HYDROGEOLOGIC CHARACTERIZATION OF GROUND WATERS, MINE POOLS AND THE LEADVILLE MINE DRAINAGE TUNNEL, LEADVILLE, COLORADO[1]

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Abstract. The 3385 meter long Leadville Mine Drain Tunnel (LMDT) was completed in 1952 to create a free-draining tunnel to dewater existing and future mine workings in the Leadville Mining District in the Sawatch Mountains of central Colorado. Since 1952 mining has been mostly discontinued in the Leadville district and the physical condition of the LMDT, which discharges approximately 82 l/s, has deteriorated. Roof falls have resulted in blockages which can cause water to pool up, increasing the hydraulic head and presenting a potential blowout problem. Using its' authority under CERCLA, the US EPA is planning to implement a number of hydraulic and source control elements which are designed to contain and control mine pool water. To support this work the US EPA has completed a rigorous hydrogeologic characterization aimed at developing a sound conceptual understanding of the hydrologic, geologic and geochemical conditions that control inflow of ground water to the underground workings associated with the LMDT and the outflow of mine water from these workings. The investigations discussed here included hydrogeologic mapping, interpretation of water chemistry data and isotopic tracer analysis. The results of this investigation indicate that the LMDT drains only a small volume of mine pool water and a very large volume of regional bedrock and adjacent alluvial ground water. These understandings have been used to design a containment system will be used to control and manage the ground water intercepted by the LMDT and the mine pool(s) that are connected to the LMDT.

Additional Key Words : Mining, loading analysis, end-member mixing analysis, isotope hydrology

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Introduction

At many hardrock mines underground source control techniques can be effectively applied as an element of a mine closure plan or a remedial action where acid mine drainage is an environmental concern. Source control techniques include the use of plugging and/or backfilling tunnels and shafts, grouting ground-water inflow zones to tunnels and shafts, and segregation of “clean” inflows from “contaminated” inflows. These techniques can be used to: isolate contaminated mine pools, divert clean inflows around mine workings, reduce/control the volume of discharge from adit/tunnel portals and to reduce the risk of tunnel blowout. However, application of these techniques has been limited due to inadequate knowledge of ground-water flow system(s) that discharge to or receive water from underground mine workings. In order to determine if an underground source control measure would be effective it is necessary to complete a rigorous hydrogeologic characterization aimed at developing a sound conceptual understanding of the hydrologic and geologic conditions that control inflow of ground water to the underground workings being evaluated and the outflow of water from these workings. Based on past and ongoing work in Operable Unit 6 at the California Gulch NPL site in the Leadville mining district, this paper describes a comprehensive approach to hydrogeologic charactertization of the Leadville Mine Drain Tunnel (LMDT) and surrounding workings. A number of quantitative and qualitative characterization tools were utilized to characterize the sources and flow paths of ground-water inflow into and out of the LMDT and associated mine workings.

The LMDT hydrogeologic investigation began in November of 2002 and extended through June 2005. The investigation was designed to provide data to support the selection of a remedy for OU 6. The overall remedy for OU 6 must address both the water quality problems associated with uncontrolled mine pool discharge and the safety issues related to the potential for blowout that may occur as a result of blockage due to roof collapse . The objective of the remedial action that will be designed and implemented is to manage and control the ground waters captured by the LMDT and the mine pool(s) that are connected to the LMDT (Frontier Environmental Services, 2005).

A variety of characterization tools (both quantitative and qualitative) were utilized in the hydrogeologic investigation including:

a) Hydrogeologic mapping to assess geologic controls on ground-water flow pathways and the nature and extent of underground workings,

b) Analysis of data from ten synoptic sampling events which included 46 ground-water, mine-water and surface water locations, three snow sampling locations and ten rain sampling sites,

c) Detailed analysis of approximately 177,00 water level measurements from 39 locations

d) Use of stable and radioactive isotope data as an aid in determining relative ages and sources of water to underground workings,

e) Ground-water and tunnel tracing, using fluorescent dyes (injection of tracer into the RES, the Marian shaft and tunnel wells and analyzing data from breakthrough curves),

f) Use of End Member Mixing Analysis and Principal Component Analysis to quantitatively determine sources of water to the underground workings, and

g) Metals loading analysis – Marion collection system and INF-1

Data interpretation results from these activities were used to develop and refine a conceptual model that describes the ground-water flow conditions within the California Gulch NPL site with particular focus on OU6. A sound understanding of the regional bedrock ground-water system, including an understanding of the perturbations to the flow system and an understanding of the current bedrock / mine pool ground-water flow system, is critical for developing an appropriate and effective remedy for OU6.

This paper discusses the data and findings from three of the hydrogeologic characterization tools listed above: hydrogeologic mapping, the analysis of ground-water elevation and LMDT discharge data and the analysis of water chemistry and isotopic data. This paper does not include a discussion of the detailed analysis of the End Member Mixing Analysis or the results of the 11 ground-water / tunnel tracer tests.

Background

Leadville Mining District

The Leadville mining district is one of the largest precious and heavy metal mining districts in the western United States. The district is located on the west slopes of the Mosquito Range in the central part of the Colorado Mineral Belt, a NE-SW trending zone that extends from Boulder, CO to Telluride, CO. The Leadville district has been divided into sub-districts based on fault-block boundaries. The major sub-districts include Fryer Hill, Carbonate Hill, Iron Hill, Breece Hill, Graham Park and Downtown Basin. The most productive part of the Leadville district was a 20.5 km^2 area immediately east of the City of Leadville. Within the district Au and Ag occur primarily as replacement deposits in lower Paleozoic carbonates. Mining, mineral processing and smelting activities produced Au, Ag, Pb, and Zn for more than 130 years.

Placer mining began in the Leadville district in 1859 and continued until about 1863. By 1868, extensive underground mining had begun and continued until the 1990s. By 1874, Pb and Ag had become the most important mined metals in the district. There are more than 2800 patented mining claims in the district. By 1927 more than 1600 prospects, 1300 shafts, and 155 adits had been constructed in the district. The total length of drifts, tunnels and shafts may exceed 325 kilometers (MFG, 1998). From 1932 to 1940 very little mining occurred in the District, however during World Wars I and II Pb and Zn production from the Leadville Mining District was critical to the US war efforts. The US Bureau of Mines and the US Geological Survey played important roles in characterizing and mining the metal deposits within the Leadville district. The Black Cloud Mine was the last producing mine in the district. The Black Cloud, a Pb-Zn mine, operated until 1998.

California Gulch NPL Site

In 1983 a 43.3 km^2 area within the Leadville mining district was included on the National Priority List (NPL) and became the California Gulch NPL site. The NPL site is located in Lake County, Colorado and includes the towns of Leadville and Stringtown, the confluence of California Gulch and the Arkansas River, Evans Gulch and, Stayhorse Gulch (Fig. 1). Elevations range from 2928 meters above mean sea level at the Arkansas River to 3846 meters above mean sea level in the upper, eastern boundary of the site. More than 2000 mine waste piles and three draining mine tunnels are located within the California Gulch NPL site. The LMDT portal is located in lower Evans Gulch. Discharge from the LMDT is typically greater than 64.5 liters per second (l/s), ranging up to 94.6 l/s. The Yak Tunnel portal is located in upper California Gulch. Discharge from the Yak fluctuates seasonally between approximately 17.0 and 45.4 l/s.

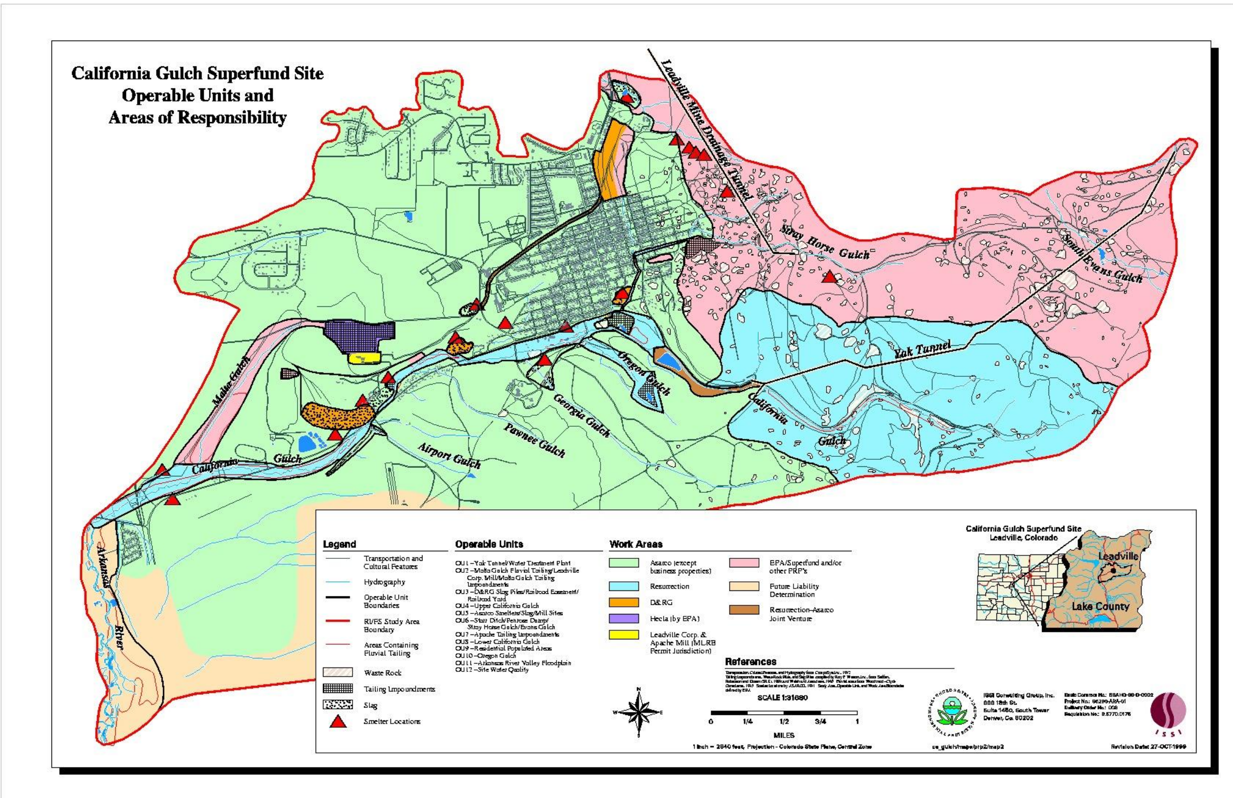

Figure 1 – Operable units –California Gulch SUPERFUND Site

Discharge from the Yak is controlled by a bulkhead plug installed about 1500 feet from the portal. A third mine drain tunnel, the Canterbury Tunnel, is located just north of the NPL site. Average discharge from the Canterbury portal ranges from about 15.8 to 25.2 l/s. The Parkville Water Company (PWC) uses water from the tunnel for municipal water supply. The PWC owns and maintains the first few hundred feet of the tunnel. The US Environmental Protection Agency and the Colorado Department of Public Health and Environment have directed characterization and remediation activities at the NPL site since 1983.

Operable Unit 6. Operable Unit 6 (OU6) underlies about 9.0 km^2 within the northeastern part of the California Gulch NPL site. OU6 includes the Strayhorse Gulch watershed and the lower part of Evans Gulch watershed, an east –west trending intermittent drainage in the northern portion of the Leadville Mining District (Fig. 1). Numerous waste rock piles occur within upper Strayhorse Gulch. These waste rock piles contain low-grade ore that is rich in pyrite, which is easily oxidized when snowmelt and rainfall infiltrate through the piles resulting in acid generation, low pH and the subsequent release of Zn and Cd. Mobilization of Zn, Cd, Mn, and Pb from these sources and subsequent transport of these metals to the Arkansas River is a significant environmental problem. Human ingestion of Pb from contact with solid mine waste is also a major potential human health problem. Currently storm runoff is diverted around the major mine waste piles in upper Strayhorse Gulch and delivered, via a system of ditches, to the collar of the Marian shaft. Contaminated water delivered to the Marian shaft flows into mine workings connected to the shaft. A portion of this contaminated water flows into a mine pool beneath Graham Park to the south of the Marion shaft and a portion flow to the Robert Emmet shaft (RES), which is connected to the LMDT. The amount of water that flows to these two locations varies significantly depending on the volume of water delivered to the Marion shaft.

Mine Pools. Three large mine pools exist beneath OU 6. The mine pools were created when the extensive mine working associated with Fryer Hill, Carbonate Hill and Downtown sub-districts filled with ground water after mining ended (Fig. 2). Within these sub-districts three ore bodies were delineated; the blue limestone (Leadville LS.) under white porphyry, the blue limestone under gray porphyry and the white limestone (Manitou Dolomite). Estimates of the volume of ore excavated were based primarily on Plate 45 in Emmons, et al, (1927, USGS PP 148). Plate 45 depicts the areas of the ore bodies mined within the district and shows many of the shafts, winzes and workings.

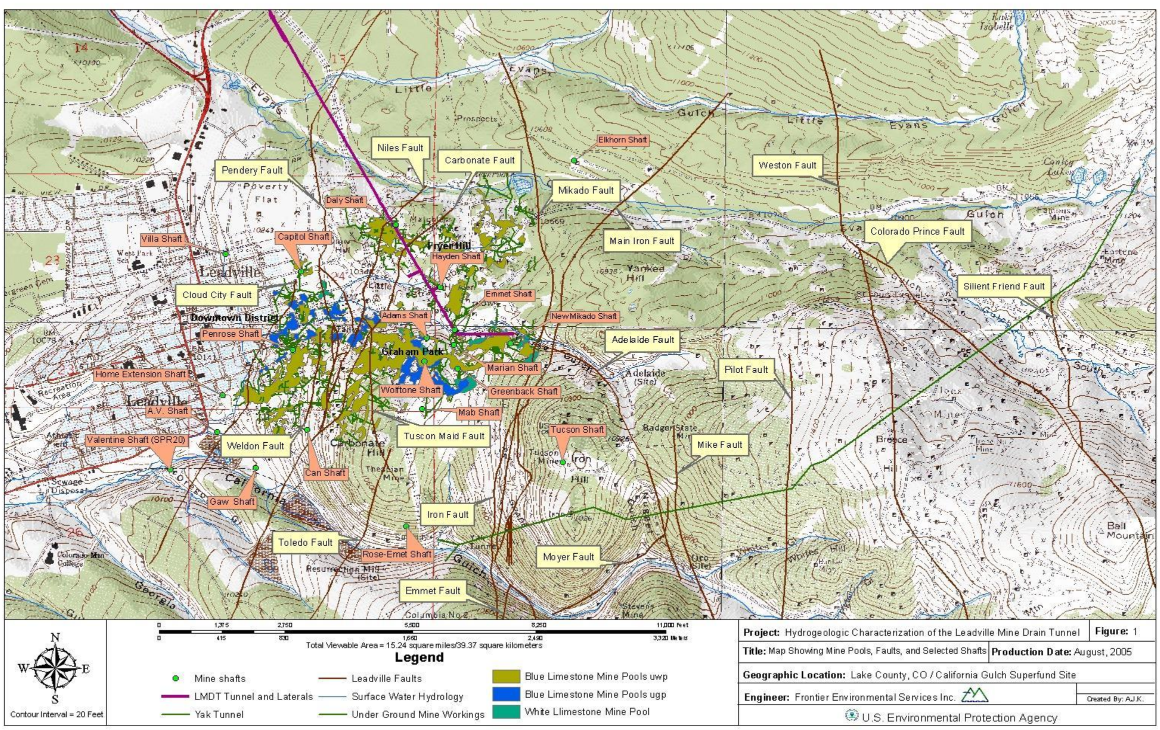

Figure 2- Map Showing Faults, Shafts and Mine Pools- California Gulch SUPERFUND Site

Data used to estimate the volume of water in the mine pools included: (1) area of ore body removed, (2) average elevation of ore body, (3) average thickness of ore body, (4) extent of mine workings and (5) current water level elevations within the mine pools. As reported by EPA (2002), the estimated volume of mine pool water contained in working that are higher in elevation than the LMDT ranges from 0.54 to 1.47 billion gallons. As discussed in the background section, subsequent research of historical mining records indicates that this estimate may be low due to underestimating the volume of rock that was stoped. The total mine pool volume, which would include water contained in workings at an elevation below the LMDT, would be significantly greater. The three mine pools are connected to an unknown degree by mine workings and geologic structures. Since 1953, some discharge from these mine pools has occurred through the LMDT and the Yak Tunnel.

Leadville Mine Drain Tunnel. The LMDT is a 3385-meter long tunnel completed in 1952 by the US Bureau of Mines. The tunnel entrance is located about 2.4 kilometers north of the town of Leadville, Colorado. The tunnel was started in 1943, and was constructed to facilitate exploration for additional ore reserves (that part of the Leadville mining district east of the LMDT had not been thoroughly explored in 1943) and, equally important, to create a free-draining tunnel to dewater existing and future mine workings beneath Fryer Hill, Carbonate Hill and Graham Park sub-districts. The LMDT is connected to the Robert Emmet shaft via a 9.2 meter (30 ft) lateral at 3000 meters from the portal. The tunnel is also connected to the Hayden shaft via a 58.8 meter (191 ft) lateral at approximately 2700 meters from the portal. At approximately 2560 meters from the portal the LMDT is connected to the Ponsardine raise via an 89.5 meter (291 ft) lateral. The Ponsardine raise is within the Downtown sub district. Data from the US Bureau of Mines indicate that from 1953 to 1959, the average minimum tunnel discharge was 88.3 l/s (1400 gpm) and the average maximum tunnel discharge was 135.6 l/s (2150 gpm). From 1993 to 1996, the average minimum tunnel discharge was 31.5 l/s (500 gpm) and the average maximum tunnel discharge was 80.2 l/s (1275 gpm). In 1959, management of the tunnel was transferred to the US Bureau of Reclamation (USBR) as part of the Arkansas - Frying Pan irrigation project. In 1992, the USBR constructed a treatment plant to treat the discharge from the LMDT. Currently the tunnel is not accessible beyond 400 feet from the portal. During the period from November 2002 through February 2004 dissolved Zn concentrations in the discharge water ranged from 2680 to 11,900 ug/l and dissolved Cd concentrations ranged from 6.7 to 71.7 ug/l.

Throughout the mining history in the Leadville district collapse of rock fall from tunnel roofs, stopes and shafts has been common. The geology of the district is extremely complex and is characterized by extensive faulting associated with folded Paleozoic sedimentary rocks and emplacement of Tertiary granites and porphyries. Most of the ore occurs as replacement deposits that are hosted by lower Paleozoic carbonate rocks. Numerous collapses have occurred in the LMDT since it’s completion in 1953. It is suspected that these collapses occur within the two sections of folded lower Paleozoic rocks which include limestone and dolomite formations. The collapses sometimes result in significant blockage, which causes tunnel water to back up behind the rock “dam”. This creates a potential for a portal blowout if the rock fall “dam” fails as a result of too much hydraulic head being generated by the pool of water that builds up behind the rock fall.

Hydrogeologic Setting

Regional Geology

The geology and ore deposits within the Leadville Mining District have been described in detail by Emmons (1927) and Behre (1953). This brief summary of the geology of the area surrounding the LMDT is taken largely from those publications. The ore bodies that have been mined in the Leadville Mining District occur primarily within lower Paleozoic sedimentary formations that flank the west slopes of the Mosquito Range in central Colorado. The mountains that comprise the Mosquito Range were uplifted during the Laramide progeny, which occurred during late Cretaceous and early Tertiary time and included two distinct periods, each characterized by large scale faulting followed by intrusion. During these periods, igneous rocks were intruded into existing Pre-Cambrian granites and lower Paleozoic sedimentary rocks (primarily carbonates and shales). The intrusive rocks, mapped as porphyries, are comprised primarily of granodiorites (white porphyries) and quartz monzonites (gray porphyries), and were intruded primarily as sills and less commonly as dikes and plugs. Faulting associated with the two periods of uplift occurred along four distinct sets of normal/reverse faults. There was a common tendency for faults to be repeating with movement in both directions along the same fault plane. The fault sets trend north-northwest to north, whereas the Laramide intrusives and the mineral belt of Central Colorado trend north-northeast.

Within the area included in the assessment of the LMDT, folded sedimentary rocks ranging in age from Cambrian to Pennsylvanian are separated by Pre–Cambrian granites and Laramide porphyries (Fig. 3). The Paleozoic rocks that were intruded by the porphyries include, in ascending order, the Cambrian age Sawatch quartzite and Peerless shale, the Ordivician age Manitou dolomite, the Devonian age Chaffee Fm (Parting quartzite overlain by the Dyer dolomite), the Mississippian age Leadville Limestone, and the Pennsylvanian age Minturn Fm. (formerly known as Weber Fm.) The Minturn Fm. is comprised of shale with significant limestone lenses. The Sawatch is highly fractured and the Mississippian carbonates have

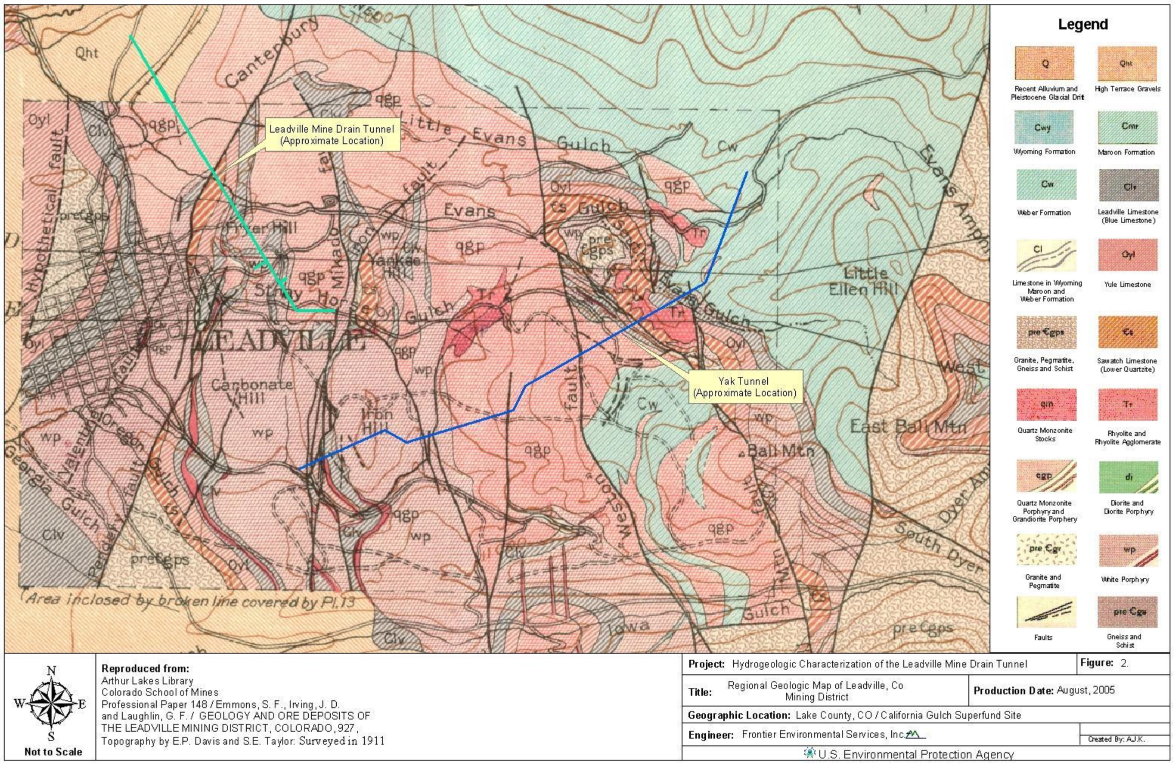

Figure 3- Geologic Map –Leadville Mining District

extensive paleo-karst features which resulted in significant development of secondary porosity and permeability in these rocks.

The Leadville Limestone outcrops over a large area that extends north - south along the east side of the Mikado fault in the Strayhorse- Evans Gulch area; along the east and north flanks of Fryer Hill; along the Iron, Dome and Emet faults where they cross the southwest flanks of Iron Hill and over large areas north of the South Dyer fault. Timberline occurs at about 11,800 feet along the west slopes of the Mosquito Range. North of the Ball Mountain fault most of the area between 11,000 and 12,000 is underlain by Minturn Fm.

Geology of LMDT. The portal of the LMDT is located about 2.4 km north of Leadville at an elevation of 3065 meters. The tunnel trends southeastward (S 28 degrees E) for about 3077 m where it is connected to the RES. From the RES the LMDT trends eastward for another 369 m where it crosses the Mikado fault and ends in Pre-Cambrian granite on the up-thrown (east) side of the fault. For the first 185 m the tunnel is constructed in glacial till and terrace gravels on top of the Minturn Fm. From 185 to 646 m of the tunnel is constructed in the Minturn Formation. The tunnel then extends through folded Cambrian, Ordovician and Mississippian rocks from 646 meters to about 1292 m from the portal where it crosses the Pendery fault. On the east side of the Pendery fault the tunnel is constructed through Pre-Cambrian granite for about 615 m. At about 1908 m from the portal, the tunnel again enters a section of folded Cambrian, Ordovician and Mississippian rocks. These rocks underlie Fryer Hill, and are displaced by the Niles and Carbonate faults. At about 2954 m from the portal, the tunnel enters the thick white porphyry.

The last 492 m of the LMDT extends through the porphyry. The LMDT terminates in Precambrian granite east of the Mikado shaft and the Mikado fault.

The land surface above the tunnel alignment is underlain by terrace gavels and morainal deposits along the entire length of the tunnel. These deposits have a combined thickness of 15.4 to 30.8 m over most of the tunnel alignment; however they exceed 61.5 m at 615 m from the portal. A thick (30.8 m) deposit of terrace gravels overlies the tunnel alignment from about 1077 m to 1692 m from the portal. The vertical distance from the land surface to the top of the LMDT varies from 61.5 m (station 20+00) to 166 m (station 112+99).

Mineralization and ore bodies. Mineralization in the Leadville district is described in detail by Emmons, 1907, Emmons, 1927 and Behre, 1953. The brief discussion here is included for purposes of describing the areas that were heavily excavated for underground workings. This is relevant to the geometry of the mine pool(s) that exist in the district and the perturbations to the regional bedrock ground-water flow system(s).

The principle ores in the district commonly occur in tabular "blanket" type ore bodies in limestones and dolomites and are formed by replacement or fissure filling. Replacement was especially effective in the upper part of the Mississippian age Leadville Limestone due to: (1) the presence of low permeability porphyry sill or shale caps on top of the limestone and (2) the abundance of solution openings in the limestone. The richest ore bodies occurred where the Leadville limestone is trapped between porphyry sills. These types of ore bodies occurred most frequently in the Fryer Hill and Carbonate Hill sub-districts. Mineralization also occurred in the stratigraphically lower Dyer dolomite and the Manitou dolomite (though much less extensively than in the Leadville Limestone), and along contacts between the porphyries and carbonates and between the porphyries and quartzites. These ore bodies are usually much thinner. The most common sulfide minerals are galena and sphalerite –neither yield significant secondary sulfides. It is important to note that pyrite is not a major sulfide mineral in the district. The most abundant oxide minerals are those of Mn and Zn, which are common in blanket ore bodies. Many older, higher mines did not mine sulfide ores.

Post mineralization faulting was significant and displaced many ore deposits. The lower Paleozoic carbonates are typically in fault contact within the mining district. T he displacement of ore bodies by faulting and the fingering of the intrusive porphyry sills with the carbonates resulted in many semi –separated ore bodies. This is one of the reasons there were so many mines in the Leadville district. The displacement of the limestone also greatly increased the complexity of ground-water flow within the permeable limestone / dolomite beds.

Ground Water in Recent Unconsolidated Deposits

The surficial geology in the Leadville District is discussed in detail by Emmons (1927) and Behre (1953). Large-scale maps of the surficial deposits are included as plate 7 from Emmons and Plate 4 from Behre. The unconsolidated deposits that overlie the bedrock in the area between the East Fork of the Arkansas River to the north and Iowa Gulch to the south are primarily glacial deposits. Unconsolidated deposits from three glacial periods have been mapped in the area. During the Wisconsin glacial period alpine glaciers occurred in the valleys of the East Fork, Evans Gulch and Iowa Gulch. Associated with these glaciers are four lateral moraines that form ridges along the southeast side of the East Fork valley, along the north and south sides of Evans Gulch and along the north side of Iowa Gulch. The lateral moraine on the north side of Evans Gulch ranges in thickness from 37 to 77 meters while the moraine on the south side of Evans Gulch is about 30 meters thick. This moraine forms the divide between Little Strayhorse Gulch and Evans Gulch. The streams that drain Strayhorse Gulch and little Strayhorse Gulch are tributary to California Gulch.

Thick (30 to 60 meters) terminal and ground moraine deposits overlie the bedrock in lower Evans Gulch, in Little Strayhorse Gulch, Fryer Hill and Fairview Hill. In Iowa Gulch, the lateral moraines extend westward to the town of Leadville and only small areas of terminal moraine have been mapped. No morainal deposits occur in California Gulch, as this drainage was not glaciated. Thin alluvial deposits and disturbed mine waste sediments underlie the bottom of California Gulch.

The western ends of the lateral moraines and the terminal moraine / ground moraine deposits overlie an older (Pre-Wisconsin) deposit of high terrace gravels. These deposits consist of well-sorted, imperfectly stratified gravels with occasional sand lenses and little or no clay. The deposits extend from the Arkansas River eastward for 3.2 to 4.8 kilometers. The gravels are coarser towards the mountains and finer towards the Arkansas River. The gravels are thickest beneath the Arkansas River floodplain (up to 245 meters) and thin eastward. Thicknesses commonly reach 60 meters in the lower parts of Evans Gulch, California Gulch and Iowa Gulch. Emmons (1927) and Behre (1953) interpret these gravels as outwash deposits from an older glacial period. The streams in Evans Gulch, California Gulch and Iowa Gulch have cut deeply into these gravels.

With the exception of the Pre-Wisconsin outwash gravels that underlie the floodplain of the Arkansas River, saturated thicknesses in the unconsolidated deposits are very small. Depth to water in ground-water monitoring wells that are constructed in these deposits in Evans Gulch, Strayhorse Gulch California Gulch and Oregon Gulch is typically greater than 45 meters. The streams in Evans Gulch (below the Mikado fault), California Gulch, Oregon Gulch and Strayhorse Gulch are losing streams. The entire stream sinks into the glacial sediments in lower Evans Gulch.

East of the Mikado fault ground water discharges from the adjacent glacial deposits into the stream in Evans Gulch. This portion of Evans Gulch has perennial flow. The PWC has installed a number of intake boxes/infiltration galleries in this location. In September 2005 the combined inflow to the infiltration galleries was approximately 50 l/s.

Water level elevations in the alluvial wells are typically significantly lower than water levels in nearby bedrock wells. This is a common situation where thick glacial deposits overlie the bedrock. Ground water that occurs in the bedrock is highly confined due to the thick, overlying glacial deposits and due to the significant relief between the recharge area and the lower parts of the east-west drainages. The relationship between bedrock and alluvial water levels results in an upward vertical gradient wherever there are thick unconsolidated glacial deposits overlying bedrock.

Ground Water in Bedrock

Data and information from tunnel construction records, monitoring wells, US Geological Service (USGS) reports, US Bureau of Mines reports and other sources provide information about ground-water flow through the bedrock formations within the Leadville mining district. Prior to extensive mining, ground-water flow in the Leadville district occurred primarily in the thick carbonate sequence that includes the Sawatch quartzite and the Manitou Dolomite. The Cambrian, Ordovician, and Mississippian rocks likely function as a single hydrostratigraphic unit over large areas. Regional ground water flow within this stratigraphic series of rocks is from the recharge areas in the upper portions of the watersheds towards the westward towards the Arkansas River (Fig. 4). Recharge occurs primarily via infiltration of snowmelt at elevations above 3075 m. Ground-water discharge occurs to underground mine workings, bedrock springs, the thick alluvial deposits that underlie the Arkansas River floodplain and to the Arkansas River. Isotope and water level data indicate that there is a five to six-month lag time between the hydrograph peaks for surface waters and those for ground water. Figure 4 shows the potentiometric surface for annual high ground-water levels, which occur in October – November. Seasonal water level data for the bedrock flow system indicate that there are locally significant difference in flow direction and gradient during annual low ground-water levels which occur in April and May.

Ground water within the carbonate formations is typically undersaturated with respect to calcite suggesting that there are some karstic pathways as well as interconnected workings that transmit recharge water rapidly along specific pathways.

There are numerous large displacement, high angle, north-south trending faults between the crest of the Mosquito Range and the Arkansas River (Fig. 2). Ground-water flow in the bedrock formations is affected by these faults. Prior to major underground excavation the major faults in the district functioned as hydraulic boundaries, essentially separating ground-water flow systems. Permeable fault zones may divert ground water flow from bedrock formations if low permeability formations occur on the downgradient side of the fault zone.

The Pendery fault zone is a major hydraulic boundary, which separates ground-water flow systems that occur in the bedrock between the Mikado and Pendery fault zones and the bedrock between the Pendery fault zone and the Arkansas River. It is likely that ground water recharges the Pendery fault zone northeast of the LMDT at elevations significantly higher than the LMDT. Discharge from the Pendery fault zone is thought to occur in lower California Gulch. The Pendery fault crosses the LMDT at about 1231 meters from the portal.

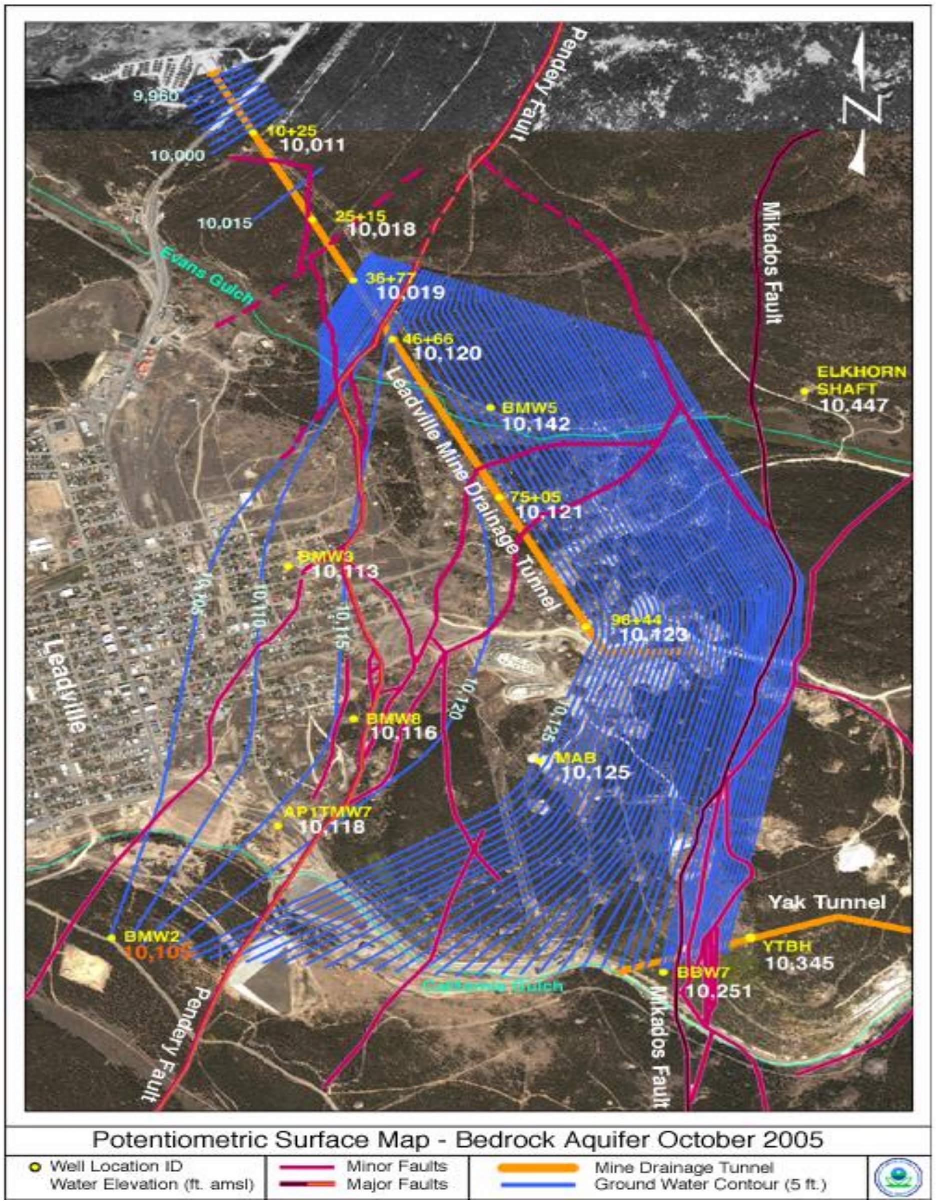

Figure 4 – Potentiomentric Surface Map –Bedrock Aquifer, Leadville Mining District

The extensive underground workings, shafts and drain tunnels have perturbed the ground-water flow conditions within the mining district. Tunnels and underground workings cross the major faults and provide some degree of connection between the ground-water flow systems that were originally separated. The large mine pools that occur beneath Fryer Hill, Graham Park, Carbonate Hill and the Downtown district are now an integrated part of the regional ground-water flow system(s). As shown on Fig. 4 the storage of ground water in mine pools has greatly reduced the gradient on the potentiometric surface east of the RES.

Analysis of Water Chemistry and Isotope Data

Sampling Program

Primary sample-collection efforts extended from November 2002 through June 2004. However selected sampling continued until June 2005. Sampling efforts focused on collecting representative samples of surface water, ground water, springs, mine waters and precipitation (rain and snow). In total, more than 300 samples were collected from 57 locations during ten separate sampling events. Forty-six locations were sampled for surface water, mine-water or ground water and 11 locations were included in the precipitation sampling. Most sampling events were completed within 2-4 days. Analysis included field parameters (pH, conductivity, temperature, and discharge), major anions and inorganic compounds (HCO_3^-, carbonate, Cl^-, NO_3^- as N, K, silicate, Na, and SO_4^{-2}), dissolved metals (Al, As, Cd, Ca, Cu, Fe, Pb, Mn, Mg, and Zn), total dissolved solids, total alkalinity as $CaCO_3$, stable water isotopes (^{18}O, ^{2}H) and tritium (^{3}H). Data from forty-one of the fifty-seven locations was used to evaluate the chemistry and contamination of ground waters, mine waters and surface waters within the area of the investigation (Table 1).

Twenty-one of the forty-one locations were sampled seven or more times during the November 2002 through June 2004 period. Three of the locations were only sampled one time. Five of the sampling locations are mine shafts and five are wells constructed in the LMDT (Table 2).

AMD and Metals Contamination of Water Resources

The forty-one locations used to assess contamination of water resources from acid mine drainage (AMD) included 16 locations where mine water was sampled, 13 locations where ground water was sampled, and 12 locations where surface water was sampled. Chemistry data for selected AMD indicator parameters was used to evaluate the extent of ground-water and surface water contamination by AMD constituents. Concentration data from zinc, lead, manganese, sulfate and pH data have been used to characterize the extent of AMD contamination. Table 3 lists 14 sampling locations where the mean concentration of at least one of the five AMD constituents is significantly higher than mean concentrations at all other locations. At three of these 14 locations (WCCPZ1, BBW5, CGO3YD), only one AMD constituent had a high mean value. At nine of the remaining eleven locations, mean concentrations were high for at least three AMD constituents. The mean concentration is high for all five AMD constituents at seven locations; YTPD, YTBH, RES, SHGEMSP, MARION, SDDS, SDDS2.

Table 1 – Sample locations and number of samples – LMDT hydrogeologic investigation

Sample Location	Location description	Sample type	# of samples
BMW3	Bedrock well	Ground water	8
BMW4	Bedrock well	Ground water	4
BMW5	Bedrock well	Ground water	1
NW5D	Bedrock well	Ground water	9
WCCPZ1	Bedrock well	Ground water	10
BBW5	Bedrock well	Ground water	3
BBW10A	Bedrock well	Ground water	4
BMW8	Bedrock well	Ground water	2
LMDT1	Alluvial well	Ground water	7
NW5C	Alluvial well	Ground water	10
OG1TMW1	Alluvial well	Ground water	8
WO3	Alluvial well	Ground water	10
SDDS2	Spring	Ground water	8
LMDT25+15	Tunnel well	Mine water	3
LMDT36+77	Tunnel well	Mine water	3
LMDT46+66	Tunnel well	Mine water	4
LMDT75+05	Tunnel well	Mine water	3
LMDT96+44	Tunnel well	Mine water	2
CT	Canterbury tunnel	Mine water	9
Elkhorn	Elkhorn shaft	Mine water	9
RES	Robert Emmet shaft	Mine water	10
INF-1	LMDT discharge	Mine water	10
LMDT-PD	LMDT portal disch.	Mine water	2
SPR20	Valentine shaft	Mine water	8
SPR23	Gaw shaft	Mine water	7
SPR23 (200)	Gaw sh. @ 200 ft.	Mine water	8
MAB	Mab shaft	Mine water	8
YTBH	Yak tunnel bulkhead	Mine water	5
YTPD	Yak tunnel portal	Mine water	5
SHG07A	Strayhorse Gulch	Surface water	4
MARIAN	Inflow- Marian shaft	Surface water	8
WRIGHT	Inflow-Wright shaft	Surface water	2
SHGEMSP	Leachate seep SHG	Surface water	3
CG03YD	California Gulch	Surface water	1
CG03BF	California Gulch	Surface water	9
LEGO4	Little Evans Gulch	Surface water	3
CG04BF	California Gulch	Surface water	8
PWRES	Parville – reservoir	Surface water	2
EG04	Evans Gulch	Surface water	7
EGBER	EG-Big Evans Res.	Surface water	3
SDDS	Starr Ditch – CG	Surface water	8

Table 2 – Mine shafts and tunnel wells sampled for LMDT hydrogeologic investigation

Mine shaft / tunnel well	Description	Depth (meters)
Robert Emmet shaft	SHG between Mikado Carbonate faults	271
Mab shaft	NE Slope of Carbonate Hill between Mikado & Carbonate faults	246
Elkhorn shaft	NE of Evans gulch	266
Valentine shaft	California Gulch –between Pendery and Cloud City faults	185
Gaw shaft	California Gulch –between Pendery and Cloud City faults	Approx. 209
LMDT well 25+15	Former vent pipe	86.5
LMDT well 36+77	Former vent pipe	91.2
LMDT well 46+66	Approx 4.6 m from LMDT	110.8
LMDT well 75+05	Former vent pipe	143
LMDT well 96+44	Approx 4.6 m from LMDT	164.6

Table 3 – Sampling locations with relatively high mean concentrations of AMD constituents

AMD indicator > **Location**	**Mn > 10,000ug/l**	**Zn > 10,000 ug/l**	**Pb > 10 ug/l**	**SO^4 > 1000 mg/l**	**pH <6**
RES	X	X	X	X	X
YTPD	X	X	X	X	X
YTBH	X	X	X	X	X
WO3	X	X	X	X	
WCCPZ1			X		
BBW5				X	
BBW10A		X		X	
SHGEMSP	X	X	X	X	X
SDDS	X	X	X	X	X
SDDS2	X	X	X	X	X
CGO3YD				X	
CGO3BF			X	X	
CGO4BF	X		X	X	
MARION	X	X	X	X	X

Based on these data the following conclusions are presented:

a) Mine water discharging from the Yak Tunnel is contaminated with AMD constituents. The high mean Zn value at BBW10A and the high mean SO_4^{-2} value at BBW5 indicate that the mine workings associated with the Yak contain mine water that is contaminated by AMD constituents. Both of these wells are completed in flooded mine workings. Three surface water sampling locations in California, CGO3YD, CGO3BF and CGO4BF had high mean concentrations of SO_4^{-2} or Pb values. These locations are immediately downstream of the confluence with Starr Ditch.

b) The AMD contamination at locations RES, MARION, SHGEMSP, SDDS and SDDS2 is due to leachate generated by dissolution of metals from waste-rock piles in upper Strayhorse Gulch, primarily during run-off in April and May. Location SHGEMSP represents a leachate spring located immediately west of the RES. This leachate is from the waste-rock piles in upper Strayhorse Gulch. Sampling location SDDS and SDDS2 are located along Starr Ditch along the northern edge of California Gulch – north of the Apache tailings pile. Based on mean ^3H values, the waters sampled at SDDS (mean ^3H value -11.3) and SDDS2 (mean ^3H value -13.3) represent a mixture of waters that include sources not apparent at SHGEMSP (mean ^3H value 9.9). Locations SDDS and SDDS2 are about a mile southwest of SHGEMSP. Along this length of Starr Ditch there is likely inflow of surface water and inflow of leakage from PWC pipes. Location SDDS2 is a collection of small seeps that discharge near a drop structure on Starr Ditch (SDDS). These seeps may be due to discharge of bedrock ground water via the AV shaft which is located adjacent to the drop structure and is totally buried.

c) The leachate derived from infiltration through the waste rock piles is contaminating rain and snowmelt runoff. Prior to 1996, run-off water from upper Strayhorse Gulch was not captured or diverted. In 1996 and 1997, EPA relocated and capped five waste-rock piles: the Mahala, the Maid of Erin, the Wolftone, the Hamms and the Penrose. These five waste-rock piles were consolidated under four capped systems. In 1998, EPA constructed storm water run-on diversion channels and detention and retention ponds to collect storm water and snowmelt water, which is highly contaminated with AMD constituents. When necessary, overflow from the retention ponds was diverted to Strayhorse Gulch and subsequently to California Gulch via Starr Ditch. In 2001, EPA began to divert upper Strayhorse Gulch run-off water into the Marian standpipe, which delivers water to a lateral tunnel at about 132 feet below the ground surface. This lateral tunnel extends from the RES southward to the Mahala shaft. Some of the runoff also infiltrates to the subsurface into unconsolidated deposits and migrates as interflow to Strayhorse Gulch and mine workings, including the RES.

During the summer of 2003 five new wells were constructed to intercept the LMDT. The five tunnel wells are located at distances of 774 m (2515 ft), 1131 m (3677 ft), 1436 m (4666 ft), 2309 m (7505 ft) and 2967 m (9644 ft) from the portal (these distances are from the original portal location, which no longer exists – the current portal location was excavated in 1989). Two of the tunnel wells, LMDT 46+66 and LMDT 96+44 did not directly intercept the tunnel but intercepted fractures that are connected to the LMDT at 106 m and 157 m below the surface, respectively. Both of these wells are within 4.5 m of the tunnel. The other three wells were constructed at existing, cased exploration holes that were drilled prior to the tunnel construction and located along the proposed tunnel alignment. The holes were drilled to obtain stratigraphic and lithologic information. The existing holes were reamed out; deepened and monitoring wells were constructed in the tunnel. These five wells were sampled in February and June 2004. Data from the February 2004 sampling event is included in Table 4 for the five wells, the Robert Emet shaft (RES) and the LMDT portal discharge (INF-1).

Table 4 - Data for field parameters, SO_4^{-2}, Cd, and Zn - LMDT wells – February 2004

WELL	Distance from portal (m)	PH	Cond.	TDS (mg/l)	T Degrees C	SO^4 (mg/l)	Cd (ug/l)	Zn (ug/l)
RES	3000	3.50	3948	4676	3.5	4138	2200	305,000
96+44	2893	7.09	366	245	7.2	65	1	79
75+05	2251	7.61	382	178	5.0	19	2	154
46+66	1367	6.63	786	427	7.4	427	15	4740
36+77	1103	6.70	1033	813	7.8	442	17	5470
25+15	754	7.04	882	560	5.8	285	8	2740
INF	portal	7.04	733	520	8.7	251	7	2370

Based on interpretation of the data from both sampling events the following conclusions are presented:

a) Mean concentrations of AMD constituents are relatively low for the five LMDT tunnel wells, the INF-1 discharge and the locations to the northeast of the LMDT. This indicates that only a small part of the total metals load at INF-1 is due to infiltration of contaminated leachate into the RES or workings that are connected to and upgradient of the RES. Mean concentrations are also relatively low for all of the bedrock wells located in Evans Gulch and lower California Gulch. Mean concentrations of AMD constituents are also relatively low at the Canterbury Tunnel, the Elkhorn shaft, the Mab shaft, the Gaw shaft and the Valentine shaft.

b) The great difference in concentrations of numerous parameters between the RES and well 75+05 indicates that the source of water to well 75+05 is not (primarily) the RES. The chemistry of the water from well 75+05 suggests that there is significant ground-water inflow to the LMDT near well 75+05. The June 2004 temperature at well 75+05 (6.8 C) also is consistent with a ground-water inflow.

c) The increase in AMD constituents (decrease in pH) between well 75+05 and well 36+77 indicate that there may be an inflow to the LMDT near well 46+66. The Pendery fault crosses the LMDT between well 46+66 and 36+77. The section of the LMDT between well 75+05 and well 46+66 passes beneath mine workings that are excavated in the Leadville Limestone beneath the northwest slopes of Fairview Hill. Inflow from the Pendery fault and/or inflow from these mine workings are possible sources of water to the LMDT. The slight increase in metals would suggest that there is inflow from the overlying mine workings.

d) The decrease in concentrations of AMD constituents between well 36+77 and INF-1 suggest that there is inflow to the LMDT from alluvial deposits down-tunnel from well 36+77. The alluvial ground water has low concentrations of AMD constituents and d is significantly warmer –as indicated by the temperature of 10.0C at well 25+15.

<u>Metals Loading to INF-1</u>

To evaluate and compare metal loadings associated with the leachate from the waste rock piles in upper Strayhorse Gulch and total metals loads at the LMDT Treatment Facility inflow (INF-1) a flow-weighted mass-balance loading analysis was completed for Zn, Mn, Fe and Cd (Wireman and Gertson, 2005). Two data sets are used: long-term annual loading for INF-1 and spring runoff load for 2003 and 2004 for both the INF-1 and the Marian system. The long-term loading data for INF-1 was obtained from water quality sampling conducted weekly by the USBR beginning in June 1992. Water quality samples were analyzed for total recoverable metals. The 2003 and 2004 spring runoff data are based on total recoverable metals data from samples collected by the USBR from the Marian pond and INF-1. These samples were analyzed specifically for total Zn, Fe, Mn, and Cd. During spring runoff in 2003 and 2004 water quality samples were obtained from the Marian pond and INF-1 using an ISCO auto sampler that collected a composite water sample once a day from 4 different aliquots, six hours apart.

Key conclusions from the flow-weighted loading analysis include:

a) Annual loading at INF-1 for Zn, Fe, Mn, and Cd has reduced significantly since 1996. Annual Mn loads at INF-1 during the period from 2001-2004 have been reduced by 25% relative to the period from 1993-1996. Zinc loads have been reduced about 17% for the same time periods.

b) In 2003 approximately 53 – 54 % of the Zn and 36 -64% of the Mn delivered to the Marian standpipe did not reach INF-1. In 2004 approximately 36 -69% of the Zn and 10-94% of the Mn delivered to the Marian standpipe did not reach INF-1. It is not known with certainty where the metals are lost. However, it is possible that some water moves southward in the lateral tunnel that is connected to the Marian shaft at 132 feet below the surface. Regional ground-water flow direction in the vicinity of the RES and LMDT flows southwestward. Thus any water that is lost to the south from the Marian shaft, and recharged to the regional flow system, would not reach the LMDT. The loss of dissolved metals due to precipitation resulting from redox reactions was also considered. Attempts were made to collect sludge samples from the bottom of the LMDT using two of the LMDT wells. A downhole camera was lowered down three of the five tunnel wells. It was determined that very little sludge occurs within the LMDT.

Water Isotope Data.

From November 2002 through June 2004, 56 locations within the Leadville mining district were sampled numerous times for stable and radioactive water isotope analysis. Sampling locations include nine surface water locations, 12 ground-water locations, 16 mine water locations, six springs, two locations which are mixtures of ground water, surface water and spring water and 11 precipitation locations (Table 5). Samples were collected and analyzed for ^{18}O (288 samples), Deuterium (90 samples) and ^{3}H (244 samples). Data from these isotopic analysis were used to assess sources of water to the LMDT and residence times of ground water.

Deuterium and ^{18}O

A plot of delta ^{18}O vs. delta deuterium, using the 90 samples for which both deuterium and ^{18}O were analyzed is shown in Fig. 5. The slope of the local meteoric water line (LMWL) is very close to the global meteoric water line (8.13) and almost all of the data points are on or very close to the LMWL. This indicates that evaporation is not a major fractionation process for the waters that were sampled for this investigation. Figure 6 is a plot of delta ^{18}O vs. delta deuterium for the non-rain samples included in Fig. 5. It is clear from Fig. 6 that all of non-rain samples are highly depleted in ^{18}O with values falling between -16 ‰ to -19‰. ^{18}O values for ground water fall within an even narrower range, -17.5 ‰ to -18.5‰. ^{18}O values for mine water (including LMDT tunnel wells) range from about -17 ‰ to -19‰. These values are still highly depleted, though perhaps representing some mixing with slightly more enriched waters. Surface water and spring samples are slightly more enriched with ^{18}O values ranging from -16 ‰ to -17‰. For most of the mine and ground-water samples, the delta^{18}O median values cluster around -18.2‰. These results suggest that much of the recharge to the subsurface system at Leadville occurs during snowmelt runoff. Rainwater does not appear to make much of a contribution. Delta^{18}O values of surface waters show a greater range with median values around -16‰, indicating a contribution of rain water to surface flows at certain times of the year.

Table 5 – Isotope Analysis Statistics –LMDT Hydrogeologic Investigation

		Precipitation		Ground	Mine	Spring	Surface
		Snow	Rain	Water	Water	Water	Water
Delta D (o/oo)	N	17	22	12	16	7	16
	Mean	-148.15	-60.82	-140.05	-137.06	-132.46	-129.41
	Min	-165.12	-94.77	-143.20	-145.00	-140.00	-135.80
	Max	-111.32	-23.63	-136.90	-130.00	-128.00	-113.00
Delta ^{18}O (o/oo)	N	23	25	66	86	33	55
	Mean	-18.87	-9.70	-18.15	-18.00	-17.25	-16.28
	Min	-21.94	-16.81	-18.65	-19.07	-18.82	-20.63
	Max	-13.97	-4.28	-16.81	-12.49	-13.43	-8.88
Tritium (TU)	N	6	0	65	84	33	56
	Mean	10.77	_	7.66	9.98	11.78	10.77
	Min	10.2	_	0.08	0.48	6.8	5.3
	Max	10.5	_	13.6	18.4	21.2	15.7

The delta^{18}O values for INF-1 showed very little variation with values from 13 samples ranging from - 18 ‰ to -18.30‰. In contrast, delta^{18}O values from Marian samples ranged from -18 ‰ to -9‰ with a median of -11.5‰. Similarly, delta^{18}O values for RES samples ranged from -18 to -11‰ with a median of -16‰. The values for the RES and the Marian suggest that water at these locations includes significant amounts of surface runoff. Note also that there is almost no overlap in delta^{18}O values between INF1 and either RES or Marian. At all times the delta^{18}O values for RES and Marian are more enriched than for INF1. The large difference in delta^{18}O values between INF1 and the RES and the Marian sites suggests that neither the RES nor the Marian make significant contributions to the discharge at INF1.

Tritium

Somewhat unexpectedly, ^{3}H values had a wider spread than delta^{18}O values, ranging from a low of 0.08 TU to a high of 21.2 TU. No rain samples were analyzed for tritium. The six snow samples ranged from 10.2 to 10.5 TU with a mean of 10.8 TU. The snow samples represent the current atmospheric contribution of ^{3}H to the hydrologic system of Leadville. Thus, ^{3}H values around 10 TU represent recent water. Values of ^{3}H greater than about 10 TU indicate a bomb-spike source from atmospheric testing of nuclear bombs in the 1960's. Values of ^{3}H less than 10 suggest no bomb-spike, though it is still possible to have a small amount of bomb-spike water

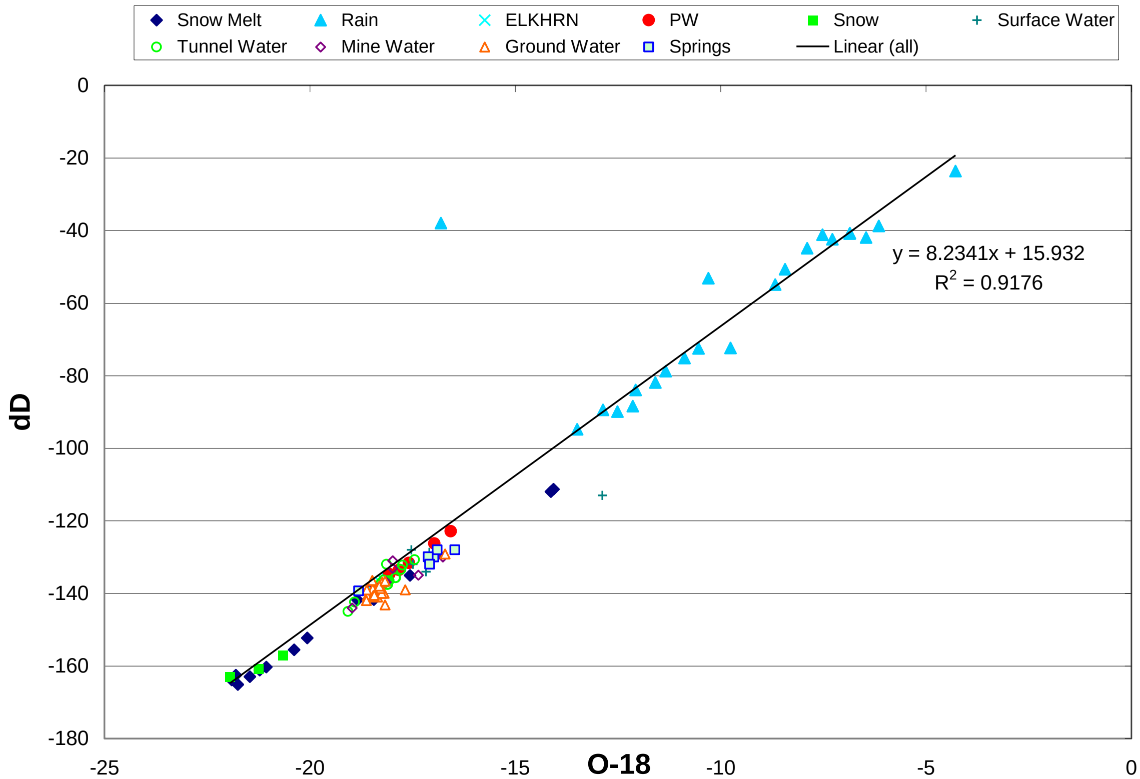

Figure 5 - Delta 18 O vs Delta Deuterium - LMDT Hydrogeologic Investigation

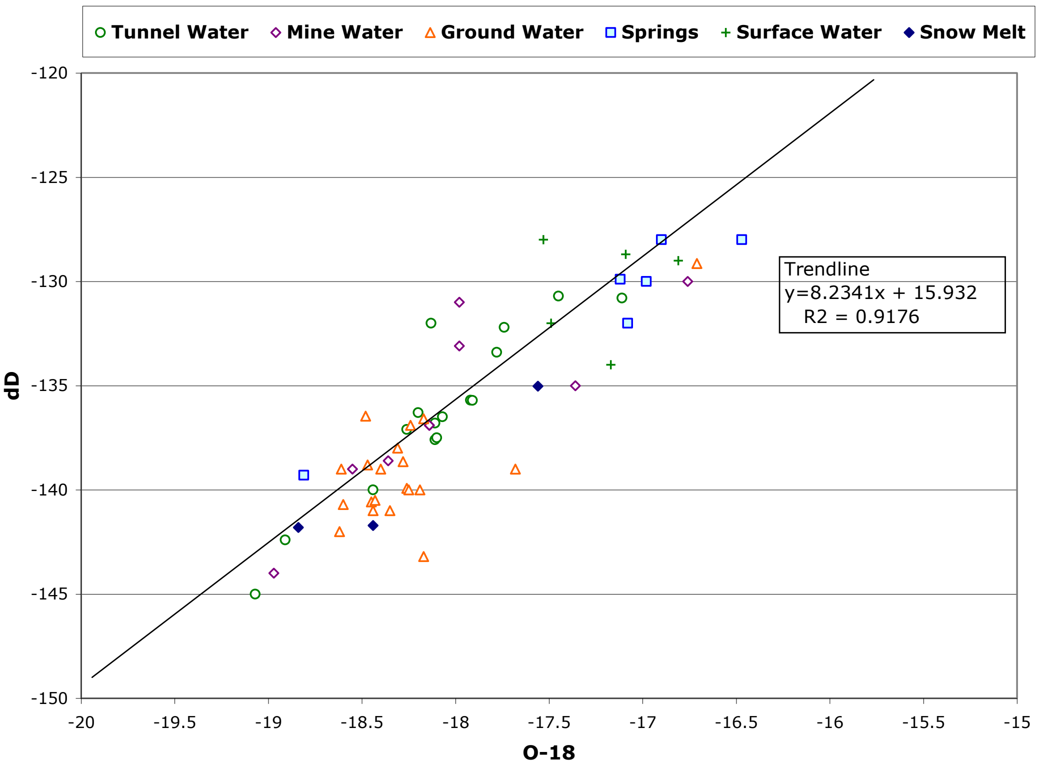

Figure 6 - Delta ^{18}O-vs Delta D-Non-Rain Samples, LMDT Hydrogeologic Investigation

mixed with large amounts of very old water with little or no ^3H. In general, the lower the ^3H value below 10 TU, the older the average age of the water.

There was also a large variation in the ^3H values for each of the components of the hydrologic system. The 65 ^3H values in ground water ranged from almost undetectable at 0.08 TU to 13.6 TU, with a mean of 7.66 TU. The 85 ^3H values for mine waters ranged from 0.48 to 18.4 TU with a mean of 9.98 TU. The 33 ^3H values for spring water ranged from 6.8 to 21.2 TU with a mean of 11.78 TU. The 56 ^3H values for surface waters ranged from 5.3 to 15.7 TU with a mean of 10.77 TU. This variation probably reflects the fact that there are multiple ground-water flow paths and most waters in the mining district are mixtures.

Tritium values also varied widely among sites. Sites with ^3H values below 1 TU, such as BMW3 (a deeper bedrock well), have water that is older than the atmospheric bomb spike of the 1960's. The average residence time of these ground-waters is greater than 50 years. Sites with ^3H values with TU less than 1 must represent very slow water movement and are not likely contributors to INF1 discharge. Sites with ^3H values greater than 11 TU must have a bomb spike signal and thus are a mixture with at least some waters that have not been in contact with the atmosphere since the 1960's. For example, water from the Elkhorn shaft ranges from 14 to 18 TU suggesting a substantial contribution of bomb spike water. The range of ^3H at INF1 from 10 to 12 TU suggests a combination of recent waters mixed with some bomb spike waters.

The ^3H values for selected sites shows clear differences in average residence time among sites. The ^3H values of about 6 TU with little change over time at the Canterbury Tunnel (the portal of this tunnel is northwest of the LMDT) suggest a regional ground-water source that is well-mixed, with an average residence time of about a decade. The range in ^{3}H values from 14 to 18 TU at the Elkhorn site suggest a regional ground-water signal with an average residence time of several decades, but one that is not well mixed. The range in ^{3}H values for Elkhorn appears to be related to pumping during the winter months for water resources by the local water supply agency. Prior to 2004, the PWC pumped water from the Elkhorn from November to June at a rate of 270,000 gallons per day to 330,000 gallons per day. From November 18, 2003 to May 3, 2004 approximately 120 acre-feet of water was pumped from the Elkhorn. The pumping of water from the shaft creates a cone of depression, bringing in newer water (possibly surface run in and shallow ground water) and lowering the ^{3}H values.

The ^{3}H values for samples from the Marian run-in water were generally between 9 and 10 TU, suggesting that most of the Marian run-in water was composed of new and/or recent precipitation, which is true. The ^{3}H values for RES were always greater than the Marian but tended to track changes in the ^{3}H values of the Marian. These ^{3}H values suggest that the RES water is a mixture of older water with a small bomb-spike signal and the new water from the Marian.

Water samples from INF1 showed a larger range in ^{3}H values than delta^{18}O values. The ^{3}H values for INF1 were very consistent at the start of sampling, always about 11 TU. Values then became enriched about two TU. The enrichment suggests a change in contributing waters, perhaps as a combination of the 2002 drought (which would lead to older water and higher ^{3}H values) and pumping at the Elkhorn. Here the real surprise is that there appears to be more information in the ^{3}H values than in the delta^{18}O values.

Ground-Water and Mine Pool Elevations and LMDT Discharge

To better understand ground-water flow within the area included in this investigation, ground-water elevation and mine-pool elevation data from 39 locations was compiled and analyzed (Fig. 7). These locations included 17 bedrock wells, 8 alluvial wells, 9 tunnel wells, 4 shafts and the bulkhead of the Yak Tunnel. Ground water and mine pool elevation data was obtained by measuring the depth to water in wells and shafts and the pressure behind the adit bulkheads and converting these data to elevations. Approximately 177,000 water-level elevation measurements were obtained from these locations between 1992 and 2004.

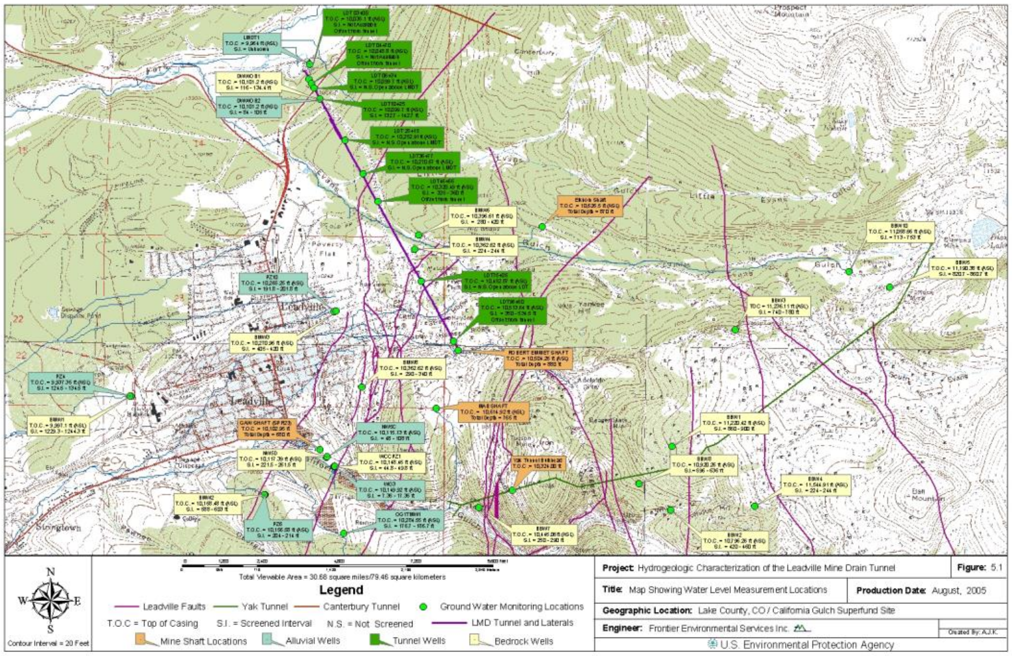

Figure 7 – Map Showing Water Level Measurement Locations

LMDT discharge data was obtained from the USBR for the period from January 1998 to July 2004. Discharge from the LMDT was measured 225 times during this period by the USBR (Table 6). The discharge includes the water pumped from two dewatering wells located about 315 meters (1025 ft) from the portal and the portal discharge. The section of the LMDT between the portal and the 10+25 well is collapsed, which prevents the USBR from keeping this section open. This prevents free flow from the portal. The collapse is related to the fact that the lower 1000 feet of the tunnel is constructed in unconsolidated glacial deposits and shallow bedrock of the semi-consolidated Minturn Formation. Therefore, it is necessary to remove water from the LMDT via two de-watering wells located near the 10+25 tunnel station.

Table 6 – LMDT discharge measurements (January 1998 – July 2004)

Year	# of measurements	Month	# of measurements
1998	43	January	17
1999	32	February	17
2000	39	March	17

2001	41	April	21
2002	34	May	25
2003	25	June	22
2004	11	July	19
		August	21
		September	19
		October	16
		November	17
		December	14
Total	225		225

Ground-Water & Mine Pool Water Level Data

Water level elevation data is useful for determining: (a) the magnitude and direction of ground-water flow and the extent to which bedrock and alluvial aquifers are hydraulically separated or connected, (b) the connection between the mine pools and bedrock ground water, (c) the hydraulic connection between the LMDT, the mine pools and the bedrock aquifer(s) and (d) the flow conditions within the LMDT between the Robert Emet Shaft (RES) and the portal.

Water levels in bedrock wells – Five of the seventeen bedrock wells are located in the vicinity of the LMDT, four bedrock wells are located in California Gulch and eight bedrock wells are located near the alignment of the Yak tunnel (Fig. 7). Ten of the 17 wells are screened in porphyry, five are screened in limestone or dolomite, one is screened in the Sawatch quartzite and one is screened in the Minturn Fm.

Water level elevations for the RES, and bedrock monitoring wells near the LMDT, are shown on Fig. 8 for the period from January 2003 through December 2004. As shown on Fig. 8 the hydrographs for wells BMW-3, BMW-5 and BMW-8 are very similar to the hydrograph for the RES. These hydrographs show that annual high water levels occur in October and November and annual low water levels occur in April and May. The difference between annual low water level elevations and annual high water level elevations is about 10 to 20 feet. The hydrograph for well BMW-4 has a different shape. It appears to be quite flat and does not show as much difference between annual high and low water levels. This is thought to be because well BMW-4 is completed above the bedrock potentiometric surface and water levels recorded for BMW-4 may reflect the inflow of alluvial water at the bedrock–alluvial contact.

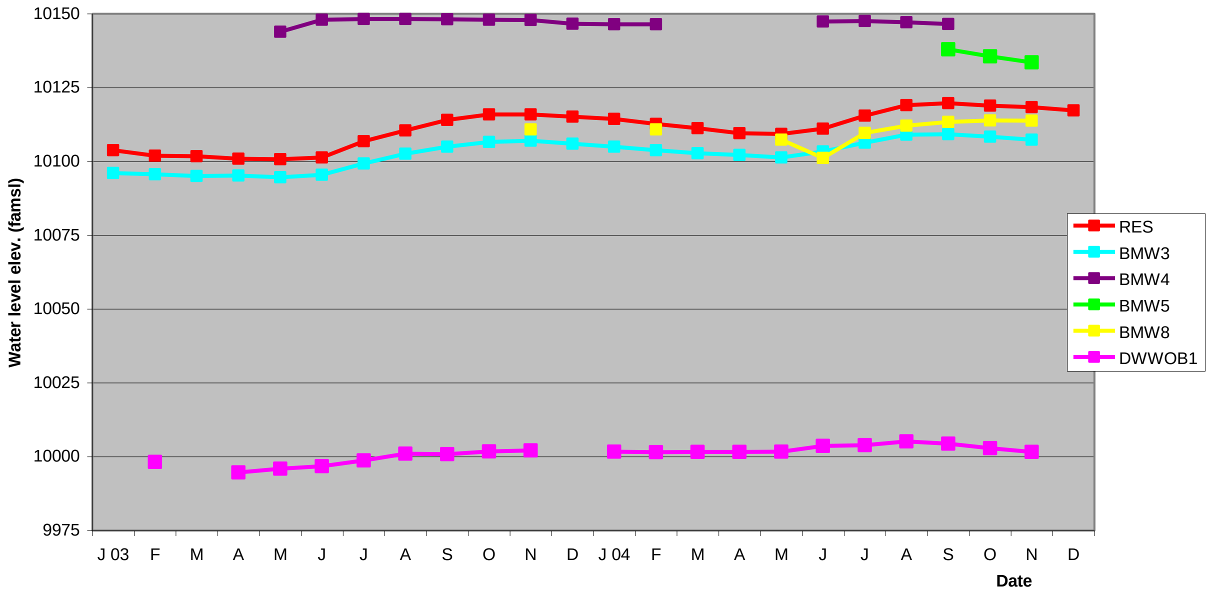

Figure 8 - Water Level Elevations - RES and Bedrock Wells in Vicinity of LMDT

Water level elevations for the RES and the four bedrock wells located in California Gulch are shown in Fig. 9 for the period January 2003 through December 2004. The hydrographs for all of these wells are similar and reflect a bedrock flow system hydrograph. Monitoring wells BMW-2, NW5D and WCCPZ1 are located between the Pendery Fault and the Cloud City fault. Monitoring well BMW-1 is located west of the Cloud City fault. Monitoring wells NW5D and WCCPZ1 are both constructed in the Pendery fault zone. Water levels in these wells indicate that this portion of the Pendery fault zone is a ground-water discharge area. As shown in Fig. 9 the water level elevation in well WCCPZ1 is about 25 feet higher than the water level in the RES. Well WCCPZ1 is located near the Yak tunnel surge pond. It is possible (though not known) that water levels in this well are affected by seepage from the surge pond. If this water level is unaffected by seepage from the surge pond, it indicates that some of the ground water discharging along the fault in California Gulch recharges the fault zone up-gradient (NE) of the RES. It is interesting to note that the water level elevation in well NW5D is above the RES during the annual low water level period (January through May) and below the RES during the annual high water period (June through December). This may be explained by the difference in time between high water levels at the location of the RES and the location of NW5D or it may be because well NW5D is screened across the contact between bedrock and the overlying alluvium. It is also interesting to note that the water level in well BMW-8 is always lower than NW5D and the RES. It is unclear why this relationship exists but it may indicate a cone of depression along the western edge of Carbonate Hill that results from discharge of bedrock ground water to the Canterbury tunnel.

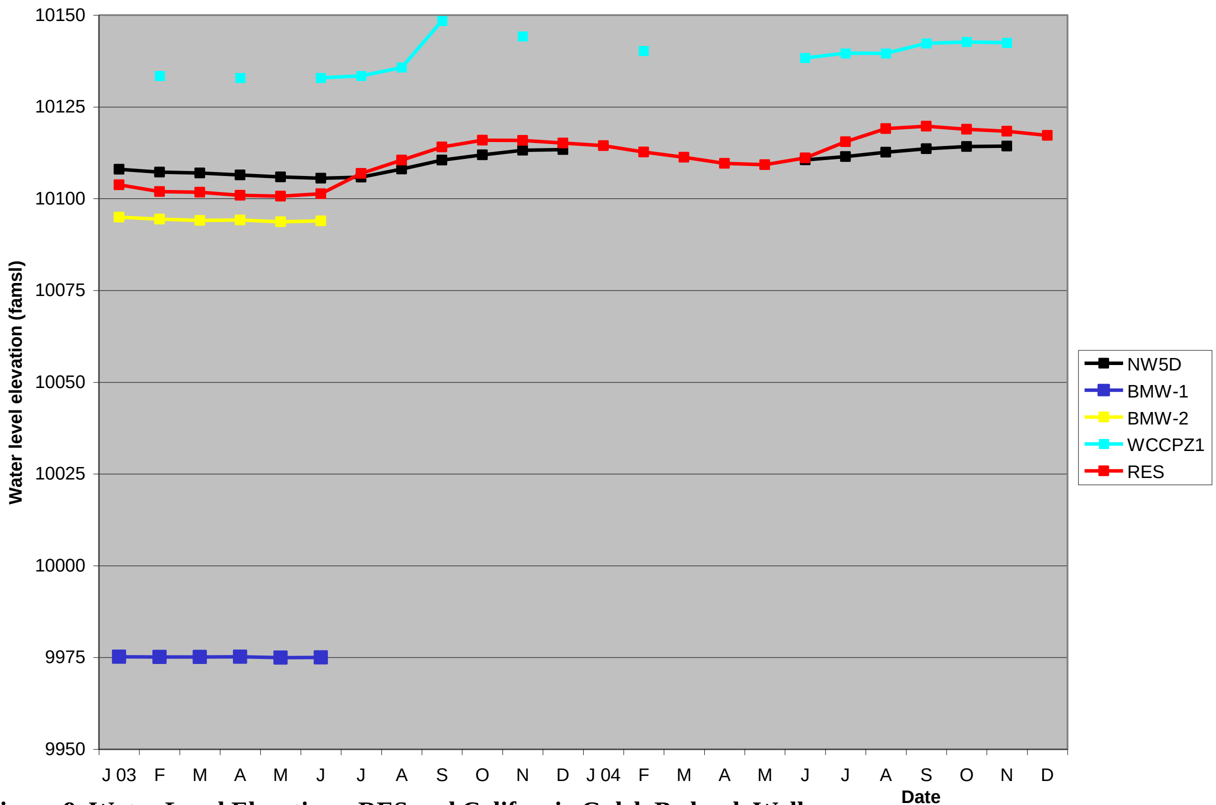

Figure 9 Water Level Elevations, RES and California Gulch Bedrock Wells

Water levels in shafts - Water level elevation data was obtained from four mine shafts as part of this investigation. The four shafts include the Elkhorn, the RES, the Mab and the Gaw (Fig. 8). Based on information form Emmons (1927) and Behre (1953) it appears that the RES and the Mab directly intersect mine workings or are connected to mine working via laterals. Apparently neither the Elkhorn nor the Gaw intersects any mine workings. The Elkhorn does not intersect extensive mine workings because the important ore deposits in the Leadville district did not extend very far north of Evans Gulch.

Hydrographs for the RES, the Mab shaft and the Gaw shaft are shown on Fig. 10 for the period from January 2002 through December 2004. As seen on Fig. 10, water level elevations for the RES and the Mab are within one foot of each other. This suggests that water levels in these two shafts are controlled by the same flow system. These two shafts are approximately 2000 feet apart and are probably connected via lateral tunnels at about 800 feet below the collar of the RES. Annual water level elevation for these two shafts varies from about 10,100 feet in April – May to about 10,120 feet during September –October. The water level elevation in the Gaw shaft is about 11 feet lower than the other two shafts. However, it is important to note that the elevation of the collar of the Gaw shaft is about 10,103 feet. Since no water level measurement higher than the collar of the Gaw can be measured, the high water level elevation at the Gaw is not known. However, historically it has been known that when the water level in the RES reaches 10,103 feet the Gaw shaft (SPR-23) flows. This is an indication that the water level elevation in the Gaw is controlled by the same flow system as the RES and the Mab. It can therefore be assumed that the high water level at the Gaw would be at least 10,120 feet. It is also important to note that the Gaw shaft was driven through 170-230 feet of unconsolidated deposits before encountering bedrock. It is very likely that there is some discharge from the Gaw into the unconsolidated deposits.

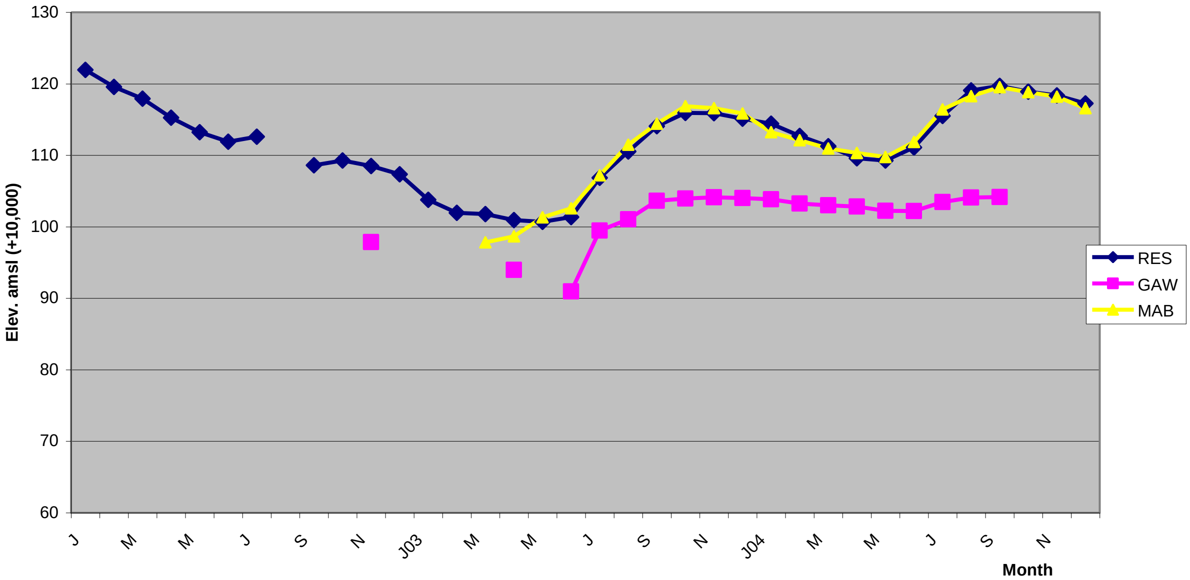

Figure 10 - Water Level Elevations in the RES, Gaw Shaft & Mab Shaft - Jan. 2002 - Dec. 2004

Historical shaft water level - Mines in the Carbonate Hill, Fryer Hill and Downtown areas were abandoned in the 1930s and over the next few years the workings filled up with water. Water level elevation measurements from the late 1930s provide an estimate of static ground-water levels in the mine pools. Hedges (1940) reported water level elevations for the Daly, Greenback and Penrose shafts as follows: Daly – 10220 feet (famsl); Greenback – 10165 famsl and Penrose – 10132 famsl. These water level elevations provide an indication of ground-water flow direction prior to the construction of the LMDT. Based on these elevations, ground-water flow was from NE to SW.

Water Levels in LMDT Tunnel Wells

There are nine wells constructed in or near the LMDT. Approximately 96,000 water level measurements have been collected from these wells. Water level elevations for the nine wells are shown in Fig. 11 for the period from October 2003 through December 2004. As shown in Fig. 11 there is a drop of about 100 feet in water level elevation between wells 46+66 and 36+77. This drop in water level elevation may be related to the Pendery fault zone, which crosses the LMDT at about 4000 feet. The Pendery fault zone is know to be relatively permeable and may drain water from the tunnel. The drop in water level may also be due, in part, to a blockage in the tunnel below the fault.

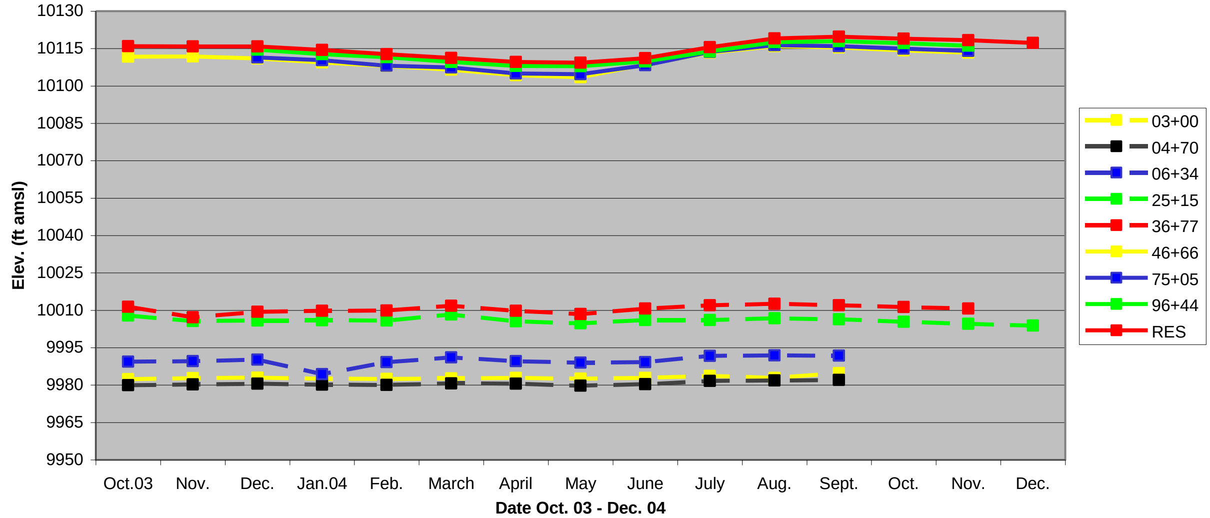

Figure 11 - Water Level Elevations - All Tunnel Wells & RES (Pendery Fault @ 4000 ft From LMDT

Hydrographs for the three tunnel wells above (southeast of) the Pendery fault, the RES and well BMW-3 are shown in Fig. 12 for the period from October 2003 through December 2004. The hydrographs for the three tunnel wells are very similar to the hydrograph for the RES and are very similar to bedrock well hydrographs and shaft hydrographs. As seen on Fig. 12 the high water levels occur in September- October and the low water levels occur in April- May. The difference between annual high water levels and annual low water levels is about 7 to 10 feet. This is an indication that water levels in these wells are influenced by regional bedrock flow. Water level elevations for five tunnel wells below (northwest of) the Pendery fault are shown in Fig. 13 for the same time period. These hydrographs are very different from those for the tunnel wells above the Pendery fault. There is only a 2 to 3 feet difference between annual high water level and annual low water levels. For wells 36+77, 25+15 and 6+34 the high water levels seem to occur in March and then again in August. The hydrographs in Fig. 12 and 13 indicate that the lower tunnel wells are influenced by a different source of water than the upper tunnel wells. As discussed previously the first 2000 feet of the LMDT is constructed in thick glacial deposits and semi-consolidated bedrock. From 2000 feet to the RES the tunnel is constructed in consolidated bedrock.

<u>LMDT Discharge</u>

LMDT discharge for the 14-year period from 1987 to 2001 varied between 2 and 4 cfs (approximately 900 to 1800 gpm). Discharge declined from a high of 4 cfs in late 1987/early 1988 to a low of 2 cfs in 1992. Discharge remained relatively low until 1997. Discharge increased from about 2.25 cfs in 1996 to 4 cfs in 1999. There were relatively high precipitation years in 1992, 1995 and 1996. Discharge from the LMDT was low during these years with discharge increasing significantly starting in 1997. This indicates a significant lag time between wet years with high ground-water recharge and high discharge from the LMDT.

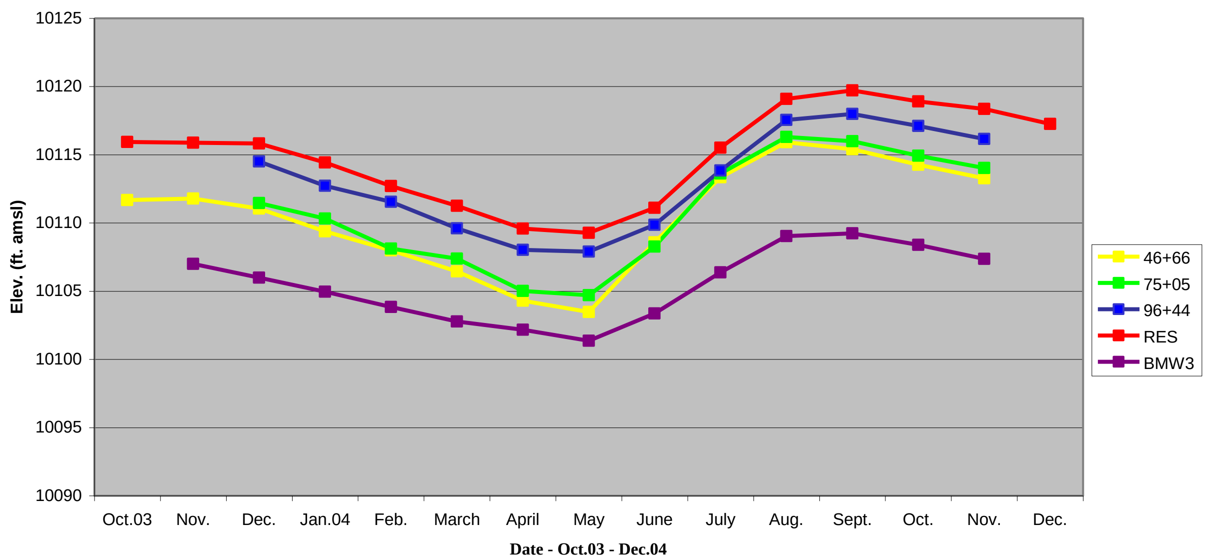

Figure 12 - Water Level Elevations - Tunnel Wells Above Pendery Fault, RES & BMW-3 - Oct. 2003 - Dec. 2004

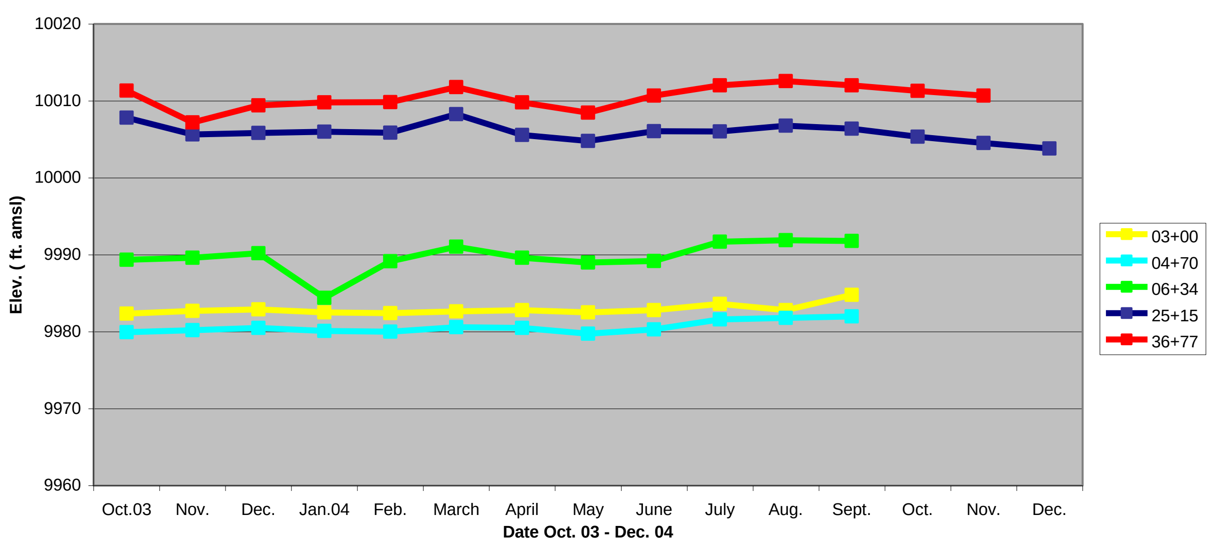

Figure 13 - Water Level Elevations, Tunnel Wells Below Pendery Fault - Oct. 2003 - Dec. 2004

Annual mean discharge from the LMDT for the years 1998 to 2004 is shown in Fig. 14. For the period from 1998 to 2000, the mean annual flow was between 3 and 3.5 cfs (1350 to 1570 gpm). Between 2000 and 2003, the mean annual discharge declined to about 2.5 cfs (1125 gpm). This decline is likely associated with the severe drought that began in about 1999 – 2000 in Colorado and other western States. Data through July 2004 indicate that the steady decline has slowed. This likely corresponds to the increase in annual snowfall in 2003-2004.

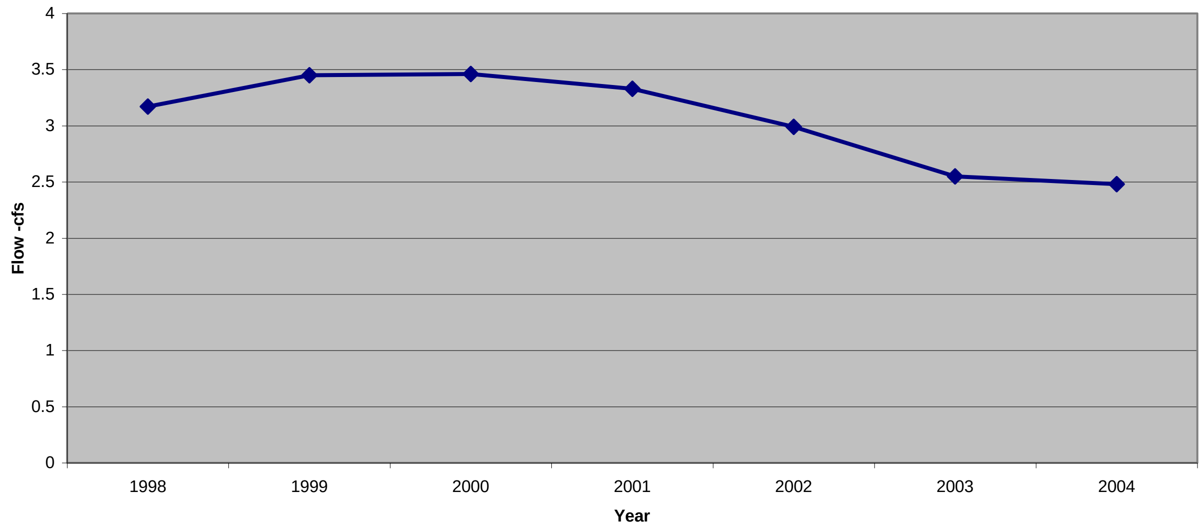

Figure 14 LMDT Mean Annual Discharge, January 1998 –July 2004

Figure 15 is a hydrograph of mean monthly discharge for the LMDT for the same period. This hydrograph has a similar shape to hydrographs of bedrock wells and shafts. The low discharge occurs in February and the high discharge occurs in September. However, a second peak occurs on this hydrograph in March-April. This peak is about 0.3 cfs lower than the September peak and may be due to inflow from snowmelt that infiltrates the alluvium and discharges into the lower portion of the LMDT. The difference between the low discharge in February and high discharge in September is about 0.4 cfs (180 gpm).

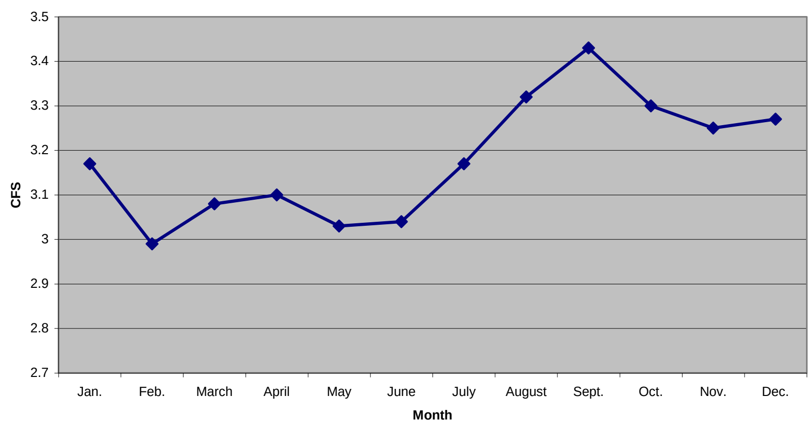

Figure 15 – LMDT Mean Monthly Discharge – January 1998 – July 2004

Findings

Key findings resulting from the LMDT hydrogeologic assessment are presented below. Key findings are grouped into the following areas: (1) findings related to the ground-water flow system(s) that occur within the bedrock formations that underlie the mining district, (2) findings related to the source(s) of water to the LMDT and flow and chemistry of water within the LMDT, and (3) findings related to metals loads at INF-1.

Ground-water flow system.

The following findings are based on analysis of water level data, water chemistry data, geologic data, mine maps and analysis of isotopic data.

a) High ground-water levels in bedrock wells occurs in October - November – low water levels occur in April – May

b) As clearly indicated by the delta ^{18}O data the primary source of ground water recharge to the bedrock aquifers is snowmelt

c) Based on potentiometric surface elevation data, the regional flow direction in the bedrock aquifers is from the NE to the SW. Locally there is significant variation in flow direction due to the interception of bedrock ground water by mine workings

d) Data show that in most areas there is an upward vertical gradient in ground-water flow – ground water in the bedrock flows upward and discharges into the overlying glacial / alluvial deposits.

e) California Gulch below the Yak surge pond is a discharge area for ground water. It is likely that ground water flowing along the Pendery fault zone discharges into California Gulch. There may also be discharge of bedrock ground water into lower California Gulch.

f) A significant percentage of the recharge to the Leadville Limestone and the Manitou dolomite occurs in upper Evans Gulch. Residence time for this bedrock ground water (the time from recharge to discharge) is about 5-10 years. Discharge occurs to mine workings in lower Evans Gulch, to the glacial deposits adjacent to Evans Gulch (east of Mikado fault), possibly to California Gulch and eventually to the Arkansas River.

g) The gradient on the potentiomentric surface NE of the LMDT is steep (the tunnel is creating a line of depression) tunnel. The gradient is flat to the SW of the tunnel. This is an indication that bedrock ground water enters the LMDT from the NE.

h) The hydrographs for shafts, bedrock wells and upper tunnel wells (above Pendery fault) are all very similar. This indicates that water levels in tunnel wells and shafts are controlled by the bedrock ground-water flow system.

i) There is a 100 ft drop in head in the LMDT where it crosses the Pendery fault. The reason for this is not fully understood. It may be that the Pendery drains water from the tunnel or it may be that there is a blockage in the LMDT near the Pendery fault, which causes the water in the tunnel to pond up behind the blockage.

j) Hydrographs for upper tunnel wells very different from hydrographs for lower tunnel wells. This indicates that these water levels are not controlled by the bedrock flow system. Water level data and empirical observations indicate that ground water discharges into the LMDT from adjacent unconsolidated deposits below the 2500 tunnel station.

k) The LMDT annual discharge hydrograph is very similar to RES annual water level hydrograph. This indicates that the bedrock flow system dominates inflow to the tunnel.

Source(s) of Water to the LMDT and Flow and Chemistry of Water Within the LMDT

The following findings are based primarily on analysis of water chemistry data and stable and radioactive water isotope data:

a) Only two sources of high Zn have been identified, (1) leachate from infiltration of precipitation and run-off water through waste rock piles in upper Strayhorse Gulch and (2) water stored in mine workings that are drained by the Yak tunnel

b) The chemistry of LMDT water is very different than the chemistry of water in the RES.

c) The mine pool water, as represented by water in the RES, is not a significant source of water to the LMDT.

Metals loading at Inf-1

Results of the detailed flow-weighted mass balance loading analysis indicated the following:

a) The annual load of at INF-1 for Fe, Zn, Mn and Cd has declined significantly since 1996. This is because, starting in 1997 the US EPA has been diverting contaminated run-off from upper Strayhorse Gulch down the Marion standpipe. Most of the water put down the Marion does not go to the LMDT.

b) During the 2004 runoff period of 32 days the INF-1 received about 25% of it's annual load of Zn, Fe and MN and about 40% of it' annual cadmium load.

c) In 2003 approximately 54% of the Zn load delivered to the Marion standpipe did not reach INF-1.

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