



Investigating hydraulic connections and the origin of water in a mine tunnel using stable isotopes and hydrographs

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ABSTRACT

Turquoise Lake is a water-supply reservoir located north of the historic Sugarloaf Mining district near Leadville, Colorado, USA. Elevated water levels in the reservoir may increase flow of low-quality water from abandoned mine tunnels in the Sugarloaf District and degrade water quality downstream. The objective of this study was to understand the sources of water to Dinero mine drainage tunnel and evaluate whether or not there was a direct hydrologic connection between Dinero mine tunnel and Turquoise Lake from late 2002 to early 2008. This study utilized hydrograph data from nearby draining mine tunnels and the lake, and stable isotope ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) data from the lake, nearby draining mine tunnels, imported water, and springs to characterize water sources in the study area. Hydrograph results indicate that flow from the Dinero mine tunnel decreased 26% (2006) and 10% (2007) when lake elevation (above mean sea level) decreased below approximately 3004 m (approximately 9855 feet). Results of isotope analysis delineated two meteoric water lines in the study area. One line characterizes surface water and water imported to the study area from the western side of the Continental Divide. The other line characterizes groundwater including draining mine tunnels, springs, and seeps. Isotope mixing calculations indicate that water from Turquoise Lake or seasonal groundwater recharge from snowmelt represents approximately 10% or less of the water in Dinero mine tunnel. However, most of the water in Dinero mine tunnel is from deep groundwater having minimal isotopic variation. The asymmetric shape of the Dinero mine tunnel hydrograph may indicate that a limited mine pool exists behind a collapse in the tunnel and attenuates seasonal recharge. Alternatively, a conceptual model is presented (and supported with MODFLOW simulations) that is consistent with current and previous data collected in the study area, and illustrates how fluctuating lake levels change the local water-table elevation which can affect discharge from the Dinero mine tunnel without physical transfer of water between the two locations.

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1. Introduction

Draining, inactive mine tunnels degrade water quality in many areas where mining occurred (Younger and Wolkersdorfer, 2004). Remedies range from construction of active and passive treatment systems (Younger et al., 2002; Walton-Day, 2003; Johnson and Hallberg, 2005), to hydraulic mitigation, which can include surface controls to limit infiltration that recharges the groundwater flowing from the mine tunnels and (or) installation of bulkheads (Colorado Division of Minerals and Geology, 2002; Marks et al., 2006). The implementation of successful hydraulic remedies and management to prevent remedies from causing additional damage (for example, by redirecting tunnel flow to a less desirable exit point) depends, in part, on identifying sources of groundwater to the mine tunnels.

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Many draining mine tunnels exist in mountainous areas where groundwater occurs in fractured-rock aquifers. Characterization of groundwater flow in these areas is often challenging due to difficult or seasonal access and a lack of wells. Complete characterization of the hydraulic properties of fractured rock is generally a multidisciplinary exercise using hydrologic, geologic, geophysical and geochemical techniques (Shapiro et al., 1999; Wireman, 2003). Adequate resources for comprehensive study are not often available so studies adopt techniques suited to the hydrologic, geologic, and geographic conditions, and available resources. Accordingly, researchers have used many different approaches to characterize the hydrology of fractured rock in mountainous areas. Monitoring water levels and water quality in boreholes and mine shafts in an extensive network of abandoned mine workings enabled hydrologic description of a large mine pool in the Leadville, Colorado, USA, mining district, which has complex geology that includes abundant fractures (Wireman et al., 2006). Collection and analysis of groundwater noble-gas, age, and temperature

signatures aided development of a conceptual hydrologic model in a Colorado alpine watershed containing an unmined mineral deposit in fractured rock (Manning and Caine, 2007). A multidisciplinary approach including geophysical, geochemical, and hydro-metric techniques enabled characterization of groundwater conditions in another Colorado alpine watershed affected by mine drainage (Ray Johnson, US Geological Survey, pers. comm., 2008).

In a few recent studies, the source of groundwater in mine tunnels has been established by locating sources of greatest mass load of contaminants to mine tunnels (Hazen et al., 2002; Marks et al., 2006). In these studies, rehabilitation activities (such as removal and structural reinforcement of mine tunnel collapses and enhanced ventilation) enabled safe access to parts of the underground workings. Sampling water flow and water-quality properties including pH and trace metal concentrations (Marks et al., 2006) and stable isotopes (Hazen et al., 2002) at locations where groundwater entered the mines and in relevant endmembers, enabled assessment of water sources that contributed the greatest metal loads exiting mine-tunnel portals. Specific hydrologic remediation (for example, grouting, underground plugging, and redirecting water flow away from mine tunnels) targeted the most impaired water sources, and subsequent sampling indicated load reductions of metals of concern were greater than 90% at the mine-tunnel portals (Hazen et al., 2002; Marks et al., 2006).

Despite the complexity of flow in fractured rock, studies of groundwater in the Rocky Mountains in Colorado indicate some generalizations that likely apply to the current study area. Snowmelt probably provides high rates of seasonal recharge to groundwater. In two other study areas, snowmelt recharge in headwater areas of catchments has supported up to 50 m (164 feet) (Manning and Caine, 2007) and greater than 56 m (186 feet) (Johnson and Yager, 2006) of seasonal water-table fluctuation. In addition, these and related studies (Ray Johnson, US Geological Survey, pers. comm., January 2008) identified two general types of groundwater in these mountainous areas: shallow, active groundwater flow that is primarily supported by seasonal recharge from snowmelt; and deeper, inactive groundwater flow that also may be recharged by snowmelt, but has longer residence times and exhibits less seasonal variation in temperature and geochemical properties. The interplay of shallow and deep groundwater in mountainous watersheds has also been discussed by Snow (1968) and Mayo et al. (2003).

Stable-isotope ratios in water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) are used to understand the origins of water in various environments (Coplen et al., 2000; Kendall and Caldwell, 1998). Isotopes of water are generally non-reactive in aquifers over relatively short time scales. At the surface, isotopic signatures of water can be altered by evaporation, and in the subsurface, isotopic signatures of water can be altered over long time scales by geothermal exchange and water–rock interaction (Clark and Fritz, 1997). Studies have demonstrated the use of isotopes to understand water sources in mountain environments (Chapman et al., 2003; Gurrieri and Furniss, 2004), mining environments (Gammons et al., 2007; Pellicori et al., 2005; Roesler et al., 2007), and in fractured-rock aquifers (Maréchal and Etcheverry, 2003; Barbieri et al., 2005).

The elevation or altitude effect describes the inverse relationship observed between the stable-isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) of precipitation and elevation; precipitation at higher elevations has lighter isotopic composition than that at lower elevations. This effect is caused by both the distillation of the parent condensing vapor that progressively becomes isotopically depleted as heavier isotopes are the first to rainout (through Rayleigh distillation), and the decrease in the temperature of condensation with elevation (Ingraham, 1998; Siegenthaler and Oeschger, 1980). In the study area, one of the dominant storm tracks is from west to east. Thus, storm water will become isotopically depleted as it moves

from west to east over the Continental Divide (Fig. 1); precipitation on the western side of the Continental Divide will be isotopically heavier than that on the eastern side. This idea leads to one hypothesis of this study: water in Turquoise Lake, which is largely derived from transmountain diversion of snowmelt from the western side of the Continental Divide, may be isotopically enriched relative to meteoric water from the eastern side of the Continental Divide. Therefore, stable-isotope ratios may be enriched in draining mine tunnels that receive water from Turquoise Lake relative to those having water derived primarily from watersheds on the eastern side of the Continental Divide. In addition, evaporation in Turquoise Lake could further enrich isotope compositions and enhance the ability to identify Turquoise Lake water in the subsurface using stable isotopes.

In this study, analysis of stable-isotope ratios in draining mine tunnels, transmountain diversion tunnels, streams, springs and seeps, a reservoir, and snowpack were used in conjunction with hydrographs and water-quality field measurements (pH and specific conductance) to evaluate the hypothesized hydrologic connection between draining mine tunnels (particularly the Dinero mine tunnel) and a nearby reservoir (Turquoise Lake) from 2002 through early 2008. The isotope data also were used to understand different sources of water to the study area and the Dinero mine tunnel, and to identify areas where mixing occurs. This approach represents a relatively low-cost, non-invasive method to evaluate a possible hydrologic connection between Turquoise Lake and the draining Dinero mine tunnel.

1.1. Study area and background

Turquoise Lake, a reservoir created behind Sugarloaf dam (with 160 million cubic meter (MCM) or 129,400 acre-feet active storage capacity; Bureau of Reclamation, 2003), lies along Lake Fork Creek, a tributary to the upper Arkansas River near Leadville, Colorado (Fig. 1). The reservoir collects native runoff from the Lake Fork Creek drainage basin upstream from the dam and also collects and stores water imported from the west side (west slope) of the Continental Divide through three transmountain diversion tunnels: the Charles H. Boustead (Boustead) tunnel, the Homestake tunnel, and the Busk-Ivanhoe tunnel (Fig. 1). Turquoise Lake is part of the Fryingpan Arkansas Project (Fry-Ark Project) of the Bureau of Reclamation that delivers water from the west slope of the Continental Divide (the Colorado River drainage basin) to the Arkansas River Basin to be used for municipal and agricultural purposes. Storage in Turquoise Lake is sought after by water users because the lake has minimal loss to evaporation. Future management may entail enlarging the reservoir to maximize high-elevation (low-evaporation) storage capacity.

The Sugarloaf mining district is located south of Turquoise Lake. Mining in the Sugarloaf district (primarily of Ag and lesser amounts of Au, Pb, and Zn) began in the 1880s and production peaked before the 1893 drop in Ag prices; some mining activity continued until the 1920s (Singewald, 1955). Several abandoned, draining mine tunnels are at elevations lower than Turquoise Lake (Table 1) and some contribute poor-quality water to Lake Fork Creek downstream from the reservoir; mass-loading studies indicated that the Dinero mine tunnel and adjacent wetland area are the largest source of Zn and Mn loads to Lake Fork Creek downstream from Turquoise Lake (Walton-Day et al., 2005). The Bartlett, Dinero, and Siwatch mine tunnels are at elevations lower than Turquoise Lake and may be hydrologically connected to the lake. The Nelson and Tiger mine tunnels are at higher elevation than Turquoise Lake and are currently hydrologically isolated from the lake (Table 1). If there is a hydrologic connection between Turquoise Lake and draining mine tunnels and if Sugarloaf dam is enlarged, the elevation of Turquoise Lake would increase, which would

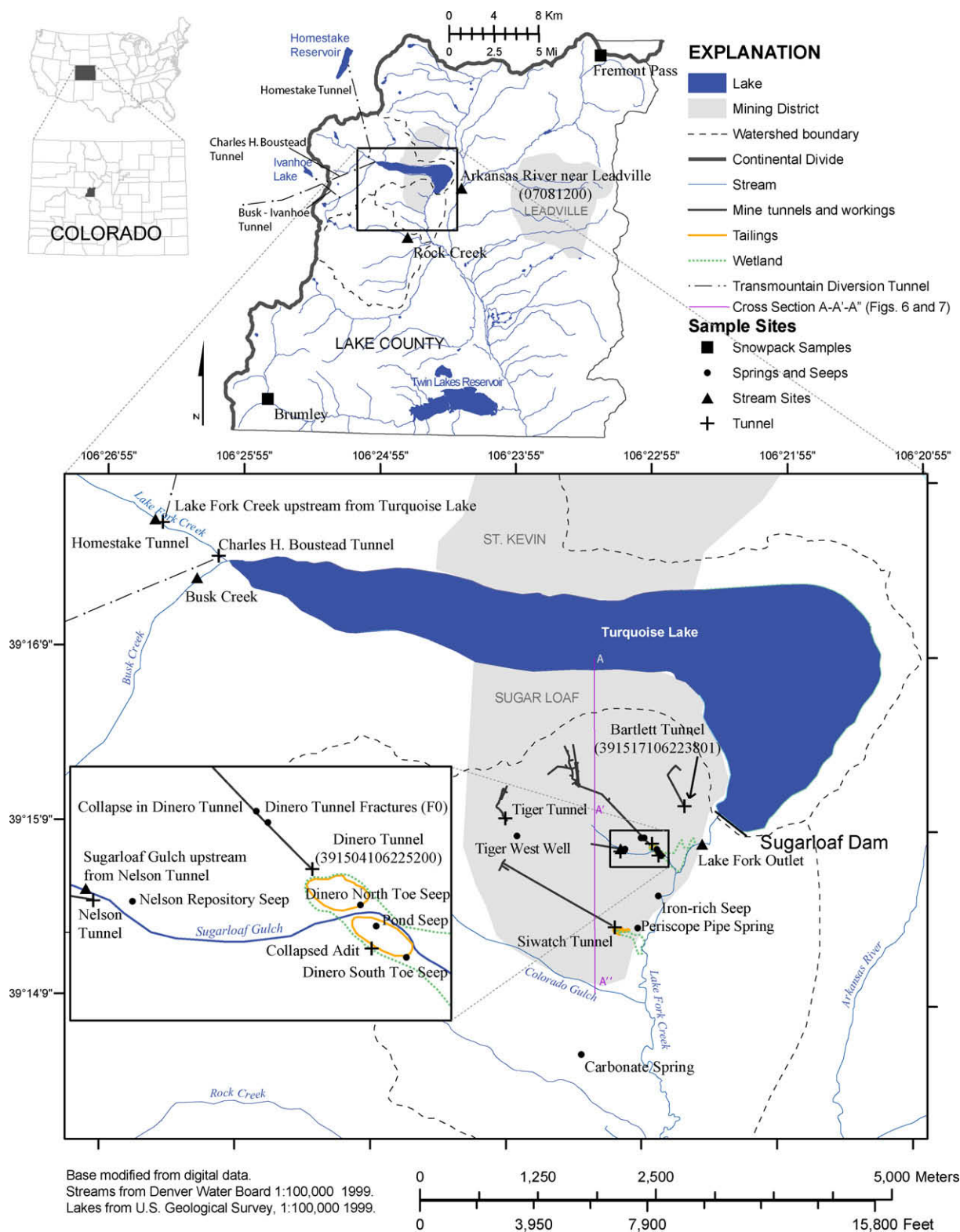


Fig. 1. Study area location map. Line A-A' generally locates the cross-section presented in Figs. 6 and 7. Line A-A'' represents the cross section used in the MODFLOW simulations.

increase the elevation of the local water table and potentially increase the discharge of poor-quality water from the mine tunnels. This action would likely further degrade the quality of Lake Fork Creek and the upper Arkansas River (Fig. 1).

Bedrock in the Sugarloaf mining district is crystalline granite and gneiss. A veneer of unconsolidated glacial deposits occurs around the southwestern shore of Turquoise Lake west of Sugarloaf

dam and continues as a glacial end moraine forming the eastern boundary of Turquoise Lake (Singewald, 1955). In the study area, groundwater flow likely occurs in interconnecting fractures and open mine workings in the crystalline rock.

Climate in the study area is typical for mid-continent high-elevation zones. Precipitation averaged 45 cm/a (average from 1971 through 2000) and occurred mostly as snow (Sugarloaf Reservoir

climate station; Western Regional Climate Center, <http://www.wrcc.dri.edu>, accessed, May 2008).

2. Methods

2.1. Hydrographs and stream gages

The US Geological Survey installed and maintains stream gages to record streamflow (discharge) at the Arkansas River near Leadville, the Dinero mine tunnel, and the Bartlett mine tunnel. The Arkansas River gage near Leadville (US Geological Survey site number 07081200) operated continuously throughout the study period (only published hydrographs were used from this site; it was not part of data collection efforts of this study). The Dinero mine tunnel gage (US Geological Survey site number 391504106225200) was installed and began operating on March 13, 2003, and continued through the study period except for part of 2004 when construction and rehabilitation in the Dinero mine tunnel interrupted operation. Rehabilitation in the tunnel may have caused a change in the baseflow conditions or other aspects of the Dinero mine tunnel hydrograph. The Bartlett mine tunnel gage (US Geological Survey site number 391517106223801) was installed on May 11, 2005, and operated continuously throughout the remainder of the study. At the Arkansas River gage near Leadville, stream stage is continuously recorded and is related to discharge using the methods of Rantz et al. (1982a,b). At the Dinero and Bartlett mine tunnel gages, tunnel discharge flows through v-notch weirs, stream stage is continuously recorded, and stage is related to discharge using equations for the weirs (Grant, 1992). Periodic measurements of streamflow using flumes (Dinero mine tunnel) and volumetric techniques (Bartlett mine tunnel) verified the weir measurements. For all three sites, data (average daily flow) are available by water year (starting October 1 of the previous year and running through September 30 of the water year) in paper copy through water year 2003 (Crowfoot et al., 2004, 2003, 2001—Arkansas River near Leadville only) and on the World Wide Web. Thereafter, data are available only on the World Wide Web (Crowfoot et al., 2005; US Geological Survey, 2006a, 2007, 2008). In addition, August et al. (2002) reported Dinero mine tunnel discharge using volumetric techniques at an average interval of 12 days starting September 1999 through September 2000. Although most data are archived according to water year, in the rest of this report the term “year” or “2002, 2003,” and so on refers to calendar year.

The Bureau of Reclamation records daily water elevation of Turquoise Lake forebay (http://www.usbr.gov/gp-bin/arc050_form.pl?TURQ, accessed September 2007). Full pool elevation of the reservoir is 3008.2 m above mean sea level (9869.4 feet). The reservoir collects and stores native streamflow from within the natural drainage basin of Lake Fork Creek upstream from Sugarloaf dam. Additionally, the Homestake, Boustead, and Busk-Ivanhoe diversion tunnels supply water to Turquoise Lake from the western side of the Continental Divide (Fig. 1). Locations where the Boustead and Homestake tunnels discharge directly into Turquoise Lake were sampled for this project (Fig. 1). Although the diversions to the tunnels were not always operating during sampling, there was sufficient water exiting the tunnels to collect water-quality samples. The Boustead tunnel is gravity fed from diversions on the western slope and drains even when there are no diversions from the west slope. Therefore, the water exiting the east end of the tunnel when diversion is not occurring likely represents native fracture flow seeping into the unlined Boustead tunnel. The gate for the Homestake tunnel is in the east (or Turquoise Lake) end of the tunnel. When the diversion is inactive and the gate is closed, the tunnel remains full of water. Therefore, streamflow exiting the

tunnel when the diversion is inactive is likely Homestake Reservoir water that is interacting with the concrete-lined tunnel and diluting or diverting any fracture seepage water that might enter the tunnel. The Busk-Ivanhoe tunnel discharges into Busk Creek which was sampled near the mouth where it flows into Turquoise Lake. These samples contained a mixture of native streamflow from Busk Creek and tunnel flow when the tunnel was active. The hydrograph of Turquoise Lake is generally controlled by the timing and magnitude of snowmelt runoff, deliveries of non-native water to the basin, and controlled releases from the reservoir to downstream users.

Discharge was recorded at Boustead tunnel, Homestake tunnel, Lake Fork Creek upstream from Turquoise Lake, and Lake Fork outlet by the Colorado Division of Water Resources (<http://cdss.state-co.us/streamflow> accessed April 2008, and Thomas Ley, Colorado Division of Water Resources, pers. comm., 2007). Average daily discharge from each sampling day is recorded in Supplemental Data Table 3. During 2006, discharge measurements were made at some sample sites using weirs and flumes (Grant, 1992).

2.2. Collection and analysis of water samples

Water-quality samples were collected periodically at six draining mine tunnels or collapsed adits, two transmountain diversion tunnels, five stream sites including the major inputs to and the outlet from Turquoise Lake, and 10 springs and seeps beginning in November 2002 and ending in October 2006 (Supplemental data Tables 1 and 2). Meltwater from two bulk snowpack samples (Brumley and Fremont Pass SNOTEL sites) collected near the study area was also analyzed. Most sites were sampled on 27 individual dates during the study period, and individual sites were sampled from 1 to 25 times. Rock Creek was sampled on five different dates (Supplemental data Table 1). Varying sampling frequency related to variations in the Turquoise Lake hydrograph, sampling needs determined from observations of seasonal data variability, and seasonal sample collection from potential isotope endmembers.

From 2002 through 2005, grab samples were collected at all water-sampling sites. At stream sites and transmountain diversion sites, grab samples were collected from the centroid of flow in the stream when flow conditions permitted wading. When flow from the transmountain diversion tunnels was too great to allow safe wading, grab samples were collected from the bank within 100 m downstream from the tunnel portal. At springs, seeps, and draining mine tunnels, sample collection occurred as close as possible to where flow emerged from the ground. During 2006, equal-width increment sampling was used at the stream sites to collect composite water samples over the width of the stream channel (US Geological Survey, 2006b). One spring (Periscope Pipe spring) flowed into a small closed basin. Samples were collected underwater in the basin from the area where groundwater, identified by “boiling” sand and rising gas bubbles, was actively flowing into

Table 1

Elevation of Turquoise Lake, mine-tunnel portals, and relative elevation between Turquoise Lake full pool elevation and mine-tunnel portals, Turquoise Lake isotope study [–, not relevant].

Location	Elevation, in meters (feet)	Elevation difference relative to Turquoise Lake full pool elevation, in meters (feet)
Turquoise Lake (full pool)	3008.2 (9869.4)	–
Bartlett mine tunnel	2991.6 (9815)	–16.6 (54)
Dinero mine tunnel	2977.9 (9770)	–30.3 (99)
Nelson mine tunnel	3017.5 (9900)	+9.3 (31)
Siwatch mine tunnel	2962.7 (9720)	–45.5 (149)
Tiger mine tunnel	3238.8 (10,626)	+230.6 (757)

Table 2

Dates and values of maximum annual elevation for Turquoise Lake and maximum annual discharge for Arkansas River near Leadville, Bartlett tunnel, and Dinero tunnel and annual runoff for Arkansas River near Leadville by calendar year, Turquoise Lake isotope study [CY, calendar year; ARO; annual runoff, in million cubic meters and (acre feet); –, no data].

CY 2000		CY 2003		CY 2004		CY 2005		CY 2006		CY 2007	
Date (month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)	Date(month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)	Date (month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)	Date (month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)	Date (month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)	Date (month/day/year)	Elevation, in meters (feet) or discharge, in cubic meters per second (cubic feet per second)
Arkansas River near Leadville (discharge data)											
5/30/2000	20.5 (725)	5/30/2003	21.3 (751)	6/8/2004	6.71 (237)	5/24/2005	11.0 (390)	5/27/2006	11.6 (410)	5/20/2007	11.2 (397)
ARO = 61.33 (49,720)		ARO = 54.16 (43,910)		ARO = 40.29 (32,660)		ARO = 48.27 (39,130)		ARO = 63.24 (51,270)		ARO = 62.56 (50,720)	
Bartlett mine tunnel (discharge data)											
–	–	–	–	–	–	5/30/2005–6/7/2005 except for 6/5/2005	0.002 (0.07)	5/25/2006–5/27/2006	0.0054 (0.19)	5/22/2007–5/25/2007	0.0042 (0.15)
Dinero mine tunnel (discharge data)											
5/12/2000	0.0057 (0.20)	8/2/2003	0.0062 (0.22)	4/27/2004 no data from 6/3/2004 to 11/12/2004	0.0057 (0.20)	5/7/2005	0.0054 (0.19)	5/29/2006	0.0088 (0.31)	7/5/2007	0.0065 (0.23)
						ARO = 0.123 (100)		ARO = 0.158 (128)		ARO = 0.159 (129)	
Turquoise Lake (lake level)											
6/8/2000	3008.1 (9869)	6/29/2003–9/30/2003	3000.8–3001.1(9845–9846)	7/4/2004	3003.8 (9855)	7/11/2005–9/6/2005	3006.9–3007.2 (9865–9866)	6/15/2006	3006.9 (9865)	7/5/2007–9/30/2007	3007.2–3007.5 (9866–9867)

the pool. The sample collected from the fracture in the Dinero mine tunnel was collected from dripping locations in the tunnel ceiling.

Four samples of snowpack were collected (two from Brumley, two from Fremont Pass) to help define endmembers in the study. The snowpack samples were collected according to protocols outlined in [Ingersoll et al. \(2002\)](#). Bulk samples collected from snow pits dug over the entire depth of snow at the end of the snow season (March and April) were melted and aliquots of the melted water were collected for isotopic analysis. The elevation at Brumley is 3230 m (10,600 feet) and at Fremont Pass is 3474 m (11,400 feet). Elevations of sampling sites range from 2940 m (9640 feet) at Carbonate springs to 3250 m (10,650 feet) at Tiger mine tunnel. Elevations in the study area range up to almost 3432 m (11,260 feet) in the drainage basin containing the Dinero mine tunnel, to over 3800 m (12,500 feet) in the Lake Fork Creek/Turquoise Lake drainage basin, to over 3960 m (13,000 feet) in the Rock Creek drainage basin for ([Fig. 1](#)). Thus, the elevations of the bulk snow samples are within the range of elevations in the study area.

Water samples were analyzed for pH, specific conductance, and stable isotopes ratios of O, $\delta^{18}\text{O}$, and H, $\delta^2\text{H}$. Rock Creek samples were collected by US Fish and Wildlife personnel who shipped chilled samples immediately after collection to the US Geological Survey for analysis of pH and specific conductance. Measurements of pH and specific conductance utilized US Geological Survey protocols detailed in the US Geological Survey National Field Manual ([Radtke et al., 2005](#); [Wilde et al., 2006](#)) however, in most cases, these properties were not measured at the collection sites, but later the same day on an aliquot of water collected onsite and maintained at 4 °C until analysis, or within a few days on chilled samples as indicated previously for Rock Creek samples. Unfiltered, untreated samples for analysis of stable-isotope ratios were collected in glass vials leaving no headspace. The US Geological Survey Reston Stable Isotope laboratory conducted stable-isotope analyses. Hydrogen-isotope-ratio analyses utilized a hydrogen equilibration technique ([Coplen et al., 1991](#); [Révész and Coplen, 2007](#)). Oxygen-isotope-ratio analyses utilized the automated ([Révész and Coplen, 2008](#)) CO_2 equilibration technique of [Epstein and Mayeda \(1953\)](#).

Oxygen and H isotope results are reported as ratios between the sample and a reference material (in this case, Vienna Standard Mean Ocean Water (VSMOW)) and normalized ([Coplen, 1994](#)) on scales such that the O and H isotopic values of SLAP (standard light Antarctic Precipitation) are -55.5 per mil (‰) and -428 ‰, respectively. The two-sigma uncertainties of O and H isotope results are 0.2 ‰ and 2 ‰, respectively. The results are reported as per mil (‰) difference between the sample and the reference:

$$\delta^{18}\text{O}_{\text{sample}} = \left(\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{reference}}} - 1 \right) \cdot 1000 \quad (1)$$

$$\delta^2\text{H}_{\text{sample}} = \left(\frac{(^2\text{H}/^1\text{H})_{\text{sample}}}{(^2\text{H}/^1\text{H})_{\text{reference}}} - 1 \right) \cdot 1000 \quad (2)$$

where $\delta^{18}\text{O}_{\text{sample}}$ and $\delta^2\text{H}_{\text{sample}}$ are the results, in ‰, for the environmental samples; $^{18}\text{O}/^{16}\text{O}_{\text{sample}}$ and $^2\text{H}/^1\text{H}_{\text{sample}}$ are the O and H isotope ratios in the water samples and $^{18}\text{O}/^{16}\text{O}_{\text{reference}}$ and $^2\text{H}/^1\text{H}_{\text{reference}}$ are the O and H isotope ratios in the reference water material ([Clark and Fritz, 1997](#)).

Quality assurance procedures included collecting replicate samples for approximately 10% of all samples. All specific conductance replicates showed less than 3% difference. Values of pH showed less than 0.2 pH unit difference except one replicate pair collected at Lake Fork outlet that had a pH difference of 0.7 pH units. Specific conductance of these samples was very low (24 microsiemens/cm at 25 °C) and the pH measurement likely had not properly stabi-

lized. All other pH measurements on similar replicate samples (low specific conductance) exhibited acceptable results. Measurements of stable isotopes on replicate samples were within the two-sigma uncertainties of the analytical methods of 0.2 ‰ for O and 2 ‰ for H for all replicates except O on one replicate pair collected at Periscope Pipe Spring. The difference in replicate O isotope measurements (approximately 0.4 ‰) is attributed to the difficulty in collecting a representative sample at the site because of the varying location and discharge of the bubbling springs at the bottom of the pool. These slight discrepancies in pH and stable isotope samples at these two sites do not affect the conclusions of this report.

3. Results and discussion

3.1. Hydrographs

Hydrographs collected during the study exemplify natural hydrologic patterns and the influence of human activities. Natural hydrologic patterns include recurring seasonal patterns and gross climate fluctuations that vary from year to year. Human activities affecting the hydrographs relate to water-supply management.

The hydrograph for the Arkansas River near Leadville is largely unaltered by human activity. There are no impoundment structures on the river upstream from the stream gage. Water imports are limited to a maximum of approximately 5.2 million cubic meters (MCM) (4200 acre feet) per year ([Colorado Water Conservation Board, 2002](#)) representing between 8 and 13% of annual runoff at the gage during the study period ([Table 2](#)). Maximum discharge occurred at the site during late May or early June each year in response to snowmelt runoff in the catchment. Subsidiary peaks were caused by early snowmelt runoff, or summer storms ([Fig. 2](#), [Table 2](#)). During the study period, the greatest annual runoff occurred during calendar year 2006 (63.24 MCM; 51,270 acre feet). The lowest annual runoff (40.29 MCM; 32,660 acre feet) occurred during calendar year 2004. The year preceding the study, 2002, was a drought year ([Doesken and Gillespie, 2005](#)) when the site recorded only 25.52 MCM (20,690 acre feet) of runoff. For the purpose of this study, annual runoff is assumed to be correlated to the volume of snowmelt runoff recharging the groundwater system; for instance, in 2006 and 2007, recharge to groundwater from melting snow was likely greater than in other years.

The hydrograph at Turquoise Lake derives largely from the effects of water-supply management, although natural conditions affect the supply of native water and the amount of water available for import ([Fig. 2](#)). Water levels in Turquoise Lake are controlled by native inflow and transmountain diversions through the Boustead, Busk-Ivanhoe, and Homestake tunnels, and outflows from the lake including releases through Sugarloaf dam to Lake Fork Creek and releases through the Mount Elbert Conduit, an underground conveyance system that transports water to locations south of the reservoir. Increases in reservoir water levels and storage are more dependent on transmountain diversions than on native inflow ([William Tully, Bureau of Reclamation, pers. comm., 2007](#)). The amount and timing of water diversion generally depends on the amount of snowpack on the west slope of the Continental Divide, the timing of snowmelt runoff, maintenance of instream flow in west-slope creeks, and the amount of water available to those with storage accounts in Turquoise Lake. During the study period, the water level in Turquoise Lake rose each spring and started to decline as early as July (2004) and as late as October (2003), declining throughout the winter and early spring months ([Fig. 2](#)). The highest water level during the study period (3007.1 m; 9865.8 feet) occurred on July 28, 2005. During 2000 (before the study period), full pool elevation (3008.2 m; 9869.4 feet) was recorded on June 10.

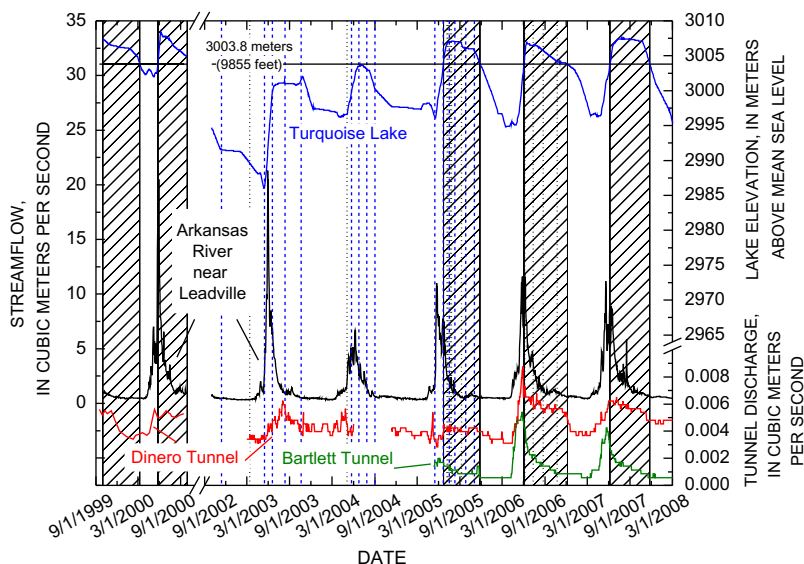


Fig. 2. Hydrographs of Turquoise Lake elevation, streamflow at the Arkansas River at Leadville stream gage, and discharge from the Dinero and Bartlett mine tunnels. Dotted vertical lines indicate sampling events when most of the sites were sampled. Dashed vertical lines indicate sampling events when a limited set of sites was sampled. Hash marked areas indicate periods when the elevation of Turquoise Lake was greater than or equal to 3003.8 m (9855 feet).

Near the beginning of the study and because of the effects of the 2002 drought, Turquoise Lake elevation declined to 2986 m (9796.6 feet) equivalent to 31.9 MCM (25,894 acre feet) of storage (Fig. 2) or 20% of storage capacity (Bureau of Reclamation, 2003). The reservoir was not near full capacity again until the spring of 2005 because of natural (insufficient snowmelt runoff) and legal limits on the amount of water that can be imported each year.

The discharge records for the Dinero and Bartlett mine tunnels indicate some seasonal variation, but do not cover the entire study period (Fig. 2). The record for the Dinero mine tunnel does not indicate a consistent hydrograph pattern from year to year. During the study period, streamflow at the Dinero fluctuated between $2.8 \times 10^{-3} \text{ m}^3/\text{s}$ (0.1 cubic foot per second (ft^3/s)) and $8.8 \times 10^{-3} \text{ m}^3/\text{s}$ (0.31 ft^3/s). The timing of the seasonal maximum discharge varied and occurred in April (2004), May (2000, 2005, and 2006) and July (2007). The year 2003 is distinct because the maximum discharge occurred in August, more than 2 months after the maximum discharge in the Arkansas River near Leadville, and more than a month after the maximum summer elevation at Turquoise Lake, which was the lowest maximum level of the study period (Table 2).

The Bartlett mine tunnel record is short but showed consistent seasonal patterns. Flow ranged from $5.6 \times 10^{-4} \text{ m}^3/\text{s}$ (0.02 ft^3/s) during winter to $5.4 \times 10^{-3} \text{ m}^3/\text{s}$ (0.19 ft^3/s) May 25–27, 2006. The shape and timing of rising and falling limbs and maximum discharge for the Bartlett mine tunnel hydrograph generally followed that of the Arkansas River near Leadville ($r^2 = 0.58$) (Fig. 2; Table 2). The greatest seasonal variation and greatest maximum discharge for the Dinero and Bartlett mine tunnels occurred during 2006.

If the Dinero mine tunnel hydrograph is influenced primarily by native hydrologic conditions, then it should be similar to the hydrograph of Arkansas River near Leadville. Similarly, if discharge from the Dinero mine tunnel is influenced by anthropogenic activities (transmountain import and storage of water) then the hydrograph should be similar to the Turquoise Lake hydrograph. Three relationships between the Dinero mine tunnel hydrograph and other hydrographs indicate the influence of both the natural hydrologic cycle and anthropogenic activities. First, the general coincidence of the rising limb of the hydrograph and maximum values of the Dinero mine tunnel and Arkansas River hydrographs

in 2000 and 2006 shows the influence of recharge from snowmelt into the Dinero mine tunnel during some high runoff years (Fig. 2, Table 2). The greatest annual runoff for the Arkansas River near Leadville occurred during 2000, 2006 and 2007 (Table 2). As stated previously, relative amounts of annual runoff are assumed to approximate relative amounts of snowmelt infiltration and recharge to the groundwater system. Thus, during two of the greatest runoff years of the study (2000 and 2006), the coincidence of the rising limbs and maximum values of the hydrographs of the Dinero mine tunnel and Arkansas River near Leadville indicates snowmelt infiltrated into and recharged the groundwater system associated with the Dinero mine tunnel discharge. In addition, the rapid response of the rising limb of the Dinero mine tunnel hydrograph to recharge indicates connection to the surface through high transmissivity, low specific yield material.

Second, in 2003, differences between the Turquoise Lake, Arkansas River near Leadville, and Dinero mine tunnel hydrographs indicate that natural hydrologic conditions (drought) and not water levels in Turquoise Lake controlled the Dinero mine tunnel hydrograph. In 2003, the maximum discharge at Dinero mine tunnel occurred a month after the beginning of the water-level plateau in Turquoise Lake, and 2 months after the maximum discharge of the Arkansas River near Leadville. After maximum discharge, the Dinero mine tunnel hydrograph began to decline and was more symmetrical than in other years, even though Turquoise Lake remained high. During this time, Dinero mine tunnel may have been disconnected from the anthropogenic influence of Turquoise Lake, received minimal recharge from snowmelt, and responded as a natural groundwater system. Similar timing of groundwater hydrographs was noted by Wireman et al. (2006) who reported a 2-month delay in the maximum elevation of groundwater levels in the Leadville mining district (Fig. 1, 16 km east of the study area) relative to maximum surface-water discharge at their study sites.

Finally, the lack of symmetry in the rising and falling limbs of the Dinero mine tunnel during 2006 and 2007 may indicate an influence from high water levels in Turquoise Lake. During both years, hydrographs for the Arkansas River near Leadville and the Bartlett mine tunnel show some tailing during the falling limb of the hydrograph, but are relatively symmetrical and very similar in shape to

each other. Seasonal falling limbs on the Dinero mine hydrograph, however, exhibit pronounced shoulders that are coincident with sustained high water levels in Turquoise Lake. During both years, the Dinero mine tunnel hydrograph exhibited marked declines when Turquoise Lake levels fell during the autumn and winter. Discharge declined 26% from December 3 to 19, 2006 (when lake water levels declined from 3003.8 to 3003.2 m; 9855 to 9853 feet) and 10% from November 9 to 11, 2007 (when lake water levels declined from 3005.6 to 3005.3 m; 9861 feet to 9860 feet; Fig. 2).

These sharp declines in flow at the Dinero mine tunnel may indicate that lake elevations above approximately 3003.8–3005.2 m (9855–9860 feet) caused increased flow to the Dinero mine tunnel. If this analysis is correct, discharge from the Dinero mine tunnel should also have been elevated during 2005 when Turquoise Lake levels were substantially greater than 3003.8 m (9855 feet) for almost 6 months. Although not immediately obvious, a detailed analysis of the hydrographs indicates a subtle, but similar coincidence in the shape of the Dinero mine tunnel and Turquoise Lake hydrographs in 2005 as follows: (1) From June 11 through June 25, Dinero mine tunnel discharge increased, Turquoise Lake levels rose, and the Arkansas River at Leadville exhibited a secondary maximum in streamflow from delayed snowmelt (Fig. 2). (2) From June 26 through December 6, 2005, the Dinero mine tunnel hydrograph was generally stable, and Turquoise Lake levels remained above 3003.8 m (9855 feet). (3) After December 6, 2005, lake level began declining and slightly later, when the lake level was below 3003.8 m (9855 feet), Dinero mine tunnel discharge declined. Depletion of groundwater storage between the lake and the tunnel during the previous years of drought might have caused the smaller discharge and muted features of the 2005 Dinero mine tunnel hydrograph relative to 2006 and 2007. Alternately, it is possible that high volumes of snowmelt initially support the peak in the Dinero mine tunnel hydrograph and that recharge from melting snow (as indicated by the proxy of flow at the Arkansas River at Leadville where annual runoff in 2005 was the second lowest recorded during the study period) was inadequate to support a large increase in the Dinero mine tunnel hydrograph during 2005.

The shape of the Dinero mine tunnel hydrograph may indicate existence of a mine pool within the mine workings instead of some effect from Turquoise Lake levels. During 2004, construction in Dinero mine tunnel removed a collapse located approximately 100 m (328 feet) into the tunnel, but another collapse remains approximately 580 m (1900 feet) from the portal. Except for minor seepage of water from fractures located between the portal and the collapse, almost all of the discharge in Dinero mine tunnel originates behind this collapse. The volume of flow from Dinero related to a backup in a mine pool was calculated by estimating a baseflow recession constant and curve (using methods in Watson and Burnett, 1995, p. 474–475) for the period June 10 through December 19, 2006 and subtracting the volume of the recession curve from the volume of the actual hydrograph during this period. The resulting volume was approximately 9900 m³ (13,000 yards³) which is less than the estimated 76,000 to 153,000 m³ (100,000–200,000 yards³) of material removed from the Dinero mine workings (Al Amundsen, Colorado Division of Reclamation, Mining, and Safety, pers. comm., 2009). Storage and delayed release of snowmelt recharge from a mine pool may cause the asymmetrical shape of the Dinero mine tunnel hydrograph. The volume of the implied mine pool during June 10–December 19, 2006 ranged up to 23% of daily flow and represented a total of 10% of the total runoff during that period.

3.2. General geochemistry of study-area water

Measurements of pH and specific conductance (Fig. 3) provided a general understanding of the geochemical provenance of the

water in the study area. Specific conductance ranged from less than 5 microsiemens/cm at 25 °C for snow samples to greater than 3000 microsiemens/cm at 25 °C for Carbonate and Periscope Pipe springs (shown on Fig. 1). Values of pH ranged from between 2 and 3 at Tiger mine tunnel to as great as 9 at the Homestake tunnel. Samples are generally mixtures of four types of waters: pristine snowmelt (low specific conductance and slightly acidic pH) represented by Fremont Pass and Brumley samples; severe acid–rock drainage (low pH and elevated specific conductance) represented by Tiger mine tunnel; carbonate-rich water (near-neutral pH and elevated specific conductance) represented by Carbonate and Periscope Pipe springs; and weathering products from native, unmineralized rocks not well represented by any water samples except possibly samples obtained from Boustead tunnel when the diversion was not active. During these times, water flowing out of the Boustead tunnel originated from fractures within the tunnel (Supplemental data Table 3). Accordingly, most relatively dilute samples having near-neutral pH represent snowmelt runoff mixed with water from weathering of local, unmineralized rocks (most stream sites and Boustead and Homestake tunnels) or infiltration of snowmelt runoff (Tiger west well). Samples having acidic pH and specific conductance values greater than 200 microsiemens/cm at 25 °C are affected to varying extents by acid–rock drainage and weathering of local, unmineralized rocks (Bartlett, Dinero, Nelson, Siwatch, and Tiger mine tunnels; collapsed adit, Dinero north and south toe seeps, pond seep, Sugarloaf Gulch upstream from Nelson mine tunnel, and seep from Nelson repository). The Fe-rich seep is likely a mixture of acid–rock drainage water and carbonate-rich water.

3.3. Stable-isotope geochemistry of study-area water

Isotope ratios exhibit a broad range of values (Figs. 4 and 5) covering about 7‰ for $\delta^{18}\text{O}$ and 55‰ for $\delta^2\text{H}$. The most depleted sample was the Fremont Pass SNOTEL sample collected April 6, 2005 ($\delta^{18}\text{O} = -22.8\text{‰}$; $\delta^2\text{H} = -170\text{‰}$). The most enriched samples were from Lake Fork Creek upstream from Turquoise Lake on November 2, 2005 ($\delta^{18}\text{O} = -15.8\text{‰}$; $\delta^2\text{H} = -116\text{‰}$) and Periscope Pipe spring on August 10, 2005 ($\delta^{18}\text{O} = -14.8\text{‰}$; $\delta^2\text{H} = -118\text{‰}$). The isotope ratios indicate several patterns that help differentiate different sources of water in the study area, differing seasonal patterns among sites, the range of isotopic values of snowmelt, mixing between different sources, and possibly areas affected by seepage from Turquoise Lake.

3.3.1. Different sources of water

The isotope ratios indicate that at least two types of water, delineated by two local meteoric water lines, occur in the study area (Fig. 4). Although one could argue that because these lines were not defined using isotopic analysis of precipitation samples, they are not truly meteoric water lines (Landwehr and Coplen, 2004), all water sampled in the study area is technically meteoric as it originated as precipitation, and the term is used herein. One water type (Group 1) is generally isotopically heavier (or enriched) and samples fall on a local meteoric water line that has a greater intercept, but similar slope ($\delta^2\text{H} = 7.05 \delta^{18}\text{O} - 5.38$; $n = 47$; $r^2 = 0.82$, $p < 0.001$; regression used all data from Boustead tunnel, Busk Creek, Lake Fork Creek upstream from Turquoise Lake, and Rock Creek) to a meteoric water line for the second type of water. Water samples in the first group include the transmountain diversion waters from the Boustead tunnel, Busk Creek (that contains a mixture of native and transmountain diversion water from the Busk-Ivanhoe tunnel), native water flowing into Turquoise Lake in Lake Fork Creek, and water in Rock Creek, which is south of the study area. The second type of water (Group 2) generally is isotopically lighter (or depleted) and falls on a local meteoric water

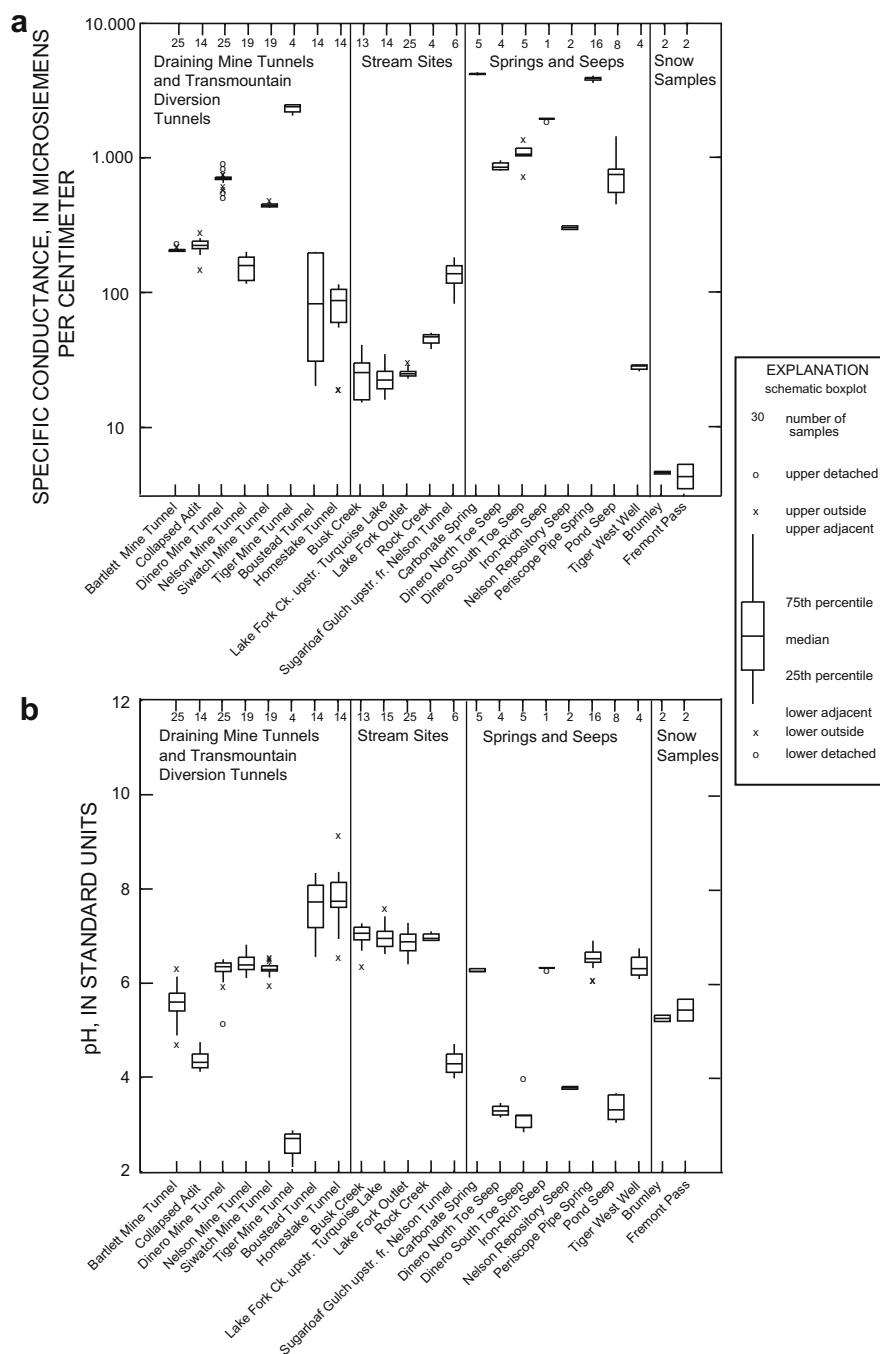


Fig. 3. Boxplots for samples indicating the range of (a) specific conductance in microsiemens/cm at 25 °C, and (b) pH, in standard units, for samples collected during the Turquoise Lake isotope study.

line having a smaller intercept than the first line ($\delta^2\text{H} = 6.92 \delta^{18}\text{O} - 11.7$; $n = 119$; $r^2 = 0.80$, $p < 0.001$; the regression used all data from Bartlett, Dinero, Nelson, Siwatch, and Tiger mine tunnels, Carbonate Spring, Collapsed adit, Nelson repository seep, and Tiger west well). Water samples in this group comprise the draining mine tunnels, seeps, and smaller collapsed adits in the study area. There are some water samples whose values fall between the two regions (Homestake, Lake Fork outlet, and pond seep). In general, the line having a greater intercept encompasses most samples of surface water (including transmountain diversions) whereas the line having a lower intercept encompasses most samples that could be classified as groundwater. The slopes of the two lines are not statistically distinct (t -value = 0.85, $p = 0.40$ or there is only

60% confidence that the slopes are different). However, the intercepts of the lines are statistically distinct (t -value = -2.43, $p = 0.016$, or there is greater than 98% confidence that the intercepts are different).

Although the ultimate origin for all water in the study area is precipitation, the separation of isotope values into two distinct water types indicates different origins for the precipitation that formed each type of water or that different processes affected the two types of water. Each line has a slope of about seven indicating the waters have been similarly affected by evaporation (Kendall and Coplen, 2001). The value of the intercept of a meteoric water line indicates effects of atmospheric recycling of the water. For example, greater values of the intercept indicate more

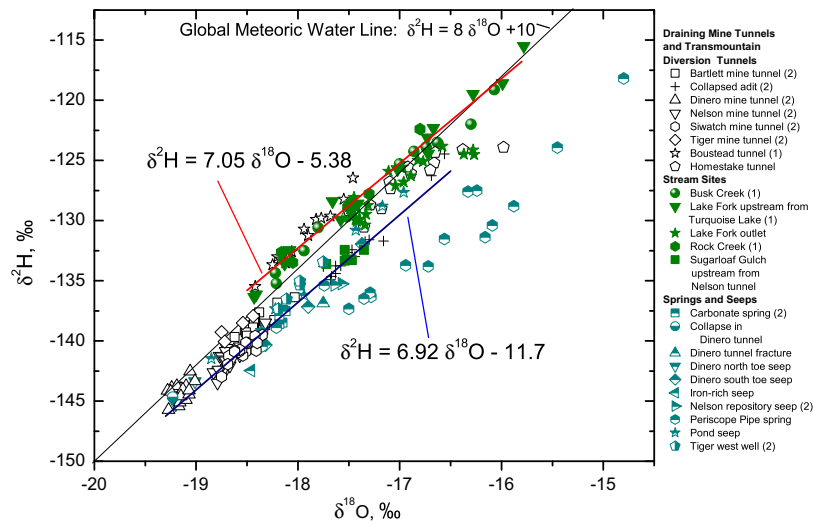


Fig. 4. Isotopic ratios for samples collected during Turquoise Lake isotope study. Two meteoric water lines were constructed using regressions for surface-water samples and groundwater samples as described in the text. The upper line represents the local meteoric water line for Group 1 waters, and the lower line represents the meteoric water line for Group 2 waters. The intermediate line represents the global meteoric water line of Craig (1961). In the explanation, (1) indicates sites used to obtain the regression line for Group 1, and (2) indicates sites used to obtain the regression line for Group 2.

recycling (repeated evaporation/condensation cycles) of the atmospheric water before precipitation (Tyler Coplen, US Geological Survey, pers. comm., 2008; Robert Seal, US Geological Survey, pers. comm., 2008; Kendall and Coplen, 2001). The differences in the intercept for the two types of water may indicate changes in storm tracks and atmospheric circulation (Rozanski et al., 1992; Rademacher et al., 2002) that produced the precipitation for the Group 1 versus the Group 2 waters, and may have implications for changing climate and storm history in the area. Interestingly, though, waters from Sugarloaf Gulch upstream from Nelson mine tunnel fall on the groundwater line (Fig. 4). This ephemeral stream flows only during the snowmelt period and is thought to represent the isotopic composition of recent snowmelt in the Dinero mine tunnel area (see following discussion in Section 3.3.2 “Seasonal variations and isotopic composition of snowmelt”). Therefore, the groundwater line (Group 2) might represent snowmelt whose isotopic composition separates from the upper line (Group 1) through evaporation of the snowpack prior to infiltration (Claassen and Downey, 1995) rather than older water sourced from different storm tracks. Another possibility is that the elevation effect and initial deposition of precipitation in different catchments have produced these differences. The isotopic depletion of Group 2 waters versus Group 1 waters is consistent with the altitude or elevation effect described previously. In fact, all Group 1 waters are transmountain diversion waters or meteoric water from Lake Fork Creek or Rock Creek drainage basins that both have higher elevation and are closer to the Continental Divide than the drainage basin containing Dinero mine tunnel and all Group 2 waters. The extreme depletion of most mine tunnel waters (Fig. 2) relative to all other samples except the snowpack samples, may indicate that the mine tunnel workings tap into a deeper regional flow system that contains recharge from colder, higher elevation snow than represented by either the Group 1 or Group 2 waters. Though provocative, the reasons for separation of Group 1 and Group 2 waters are not entirely understood and a more detailed discussion is beyond the scope of the present investigation. The separation of these two water groups is, however, characteristic of the study area and can be used to infer different sources of water in the study area and different processes that affect the two water types.

3.3.2. Seasonal variations and isotopic composition of snowmelt

Seasonal variations in the $\delta^{18}\text{O}$ data in the study area show several general patterns (Fig. 5): (1) sites where isotopic ratios show large seasonal variation and became more depleted during snowmelt runoff; (2) sites where isotopic ratios show small seasonal variation and became more enriched during snowmelt runoff; and (3) sites where isotopic ratios have a small response to snowmelt coupled with a later summer evaporative trend. Some of these seasonal patterns help indicate variations in snowmelt isotopic signatures which, in turn, may help indicate isotopic signatures of groundwater recharge, and sources and evolution of water in the study area.

Isotope ratios for several surface water sites exhibited a large seasonal variation where $\delta^{18}\text{O}$ values were depleted during spring snowmelt (primarily during May and June each year) and became as much as 3‰ enriched through the summer months (for example, Lake Fork Creek upstream from Turquoise Lake, Lake Fork outlet, Busk Creek, and Rock Creek; Figs. 4 and 5b). Depleted isotope ratios originate from cooler season precipitation and enriched values are from warmer season precipitation. Data from Lake Fork Creek upstream from Turquoise Lake (Figs. 4 and 5b) indicated that mixing baseflow with snowmelt runoff in the stream produced $\delta^{18}\text{O}$ values as low as -18.0‰ to -18.5‰ . Streamflow records (Supplemental data Table 3 and Thomas Ley, Colorado Division of Water Resources, pers. comm., 2007) for the site indicate that streamflow during snowmelt runoff is generally 10 times that during baseflow. Using these relative flows in isotope mixing calculations, a $\delta^{18}\text{O}$ value of -18.7‰ in snowmelt runoff accounts for the $\delta^{18}\text{O}$ value of -18.5‰ in the Lake Fork upstream from Turquoise Lake during maximum flow.

Draining mine tunnels (Bartlett, Nelson, Siwatch, and Tiger mine tunnels) and some of the seeps and springs (Tiger West Well and pond seep during 2006) exhibited a second type of seasonal variation of a limited seasonal response and enrichment in $\delta^{18}\text{O}$ isotopic ratios during snowmelt (Figs. 4, 5a and 5c). The smaller the seasonal response, the less a particular site is affected by seasonal recharge from snowmelt. In contrast to surface waters, baseflow isotope ratios are depleted at these sites, and the addition of snowmelt recharge enriched isotope ratios, resulting in a seasonal response opposite to that of surface water. This pattern is particularly evident for the mine tunnels in 2006, but also occurred

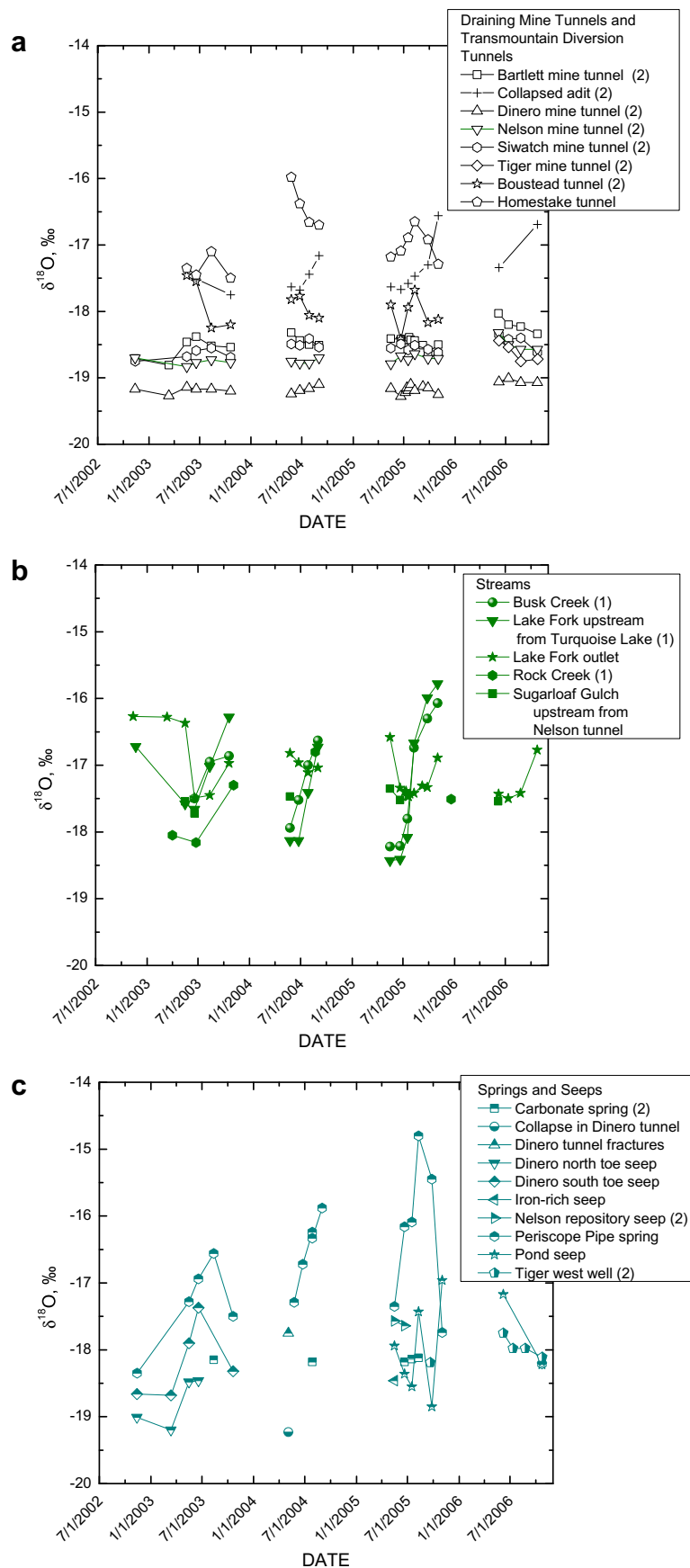


Fig. 5. Seasonal variation in $\delta^{18}\text{O}$ values for samples collected from (a) draining mine tunnels and diversion tunnels; (b) streams; and (c) springs and seeps, Turquoise Lake isotope study. In the explanations, (1) indicates sites used to obtain the regression line for Group 1, and (2) indicates sites used to obtain the regression line for Group 2.

for some of these tunnels in 2004 and 2005. The $\delta^{18}\text{O}$ isotopic ratios at Dinero mine tunnel exhibited minimal seasonal variation that was within the two-sigma uncertainty of the analysis (0.2‰). The baseflow for the Dinero mine tunnel represents the most isotopically depleted endmember (other than snowpack samples). The isotopic composition of recharge from snowmelt runoff to Dinero mine tunnel and nearby tunnels is likely indicated by the compositions at Sugarloaf Gulch upstream from Nelson tunnel ($\delta^{18}\text{O}$ value = -17.4‰ to -17.7‰), the draining fractures in Dinero tunnel ($\delta^{18}\text{O} = -17.8\text{‰}$) and the Nelson repository seep ($\delta^{18}\text{O} = -17.6$). These sites were all sampled during the snowmelt runoff period, and all sites except the Dinero mine tunnel fracture were intermittent and flowed only during snowmelt. Flow persistence at the Dinero mine fracture is not known because it was sampled only one time when safe access was possible. This range of values is more enriched than the value calculated for snowmelt for Lake Fork upstream from Turquoise Lake ($\delta^{18}\text{O} = -18.7\text{‰}$). A possible explanation is that Lake Fork upstream from Turquoise Lake drains an area having higher elevation and perhaps snowmelt has more depleted isotopes than the Dinero mine tunnel area (Fig. 1, the drainage basin that includes Dinero mine tunnel is east of and lower in elevation than Lake Fork Creek drainage basin). Alternatively, groundwater recharge and snowmelt runoff in the Dinero area may be from isotopically heavier, late season snowfall.

The estimated isotopic composition of seasonal snowmelt recharge to the Dinero mine tunnel ($\delta^{18}\text{O} = -17.4\text{‰}$ to -17.8‰) and the isotopic composition of Dinero mine tunnel ($\delta^{18}\text{O} = -19.1\text{‰}$ to -19.3‰) are enriched relative to the isotopic ratios of snowpack samples presented herein ($\delta^{18}\text{O} = -20.8\text{‰}$ to -22.8‰ ; Supplemental data Table 3). In addition, the weak seasonal isotopic enrichment of Dinero mine tunnel water (particularly evident in 2004, Fig. 5a) indicates that snowmelt recharge to the tunnel is enriched relative to baseflow in the tunnel and to the isotopic composition of the snowpack presented herein. Thus, it is likely that snowmelt recharging the Dinero mine tunnel area has a different isotopic composition than the snowpack samples presented herein, or that isotopic composition of the snowpack evolved during melting to produce $\delta^{18}\text{O}$ signatures for snowmelt in the Dinero area of -17.8‰ to -17.4‰ . Meltwater generally is isotopically enriched relative to the original snowpack due to the effects of evaporation and molecular exchange between the snow and the atmosphere (Rodhe, 1998). Enrichment of meltwater relative to snowpack has been illustrated in a high elevation catchment in Colorado (Mast et al., 1995) and in other studies reviewed by Cooper (1998). Thus, results herein are consistent with previous work.

Periscope Pipe spring and Lake Fork outlet (representing Turquoise Lake) exhibited the third seasonal pattern in $\delta^{18}\text{O}$ values of small variation during spring coupled with later large seasonal enrichment enhanced by evaporation. Periscope Pipe spring is a carbonate-rich spring that issues into a small (1 m deep by 2 m across) closed-basin pond. Although all samples were collected at the same location where water was noticeably bubbling into the base of the pond, isotope data indicate that evaporation affected the isotopic composition of samples collected during the summer months (Figs. 4 and 5c). Similarly, during the late season, isotopic compositions of samples from Lake Fork outlet show some effects of evaporation (Figs. 4 and 5b). Because of the effects of evaporation, the regressions for the meteoric water lines in Fig. 4 did not include the samples from Lake Fork outlet and Periscope Pipe spring.

3.3.3. Areas possibly affected by seepage from Turquoise Lake

The isotope values at some locations indicate possible mixing with Turquoise Lake waters. Isotopic compositions of the Collapsed adit occur on the Group 2 meteoric water line, and most samples occur near the values for Sugarloaf Gulch upstream from Nelson

mine tunnel (Fig. 4). However, two values from samples collected in November 2005 (the more enriched of the two samples) and in October 2006 are more enriched than the bulk of samples from this location. Their position between the meteoric water lines for both groups may indicate contributions from Turquoise Lake (the lake elevation was relatively high at both times), or recharge from warmer season precipitation.

During a previous study, sulfur hexafluoride injected into Turquoise Lake was detected at the Bartlett mine tunnel discharge and indicated a direct hydrologic connection with Turquoise Lake (Engblom, 2004). Some of the isotope samples for the Bartlett mine tunnel trend to more enriched values between the two meteoric water lines, which might indicate a hydrologic connection (Fig. 4). However, seasonal variations in Bartlett mine tunnel isotope values are more similar to those in other mine tunnels than to surface water (Fig. 5a and b). In addition, the hydrograph for the Bartlett mine tunnel is more similar to the Arkansas River at Leadville than to the Dinero mine tunnel. Despite the previously reported direct evidence of a hydrologic connection (Engblom, 2004), the isotopes offer only weak support for that conclusion, whereas the hydrograph data do not seem to support that conclusion. Two reasons may explain this discrepancy. First of all, the tracer injection in Turquoise Lake occurred during the highest lake levels of 2003 when the lake elevation was lower than during other years of the study. At this time, the water-table configuration may have allowed a direct path from the lake to Bartlett tunnel (lake elevation was greater than Bartlett mine tunnel elevation at that time; Table 1, Fig. 2). Secondly, because Bartlett mine tunnel is much closer to Turquoise Lake than Dinero mine tunnel, and contains very limited workings (Fig. 1), it is reasonable to expect a different hydrologic response at the two sites.

3.4. Sources of water to Dinero mine tunnel and possible effects of Turquoise Lake

The lack of seasonal variation and depleted isotopic signature of the Dinero mine tunnel help indicate sources of water to the tunnel. In addition, isotope mixing calculations help constrain the amounts of potential contributions to Dinero mine tunnel from different sources of water.

The depleted isotope values and weak seasonal response indicate that Dinero mine tunnel workings tap a deeper, regional groundwater source having longer residence time than other sites sampled in this study. An alternate explanation for the lack of isotopic variation at Dinero mine tunnel is that a substantial mine pool exists within the Dinero workings. The lack of seasonal variation in isotope composition in well samples in the Butte, Montana, USA mining area suggest a subsurface residence time long enough to allow for mixing of recharge water having varying isotopic compositions (Roesler et al., 2007). As indicated previously through baseflow recession analysis, the 2006 hydrograph at Dinero may indicate a limited mine pool having a volume equivalent to 10% of the June to December 2006 Dinero runoff. The amount of annual runoff at Dinero mine tunnel (Table 2) ranged from 128,000 m³ (167,000 yards³) to 159,000 m³ (208,000 yards³) which is similar to the estimated volume of material removed from the mine (153,000 m³ or 200,000 yards³). Residence time of water in a mine pool occupying the entire volume of the mine workings would be on the order of one year. The dampened isotope signature indicates a much longer residence time, and therefore indicates discharge of groundwater having a long residence time rather than existence of a substantial mine pool.

The two different meteoric water lines and the distinctive, depleted isotopic signature of the Dinero mine tunnel water suggest that isotope mixing calculations may help estimate potential

contributions of other water (from Turquoise Lake or snowmelt) to Dinero mine tunnel. For this analysis, it was assumed that one of the most depleted isotopic signatures for Dinero mine tunnel ($\delta^{18}\text{O} = -19.3\text{‰}$, collected on March 13, 2003 when Turquoise Lake levels were near their lowest levels of the study period) represented baseflow that was unaffected by contributions from either infiltrating snowmelt or Turquoise Lake. The mixing calculations estimated the proportion of Turquoise Lake or snowmelt water needed to mix with the Dinero mine tunnel endmember to produce the isotopic composition of Dinero mine tunnel water during periods when Turquoise Lake elevation was greater than the threshold value of 3003.8 m (9855 feet). Lake Fork outlet is the direct outlet of Turquoise Lake and represents the isotopic composition of Turquoise Lake. Because travel times between Turquoise Lake and the Dinero mine tunnel are unknown, the median isotope values for Dinero mine tunnel and Lake Fork outlet were used during the high stands of the lake in 2005 ($\delta^{18}\text{O}$ Dinero mine tunnel = -19.2‰ , $\delta^{18}\text{O}$ Lake Fork outlet = -17.4‰) and 2006 ($\delta^{18}\text{O}$ Dinero mine tunnel = -19.1‰ , $\delta^{18}\text{O}$ Lake Fork outlet = -17.4‰). Mixing calculations indicate that Turquoise Lake contributed 5% and 11% of the water in Dinero mine tunnel in 2005 and 2006. Note from Fig. 4 that the median value of Lake Fork outlet (-17.4‰) is close to the most depleted values for that site so that this calculation closely approximates the maximum possible contribution from Turquoise Lake to Dinero mine tunnel based on isotopic composition. That is, if mixing calculations used later season, more enriched isotopic values for Lake Fork Outlet, the calculated, proportional contribution of Turquoise Lake to Dinero mine tunnel would be even smaller. The isotope mixing calculations are consistent with the hydrograph analysis that indicated Dinero mine tunnel discharge decreased 26% in 2006 and 10% in 2007 when Turquoise Lake levels declined.

As discussed previously, evidence collected in this study indicates the isotopic composition of snowmelt in the Dinero area is in the range of $\delta^{18}\text{O} = -17.4\text{‰}$ to -17.8‰ . This composition is essentially the same as the estimated composition of Turquoise Lake ($\delta^{18}\text{O} = -17.4\text{‰}$) used in the mixing calculations in the previous paragraph. Thus, the isotopic mixing calculation from the previous paragraph also approximates the volume of snowmelt infiltration that may have contributed to Dinero mine tunnel. As also discussed previously, the hydrographs for Dinero mine tunnel may be attributed to existence of a mine pool that collects and slowly releases seasonal recharge from snowmelt. The estimated contribution of the mine pool to Dinero mine tunnel discharge from June to December 2006 is 10% which is also consistent with the 11% contribution from snowmelt calculated from isotope mixing during that year. Obviously, it is not possible to discriminate between these two potential contributors (Turquoise Lake or snowmelt infiltration) based on their isotopic compositions. In addition, it is interesting to note that the seasonal fluctuations of isotopic composition at Dinero mine tunnel are within the two-sigma uncertainty (0.2‰) for the analyses. This indicates that the isotope mixing calculation from the previous paragraph is the minimum amount of contribution to Dinero mine tunnel that can be detected from a source having a composition of -17.4‰ within the resolution of the isotopic analytical method. Thus, the isotopes, while not completely diagnostic, do indicate that sources of water to Dinero other than baseflow, generally represent no more than approximately 10% of the volume of water at Dinero. Therefore, the primary source of water to the tunnel is likely deep, inactive (not affected by seasonal recharge) groundwater represented by one of the most depleted isotope samples from Dinero mine tunnel ($\delta^{18}\text{O} = -19.3\text{‰}$; $\delta^2\text{H} = -146\text{‰}$, Supplemental data Table 3) collected March 13, 2003, when Turquoise Lake levels were near their lowest of the study period (Fig. 2).

The isotope data do not unequivocally show a connection between Turquoise Lake and Dinero mine tunnel; however, the hydro-

graph data may support a connection. As described previously, the asymmetry of the falling limb of the Dinero mine tunnel hydrograph may indicate existence of a small mine pool that attenuates recharge from snowmelt when sufficient recharge occurs. However, in light of the higher elevation of Turquoise Lake relative to Dinero mine tunnel, the proximity of Turquoise Lake to Dinero tunnel, and the coincidence of attenuated flow from Dinero during periods of elevated lake levels, a possible hydraulic effect of the lake on flow from the tunnel cannot be ruled out. That is, it is possible that the hydrostatic pressure from Turquoise Lake supports flow from Dinero mine tunnel without any water being physically transferred between the two locations. A groundwater field and modeling study completed during 2006 in the Dinero area indicated that the water table was elevated between Turquoise Lake and Dinero mine tunnel and generally followed topography (Schmidt, 2007). A ridge that is a drainage basin divide between Turquoise Lake and Dinero mine tunnel also suggests the presence of a groundwater divide (Figs. 1 and 6). If this configuration represents site conditions, then changes in the level of Turquoise Lake could cause flow changes at the Dinero mine tunnel without requiring any physical transport of water between the two locations. Fig. 6 is a simplified cross-section for the area (A–A' in Fig. 1) showing various configurations of the water table. Initially, Turquoise Lake is at maximum elevation and the divide is close to the lake (Fig. 6a). As lake level falls, the hydraulic gradient (slope of the groundwater table) between the maximum elevation of the water table and Turquoise Lake steepens or increases (Fig. 6b). Darcy's law (which states that groundwater flow is proportional to the product of hydraulic conductivity, groundwater slope or water-table gradient, and cross-sectional area perpendicular to the direction of flow) indicates that the increased gradient temporarily promotes increased flow to Turquoise Lake (Fig. 6b). The increased flow depletes the storage in the aquifer (Fig. 6b), the water-table elevation decreases, and the divide shifts away from the lake (Fig. 6c). When this occurs, the water-table gradient toward the Dinero mine tunnel also decreases and flow to Dinero mine tunnel decreases (Fig. 6c). Similarly, after low lake levels (Fig. 6d), when rising lake levels coincide with groundwater recharge from snowmelt (Fig. 6e), increasing lake levels cause a decrease in the groundwater gradient between its maximum elevation and the lake (Fig. 6e). Groundwater discharge toward the lake decreases, and if groundwater recharge (snowmelt infiltration) is occurring at the same time, storage in the aquifer increases, and the water-table elevation increases (Fig. 6f). When maximum water-table elevation increases, the gradient increases and flow toward Dinero mine tunnel increases (Fig. 6f). In this conceptual model, changes in lake level cause changes in flow from the Dinero mine tunnel. However, the groundwater divide between Turquoise Lake and Dinero mine tunnel prevents physical transport of water between the two locations. It is possible that deeper flow paths between the lake and the Dinero mine tunnel workings could exist beneath the local flow paths and divide depicted in the upper regions of Fig. 6a–f (e.g. Winter, 1983, 1999). However, as described previously, the isotopic evidence does not strongly support this possibility.

A cross-sectional transient MODFLOW model (Harbaugh et al., 2000; Harbaugh, 2005) confirms the viability of the conceptual model with the divide shifting and declining in response to lowering of the lake level from 3008 m to 2986 m that results in decreased discharge from Dinero mine tunnel. The model is a generic representation of a cross-section extending from A to A' in Fig. 1 with the base of the active flow zone at 2940 m (9646 feet) for the first 1700 m (5577 feet) from the lake and then declining linearly to 2900 m (9514 feet) at Colorado Gulch. The model uses hydraulic conductivity of 1×10^{-6} m/s and recharge of 4×10^{-9} m/s ($\sim 28\%$ of precipitation) both of which are consistent with the range of values explored

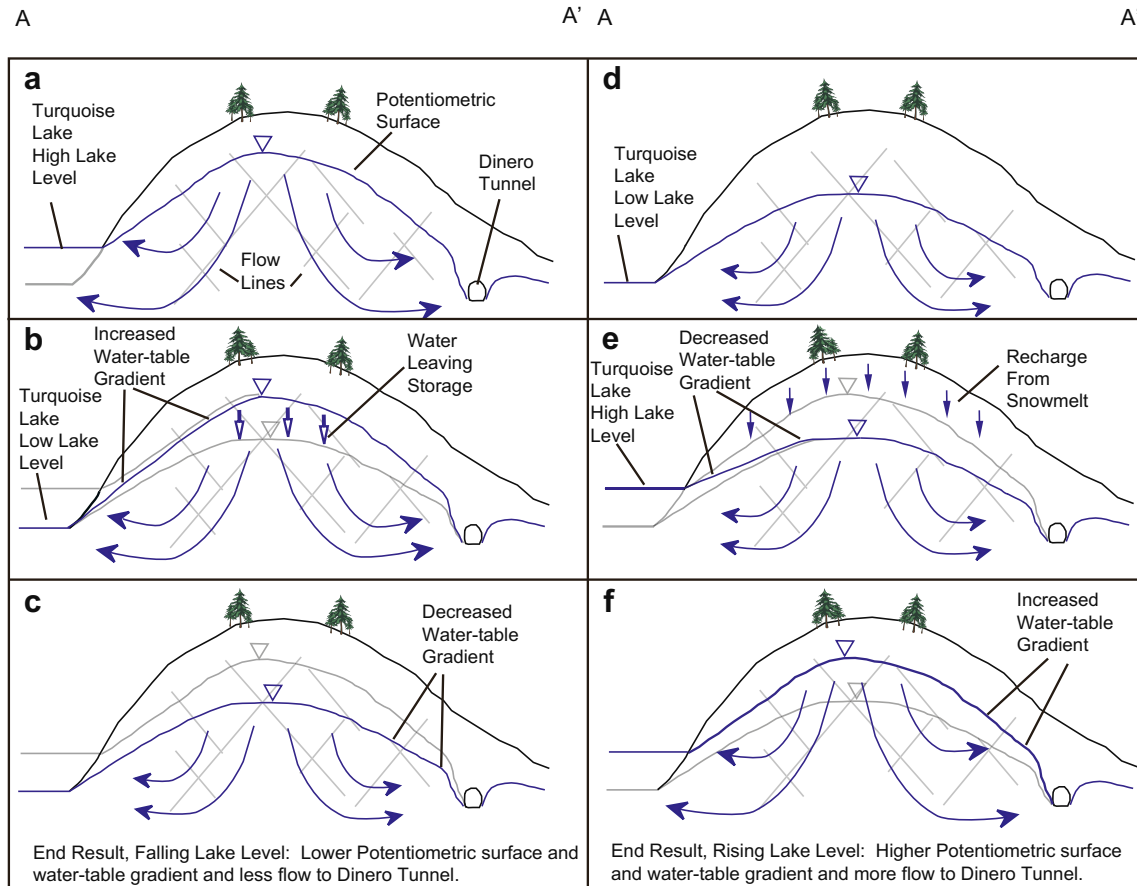


Fig. 6. Simplified, conceptual cross-sectional view of section A–A' (Fig. 1) showing water-table configuration and directions of groundwater flow between Turquoise Lake (left and north side of cross section) and Dinero mine tunnel (right and south side of cross section) (a), (e), and (f) during high levels of Turquoise Lake; (b) when lake levels and water table are falling; and (c) and (d) at low levels of Turquoise Lake.

by Schmidt (2007); and specific yield values of 1×10^{-3} and 1×10^{-2} which are consistent with the range of values indicated by others for fractured granite and gneiss (Freeze and Cherry, 1979; Moore, 1992; Maréchal et al., 2004; Krásný and Sharp 2007). The simulated decrease in discharge from the mine tunnel 6 months after the lake stage decline is 19% for a specific yield of 1×10^{-3} and 3% for a specific yield of 1×10^{-2} (Fig. 7). The model response is slower than observed in the field where flow increases and decreases over a matter of weeks when lake level changes. This difference could be because this is a porous-media flow simulation whereas fractured flow exists at the site. In fact, the response of the Dinero mine tunnel hydrograph to recharge shown by the steep rising limb of the hydrograph in 2006 (Fig. 2) indicates a rapid hydraulic connection (high transmissivity, low specific yield) that is difficult to simulate with this type of model, but that occurs at this site. Despite these differences between the model and the hydrograph responses, the simulations support the conceptual model and indicate that changes in Turquoise Lake level can affect the location and elevation of the divide between the lake and tunnel and affect the magnitude of discharge from the tunnel. More detailed modeling is beyond the scope of this paper.

The conceptual model is consistent with several of the data patterns previously described. The model explains the lack of effect Turquoise Lake had on flow in Dinero mine tunnel in 2003 and 2004. During those times, lake level was likely so low that the local flow system depicted in Fig. 6 existed at lower elevation and only minimal water-table gradients existed between the maximum water-table elevation and Dinero mine tunnel. In addition,

infiltration would not have been available to resupply the storage as shown in Fig. 6e. Another possibility is that the elevation of the local flow system was so depressed that it was disconnected, or below the elevation of the Dinero mine tunnel. The model explains the subtle effect of Turquoise Lake on the Dinero mine tunnel hydrograph in 2005 when the aquifer was beginning to recover from drought conditions. Water storage in the mountain between the two locations was likely depleted by the effects of the drought and by draining of the aquifer caused by the low lake levels. Recharge from snowmelt was small in 2005 (annual runoff at the Arkansas River near Leadville was one of the lowest of the study period) (Table 2). The water table in the mountain was likely at a relatively low elevation and flattened relative to what is shown in Fig. 6, which would minimize the effect of Turquoise Lake on flow to Dinero mine tunnel. The model also explains the near coincidence of maximum values of the Dinero hydrograph in 2006 and 2007 with maximum values in the natural hydrograph (Arkansas River at Leadville). During those years, the system had experienced a few years of high annual runoff (and thus high groundwater recharge from snowmelt) and extended periods of high lake levels. The conceptual model indicates that natural recharge combined with rising lake levels will cause the greatest rise in the water table between the two locations, steep water-table gradients, and thus greater discharge from the aquifer to Dinero mine tunnel. Additional numerical modeling to investigate the effects of wet and dry years on site hydrology is beyond the scope of the present investigation, but presents an avenue for additional research.

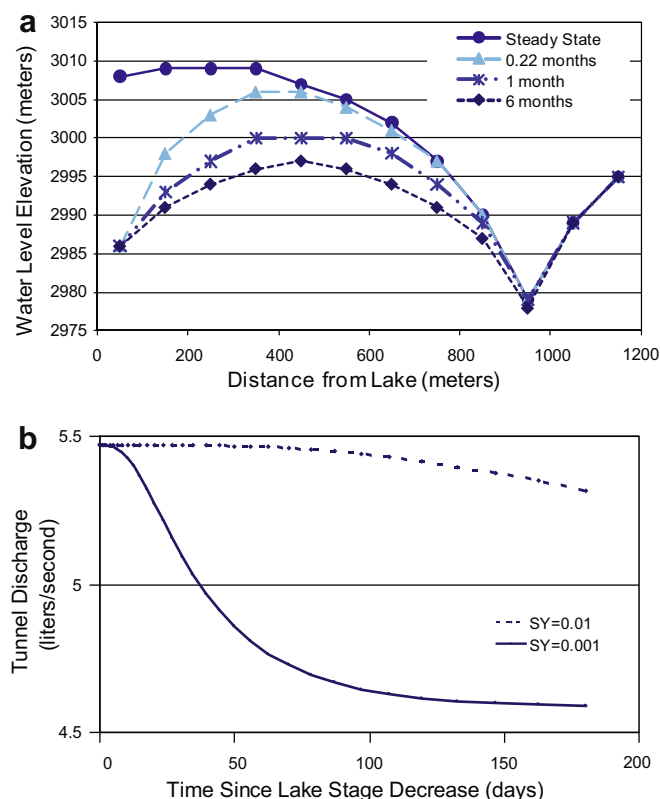


Fig. 7. Cross-sectional, transient, MODFLOW model results illustrate the viability of the conceptual model with the lake stage starting at 3008 m then rapidly declining to 2986 m. Graphs show (a) the ground water divide declining and shifting with specific yield (SY) = 0.001 and (b) discharge from the Dinero mine tunnel for SY = 0.01 and 0.001.

4. Conclusions

Analysis of hydrographs and isotope data enabled assessment of hydrologic connections between Turquoise Lake and Dinero mine tunnel, and increased understanding of the origin of water in the study area and the sources of water to Dinero mine tunnel from 2002 to early 2008. Hydrographs for the Arkansas River at Leadville were representative of natural hydrologic conditions whereas the hydrograph of Turquoise Lake derived largely from the effects of water-storage manipulations in the lake. The Dinero mine tunnel hydrograph had characteristics indicating the influence of both natural conditions and anthropogenic activities. In particular, the asymmetry of the falling limb of the Dinero mine tunnel hydrograph in 2006 and 2007 relative to natural hydrographs (from the Arkansas River near Leadville) indicated elevated flow in the Dinero mine tunnel related to seasonal recharge and draining of a limited mine pool, or to elevated levels in Turquoise Lake. Flow from Dinero mine tunnel was elevated when Turquoise Lake levels were above approximately 3003.8 m (9855 feet) during the falling limb of the seasonal hydrograph.

Isotope characteristics of water samples indicated two meteoric water lines in the study area. The lines had similar slopes (approximately 7) and statistically different intercepts. Group 1 waters were more isotopically enriched than Group 2 waters, included samples of surface water and water from transmountain diversions, indicated large seasonal variations in isotopic composition, and showed depletion of isotopic values during addition of water from snowmelt runoff. Group 2 waters were more isotopically depleted than Group 1 waters, included samples from draining mine tunnels, seeps, and springs, indicated exhibited relatively small

seasonal variation in isotopic composition, and showed enrichment of isotopic values during addition of water from snowmelt runoff. Dinero mine tunnel water represented the most depleted endmember of the Group 2 waters and exhibited minimal seasonal variation that was within the two-sigma uncertainty for the analytical methods. Seasonal isotopic enrichment of Dinero mine tunnel water could occur during mixing with snowmelt recharge or from mixing with Turquoise Lake waters. It was not possible to isotopically differentiate these two sources. Consequently, it was concluded that the source of Dinero mine tunnel water is primarily inactive (deep, older) groundwater that is seasonally supplemented (up to approximately 10%) with snowmelt recharge, or possibly minimal contribution from Turquoise Lake.

Although this study concludes that water probably does not travel from Turquoise Lake to Dinero mine tunnel, Turquoise Lake may influence the magnitude of discharge from the Dinero mine tunnel portal. A conceptual model is presented showing how Turquoise Lake levels influence the maximum elevation of a water-table divide between Turquoise Lake and Dinero mine tunnel. The model explains the varying configurations of the Dinero mine tunnel hydrograph observed during the study, and illustrates how the geometry of the water table between Turquoise Lake and Dinero mine tunnel affects flow from the Dinero mine tunnel without requiring the transfer of water between the two locations. The conceptual model is supported by MODFLOW simulations.

Ultimately, the hydrologic configuration between the Dinero mine tunnel and Turquoise Lake is not resolved. The data presented here presents intriguing possibilities ranging from (1) direct connection between Turquoise Lake and Dinero mine tunnel where the lake contributes up to 10% of flow from the tunnel; to (2) an indirect connection between Turquoise Lake illustrated by the conceptual and numeric models where lake level fluctuations influence flow from Dinero mine tunnel; to (3) the possible existence of a mine pool that seasonally recharges with snowmelt infiltration and attenuates the falling limb of the Dinero mine tunnel hydrograph by slowly releasing the recharge water through a collapse in the mine workings. Although the low cost, long term application of stable isotopes and hydrographs employed herein have helped understand some aspects of the origin of water and the hydrology of the Dinero mine tunnel, additional study involving installation of monitoring wells could help refine these results.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.apgeochem.2009.09.015](https://doi.org/10.1016/j.apgeochem.2009.09.015).

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