge because mine inflow exceeds mine outflow. It takes several months for this high flow surge to drain out of the mine. Significant mine outflow occurs after the mine drainage of the high flow surge because the ground-water baseflow is intercepted by the mine workings. The isotope data implied that direct snowmelt infiltration into the mine pool was minimal. It is believed that most of the Acid Rock Drainage (ARD) and mobilization of metals in the W-O mine workings are due to fluctuating mine water levels.

Data from the mine pool salt tracer and characterization studies, and early 1970's W-O dewatering activities suggested that the ground-water was entering the W-O mine pool in the lower workings, possibly below the Oro fifth drift level. Ground-water flow and fault seepage calculations from borehole flow meter results, historic water levels, aquifer tests, sulfate mass balance calculations, and the stream salt tracer study suggested that mine discharge rates during spring high flow conditions are approximately two to four times the low flow rate. Mine water discharge for normal snow years was estimated to average 600 gpm during high flow and 145 gpm during low flow with an average annual flow rate of approximately 240 gpm. It is believed that significantly above average snow years (i.e. 150% to 200%) could double these mine discharge rates. The mine accommodates spring high flow surge by rising mine pool levels, increased storage, and increased discharge area.

The salt tracer and stable isotope studies showed that ground-water discharge was the major component of French Creek flow below the 11-10 fault, even during spring high flow conditions. These studies also showed that the 11-10

and Bullhide Fault seepage in the vicinity of the W-O site contained high levels of metals and sulfate that originated from the underground mine pool. The deep 11-10 Fault monitoring well MW-14 was uncontaminated while the same fault was discharging high levels of metals and sulfate as it crossed French Creek during the July 1996 salt tracer and synoptic study. It was also demonstrated that the water levels for the 11-10 Fault well mimicked the mine pool levels. This would imply that deep clean ground-water from the 11-10 Fault was recharging the lower mine workings. Subsequently, rising mine pool levels were mobilizing metals and mixing with metal laden mine pool waters on its discharge pathways from the lower workings to mine water discharge areas at the base of alluvium between the 11-10 and Bullhide faults. The mine discharge pathways to the discharge areas include the fractured bedrock, faults, and mine stopes and workings. The borehole flowmeter work, isotope studies, and ground-water quality studies demonstrated that the majority of mine water discharge was occurring between the 11-10 and Bullhide Faults. The contaminated seeps downgradient of the Bullhide Fault and W-O site illustrate the role of alluvial ground-water contaminant flow pathways.

The Richard (1997) study modeled metal loading from the various sources. This work suggested that the W-O underground mine pool was responsible for over 90% of the metal loading. Total metal loading from the various sources was significantly greater than observed loading downstream in French Creek. Accounting for potential loading associated with ground-water flow and transient storage in the stream gravels and placer piles, the total metal loading from various sources could be 60% greater than downgradient loading that ultimately enters the Blue River drainage. This implies that geochemical processes are attenuating contaminants on their pathways to French Creek. Such processes could include the formation of Fe and other metal hydroxides that precipitate along ground-water or surface flow pathways, adsorption of metals to clay minerals in the alluvium, placer piles, and surface sediments, and precipitation of metals along the flow pathways due to various geochemical and physical processes.

The three potential sources of recharge to the W-O mine pool are:

1. local snow melt above the mine workings that vertically infiltrates into the upper workings;
2. alluvial ground-water and French Creek water that recharges the mine pool via upgradient faults and bedrock fractures such as the Great Northern Fault; and
3. regional deep ground-water flow within the Cretaceous and Jurassic sedimentary units enhanced by faults and fractures.

Results from the characterization studies suggest that the majority of recharge to the W-O mine pool is from lateral and deep regional ground-water.

10.0 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, ground-water systems, and French Creek, metal loading contributions 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. Spring snowmelt events appear to be driving the mine pool water level fluctuations. The mine pool water level fluctuations are probably the major mechanism for Acid Rock Drainage (ARD) and the mobilization of metals. This work also suggested that surface spoil piles contribute a small percentage of the overall metal loading to French Creek and local infiltration of snowmelt and runoff associated with the spoils are not a significant metal transport mechanism.

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 and within 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 fault block in the vicinity of the #3 Mine shaft. This mine discharge area is located in the vicinity of the western downgradient end of the W-O mine workings.

The mine pool characterization and tracer results implied that significant mine flow may be bypassing the Oro mineshaft. The stable isotope studies suggested that percolation of local snowmelt into the upper portions of the mine pool is not the major source of recharge water. French Creek headwaters and high elevation site snowmelt infiltration into the major fault systems and the fractured bedrock recharges the ground-water system resulting in a rising ground-water table. This rising ground-water table subsequently recharges the W-O mine pool. Consequently, regional ground-water flow in the Cretaceous and Jurassic sedimentary units appear to be the major pathway and source of inflow to the mine pool. An extensive fracture and fault network enhances this inflow. Minimal mine recharge water originates from French Creek and the alluvium ground-water upgradient from the W-O site.

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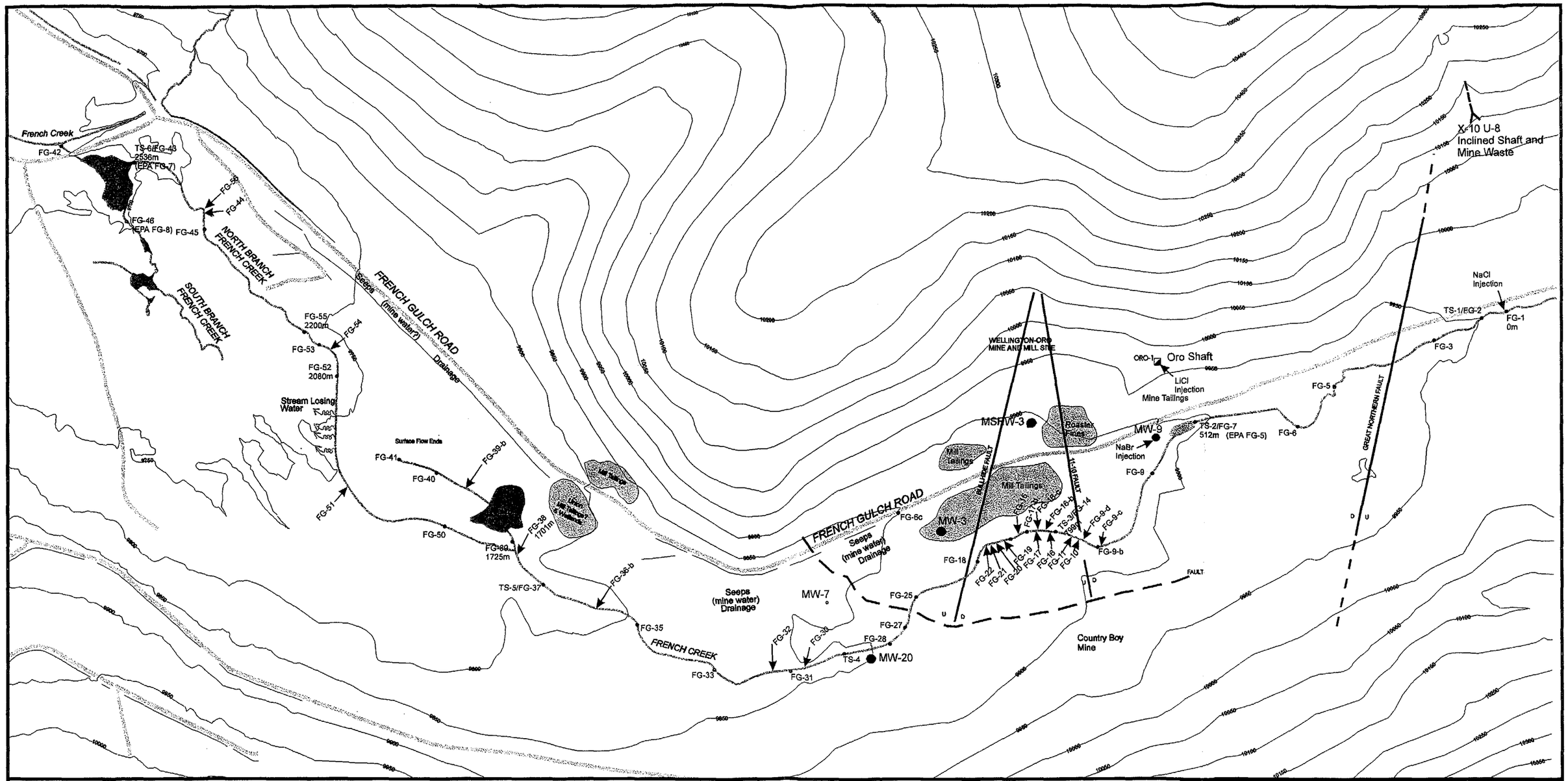

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Environmental, Geological, and Natural Resource Consultants

PLATE 1
French Gulch Salt Tracer Sample Location Map

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