Ownership of Mine-Tunnel Discharge

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Abstract

Water discharging from numerous tunnels constructed during mining in the Wasatch Mountains near Salt Lake City, Utah, flows into nearby creeks. Disputes over ownership of water feeding the creeks have resulted in extensive litigation. In the course of a legal dispute over ownership of outflow from the Kentucky-Utah (K-U) Tunnel we evaluated the patterns and rates of ground water flow using an integrated study of the geology, chemistry, isotopes, and chlorofluorohydrocarbon (CFC) composition of the water. A sequence of sedimentary rocks with a range of hydraulic conductivity values has been folded, faulted, intruded by igneous rocks, and then eroded to create the rough topography of the Wasatch Mountains. The similarity of composition among tunnel discharge, springs, and base flow in the creek indicates that the creek is fed by ground water circulating in local, shallow flow systems. Results of numerical simulations of ground water flow indicate that the K-U Tunnel likely intercepts ground water that, in the absence of the tunnel, would ultimately flow in the subsurface to Big Cottonwood Creek. CFC and tritium contents of the water indicate flow weighted average ground water travel times range from four to 23 years and support our conclusion that water discharging from the tunnel is moving within a shallow ground water flow system. Despite sparse data, the scientific understanding was deemed sufficient for the judge to rule that owners of the surface water also own the tunnel discharge because, in the absence of the tunnel, this water would supply the stream.

Introduction

Population growth in the highly urbanized Salt Lake Valley, Utah, has placed increasing pressure on water development in nearby, sparsely populated mountain watersheds. Streams flowing westward from the Wasatch Mountains to the Salt Lake Valley include Big Cottonwood, Little Cottonwood, and Mill Creeks (Figure 1). Disputes over ownership of water flowing in, and feeding, these streams have resulted in litigation throughout most of the past century.

A number of tunnels constructed during past mining operations penetrate the central Wasatch Mountains near Salt Lake City. Although originally driven to explore new ground, provide transportation access to ore bodies and to drain excess ground water from mining areas, water discharging from several tunnels now supplies public and private water systems.

The portal of the Kentucky-Utah (K-U) Tunnel is located on the southwest side of Big Cottonwood Creek at an altitude of 2484 m (sample location 15 in Figures 1 and 2). The tunnel extends approximately 2.7 km south through glacial moraine, limestone, and fissures mineralized with sulfides and oxides of lead and zinc. When completed in the 1940s, heavy inflows of water were encountered near the southern end of the tunnel. The annual water yield of the tunnel is approximately 4.5×10^5 m^3.

Recently, ownership of the K-U Tunnel discharge has been disputed. Salt Lake City corporation asserts its rights to water in Big Cottonwood Canyon and to water discharging from the K-U Tunnel based on the resolution of a 1914 case (Civil No. 8921, The Progress Co. v. Salt Lake City et al.) known as the Morse Decree.

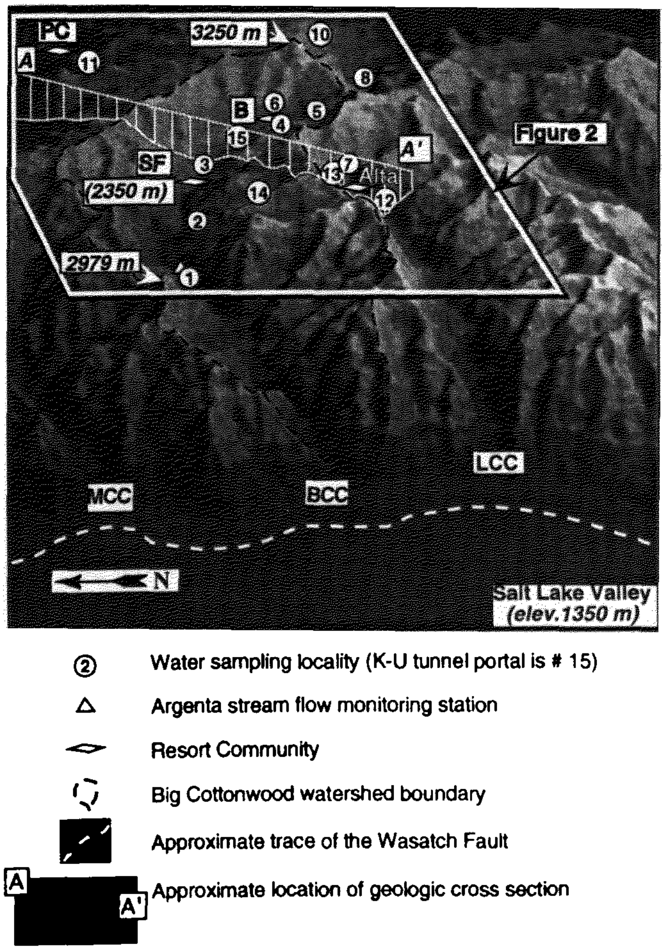

Figure 1. Shaded relief diagram of a portion of the central Wasatch Mountains, Utah. Note that north is to the left. Abbreviations used in the figure are: B, Brighton; BCC, Big Cottonwood Canyon; LCC, Little Cottonwood Canyon; MCC, Mill Creek Canyon; PC, Park City; SF, Silver Fork. A–A′ is the cross section of Figure 3.

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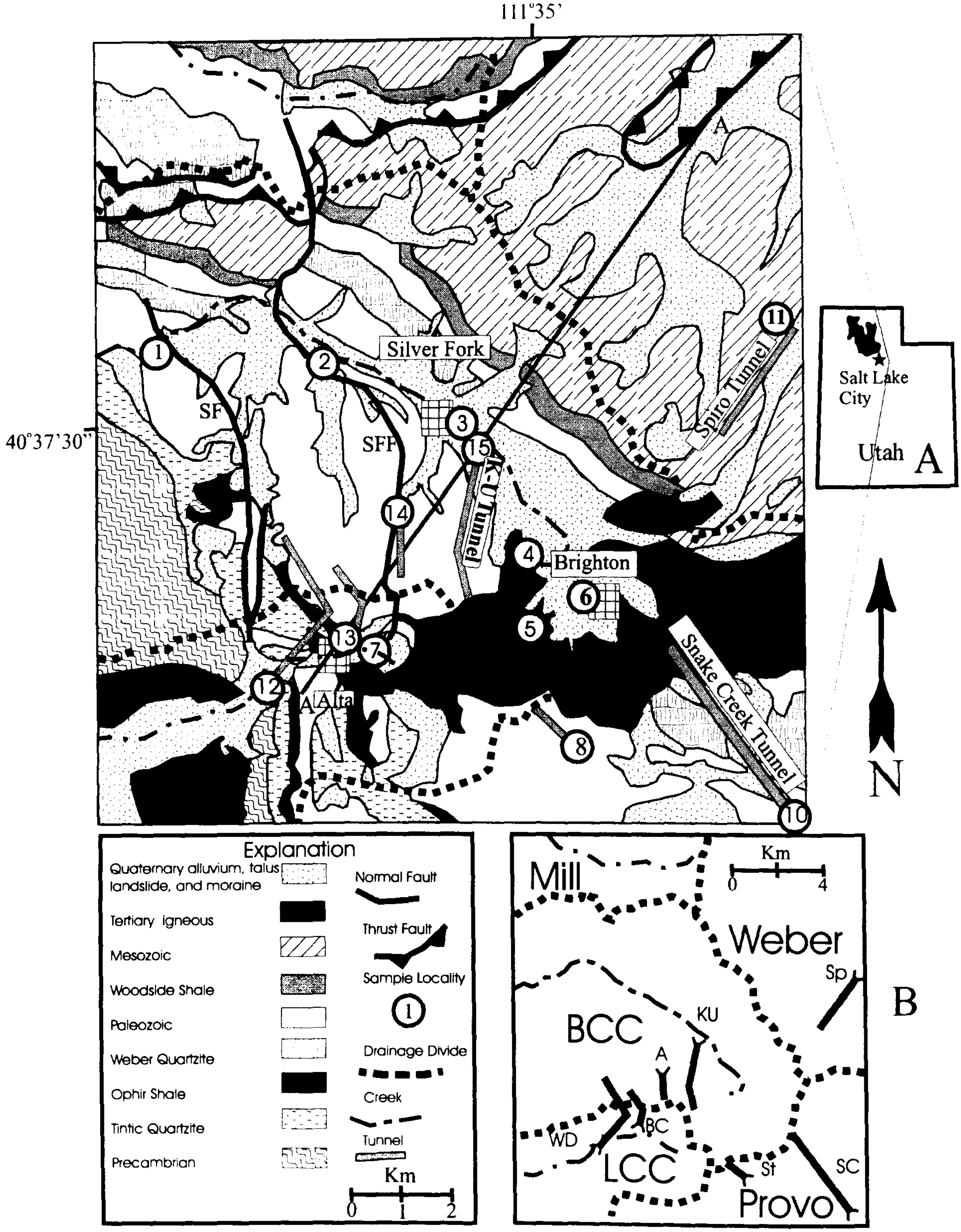

Figure 2. Generalized geology of a portion of the central Wasatch Mountains, Utah. Locations of water samples collected and analyzed in this study are shown as circles. Drainage divides are shown as heavy dashed lines and streams are shown as a dot-dash line. Heavy dashed lines mark the drainage divides that separate Big Cottonwood Canyon from Little Cottonwood Canyon on the south, Snake Creek on the southeast, Park City and the Weber basin on the northeast, and Mill Creek on the north. Major drainages shown are Little Cottonwood Creek, Big Cottonwood Creek, and Mill Creek all flowing from east to west toward Salt Lake Valley. The highest point on the map is Twin Peaks between Little Cottonwood and Big Cottonwood Canyons. SFF indicates the Silver Fork Fault and SF is the Superior Fault. Geology modified from maps by Baker et al. (1966), Crittenden (1965a, 1965b, 1965c, 1965d), and Crittenden et al. (1966). Inset map of Utah shows location of Figure 1 and Figure 2 near Salt Lake City. Note that the top of the map is north when comparing with Figure 1. Tunnels shown are only a subset of the mine workings found within the study area. Inset B shows drainage divides, canyon streams, and tunnels referred to in the text. Tunnel abbreviations are: A-Alta, BC-Bay City, KU-Kentucky-Utah, SC-Snake Creek, Sp-Spiro, WD-Wasatch Drain. LCC is Little Cottonwood Creek and BCC is Big Cottonwood Creek.

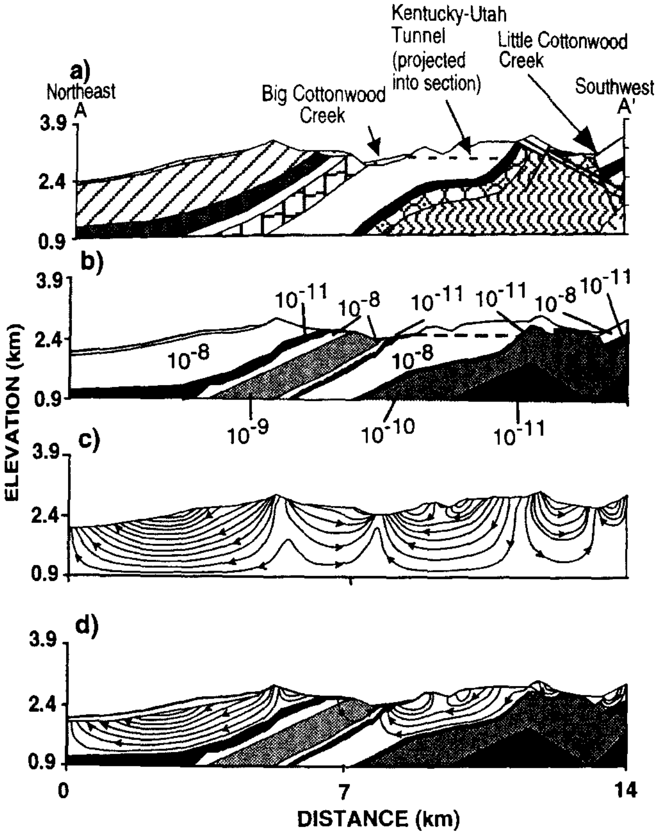

Figure 3. Vertical cross sections along A-A′ (Figures 1 and 2) showing:(a) geological structure (refer to Figure 2 for key to rock unit patterns), (b) hydrostratigraphic units showing hydraulic conductivities in m/s, (c) computed patterns of steady-state ground water flow through homogeneous isotropic rocks, and (d) computed patterns of ground water flow through the heterogeneous hydrostratigraphy of (b).

The decree states that Salt Lake City owns almost all water rights on Big Cottonwood Creek at, and immediately below, the mouth of the canyon. In the absence of the K-U Tunnel, Salt Lake City claims that water currently discharging from the tunnel would have moved through the subsurface to feed Big Cottonwood Creek. Silver Fork Pipeline Corp. (defendant) on the other hand, asserts that water discharging from the K-U Tunnel is: (1) underground water unregulated by the state until 1935 and excluded from the 1914 Morse Decree; (2) that their right is derived from use of the water prior to 1935 by miners, cabin owners, and cattle; and (3) in the absence of the tunnel, water that currently discharges from the tunnel would have flowed through the subsurface to adjacent watersheds without surfacing in Big Cottonwood Creek. As a consequence of these differences of opinion, Salt Lake City filed suit (Salt Lake City Corp. v. Silver Fork Pipeline Corp.) stating that Silver Fork has no right, title, or interest to the water flowing from the K-U Tunnel.

The major hydrological issue was whether or not water currently discharging from the K-U Tunnel, in the absence of the tunnel, would have fed Big Cottonwood Creek. The rugged mountainous terrain, sparse data, and complex geology of the Big Cottonwood watershed complicate efforts to build sound conceptual and predictive models for ground water flow in the vicinity of the K-U Tunnel. Yet, the legal proceedings required a scientific foundation for the judge to render a decision. This paper outlines an example of the growing number of situations where legal disputes must be resolved even when ground water data, and our methods of analysis, are insufficient to fully quantify the characteristics of the system. The legal question hinges on establishing the patterns of ground water flow that would be present today if the K-U Tunnel had not been constructed.

Methodology

Patterns and rates of ground water flow were evaluated, both with and without the K-U Tunnel, through an integrated study of the local geology and hydrology combined with analysis of the chemistry and isotopic character of water found in both surface and ground water flow systems. Published geological reports and geological maps (Baker et al. 1966; Calkins and Butler 1943; Crittenden 1965a, 1965b, 1965c, 1965d; Crittenden et al. 1966; James 1979) form the basis for constructing a generalized geological map of the study area (Figure 2) and a series of geological cross sections (one section is shown in Figure 3a). Water samples collected during the low stream flow period of autumn of 1992 were analyzed for major ions, total dissolved solids, pH, dissolved oxygen, and the isotopes of oxygen and hydrogen. Samples for chlorofluorohydrocarbon (CFC) analysis were collected from the same locations in autumn 1996. Results of the water sampling program help to infer the transit times and pathways followed by ground water discharging from tunnels and springs. Idealized two-dimensional numerical simulations provided a basis for placing field-derived information into context and aided in visualizing the patterns of ground water flow that might have developed near the K-U Tunnel, but in the absence of the tunnel.

Geology

Quaternary age glacial moraine covers the canyon floor in the upper half of the watershed (Figures 2 and 3a). The K-U Tunnel portal is located in glacial till. An interbedded sequence of sandstone, limestone, and shale deposited in continental shelf and adjacent near-shore environments underlies most of the area. The exposed sedimentary rocks range in age from the Precambrian Big Cottonwood Formation to the Jurassic Twin Creek Limestone (Table 1). High-permeability units (Table 1) included in the sedimentary sequence feed ground water to springs located at the bottom of the steep mountainous slopes within the watershed.

Tectonic activity in the Central Wasatch Mountains has folded and faulted (normal and thrust faults) the sedimentary rocks. The Big Cottonwood anticline is a prominent fold cored by the Precambrian Big Cottonwood Formation. The axis of the fold crosses the Wasatch Mountains near Little Cottonwood Canyon (Figures 2 and 3a). Because the K-U tunnel penetrates the north limb of this great fold, sedimentary rocks encountered in the tunnel dip to the northeast. Several thrust faults place older rocks over younger rocks in the vicinity of the K-U Tunnel. For example, the Alta Thrust fault places Cambrian age Tintic Quartzite over Mississippian age Deseret Limestone. The north-striking Silver Fork fault, located west of the K-U Tunnel, is the largest normal fault within the Wasatch Mountains. Stratigraphic throw ranging from 600 to 1500 m juxtaposes a variety of rock types with different values of hydraulic conductivity. The north-striking Superior fault zone comprises two normal faults with total displacement of about 300 m. The Wasatch Fault, located near the western boundary of the Wasatch Mountains (Figure 1), is a large, range-bounding normal fault with displacement on the order of 12 km.

Several large igneous intrusions were emplaced during the Tertiary period (Figures 2 and 3a; Table 1). These low-permeabil-

Table 1
Stratigraphy and Estimated Hydraulic Conductivity (K) of Geologic Units in the Vicinity of the Kentucky-Utah Tunnel, Big Cottonwood Canyon

Geological Age	Stratigraphic Unit	Thickness (m)	Description	K* (m/s)
Quaternary	Moraine, alluvium, and landslide debris	0 to 10	Coarse sand, gravel	10^{-4} to 10^{-1}
			Fine sand, glacial moraine	10^{-8} to 10^{-4}
			Clay, glacial till	10^{-12} to 10^{-8}
Tertiary	Clayton, Alta, and Little Cottonwood Stocks		Intermediate composition igneous intrusives	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}
Mesozoic				
Jurassic	Twin Creek Limestone	850	Silty limestone	10^{-9} to 10^{-6}
	Nugget Sandstone	244	Cross-bedded sandstone	10^{-10} to 10^{-6}
Triassic	Ankareh Formation	480	Cross-bedded pebbly quartzite with shale, mudstone, and sandstone	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}
	Thaynes Formation	3050	Limy sandstone, shale, limestone	10^{-9} to 10^{-6}
	Woodside Shale	305	Shale and limestone	10^{-13} to 10^{-10}
Paleozoic				
Permian	Park City Formation	180	Cherty limestone	10^{-9} to 10^{-6}
Pennsylvanian	Weber Quartzite	365	Quartzite and limy sandstone	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}
	Round Valley Limestone	76	Limestone	10^{-9} to 10^{-6}
Mississippian	Doughnut Formation	75	Black shale with sandstone beds	10^{-13} to 10^{-10}
	Humbug Formation	60	Limestone, dolomite, and sandstone	10^{-9} to 10^{-6}
	Deseret Limestone	260	Limestone and dolomite with lenses of chert and shale	10^{-9} to 10^{-6}
	Gardison Limestone	140	Limestone and dolomite with chert lenses	10^{-9} to 10^{-6}
	Fitchville Formation	40	Massive dolomite	10^{-9} to 10^{-6}
Cambrian	Maxfield Limestone	0 to 305	Dolomite and limestone with sandstone and siltstone	10^{-9} to 10^{-6}
	Ophir Shale	120	Shaley sandstone, limestone, and shale	10^{-13} to 10^{-10}
	Tintic Quartzite	244	Quartzite and conglomerate	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}
Precambrian	Mutual Formation	0 to 365	Quartzite and shale	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}
	Mineral Fork Tillite	0 to 914	Boulders, cobbles, and pebbles in black sand and shale	10^{-13} to 10^{-10}
	Big Cottonwood Formation	4900	Quartzite and shale	10^{-10} to 10^{-6}/ 10^{-13} to 10^{-10}

*Highly fractured/weakly fractured

ity igneous rocks transmit significant amounts of ground water only where locally intense fracturing has resulted from the processes of faulting and uplift. For example, the primary source of water flowing into the K-U Tunnel is encountered at the fractured contact between igneous and sedimentary rocks located near the southern terminus of the tunnel. In addition, deformation and heating associated with intrusive activity has locally deformed and metamorphosed the older rocks.

Hydrology

The K-U Tunnel is wholly contained within the mountainous, 130 km^2 Big Cottonwood Canyon watershed (Figures 1 and 2). The normal annual precipitation as rain and snow varies from 50 cm near the mouth of the canyon to greater than 150 cm along the highest ridges of the watershed (Hely et al. 1971). Hely et al. (1971) note that almost one half of the volume of water entering the Big Cottonwood watershed leaves as stream flow (mean annual runoff at the canyon mouth is 6.5×10^7 m^3). Up to 1.9×10^7 m^3 (13%) of the annual incoming precipitation (Holmes et al. 1986) is transferred from the watershed, within northeast dipping permeable beds, to the adjacent Weber River drainage (Figure 2). Northeast movement of ground water from the Big Cottonwood watershed is enhanced by the northeast-southwest oriented Spiro Tunnel (Holmes et al. 1986). The southwest terminus of this tunnel is near the surface water drainage divide shown in Figure 2. Higher permeability, fractured Weber Quartzite and overlying Mesozoic sediments drained by the Spiro Tunnel are exposed on the Big Cottonwood Canyon side of the divide and discharge water at Sample 11 in Figure 2. In this rugged mountainous terrain, additional unquantified amounts of ground water are likely also transferred along bedding strike northwest to the Mill Creek drainage (Figure 2). Subsurface transfer of water to the southeast, south, and southwest, however, is inhibited by low permeability igneous rocks that form the backbone of high ridges separating the Big Cottonwood watershed from the Little Cottonwood and Provo River watersheds (Figure 2).

Water passing the Argenta stream flow monitoring station in Big Cottonwood Canyon (location of Sample 1 on Figures 1 and 2)

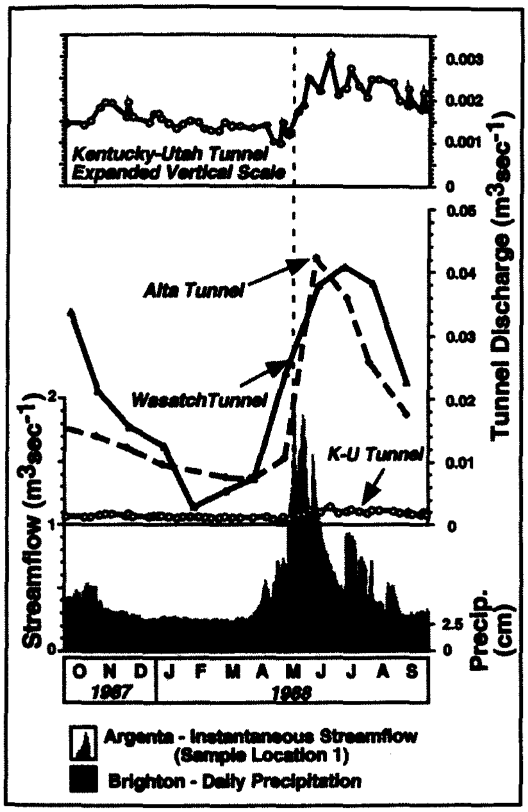

Figure 4. Comparison of surface flow in Big Cottonwood Creek shown in gray and precipitation at Brighton station shown in white on gray with tunnel discharges for 1987-1988.

responds to seasonal changes in precipitation (Figure 4). The bulk of the annual precipitation occurs during the period of low stream flow (November through March) when most incoming precipitation is frozen in the snow pack. Thus, water flowing in the creek is supplied primarily by ground water discharging from the adjacent mountain slopes. As the snow pack builds, ground water levels decline beneath the major ridges as the flow system releases water from storage to maintain stream flow in Big Cottonwood Creek. In the spring, the snow pack melts to inject a large burst of meltwater into Big Cottonwood Creek that progressively declines until the creek again approaches a base flow condition in mid-summer. Although only one year of record (1987-88 water year) is presented in Figure 4, similar patterns in precipitation and stream flow are noted in data collected since 1916.

The intimate relationship between surface water and ground water flow systems is reflected in the discharge rates presented in Figure 4 for three tunnels in the study area. The K-U and Alta Tunnels discharge to Big Cottonwood Creek (Samples 15 and 14, respectively, in Figures 1 and 2). The Wasatch Drain Tunnel (Sample 12 in Figures 1 and 2) discharges to Little Cottonwood Creek. Discharge rates for all tunnels are reported and plotted on Figure 4 as instantaneous observations. Tunnel discharge rates in all three cases decline during autumn and winter, rise gradually during spring and early summer, then decline during late summer and autumn (Figure 4). Large springtime peaks in the plots of tunnel discharge lag approximately one month behind that of the corresponding peak in stream flow that occurs in May. This clear relationship between tunnel discharge, snow pack melting, and stream flow stems from the fact that the tunnels are fed by a dynamic, shallow hydrologic system that undergoes strong seasonal changes.

The K-U Tunnel discharge constitutes less than 1% of the mean annual stream flow monitored at the mouth of Big Cottonwood Creek (6.5×10^7 m^3). Monitoring the presence or absence of this volume of water is precluded because natural variations in mean annual stream flow and uncertainties in stream flow measurements far exceed the annual tunnel yield of 4.5×10^5 m^3. This relatively small volume of water, however, would provide a significant water supply for expanding resort communities in Big Cottonwood Canyon.

Hydrostratigraphy

To evaluate the influence of geology on ground water flow systems, the following hydrostratigraphic units were identified in the study area: faults, igneous rocks and quartzite, sedimentary rocks, carbonate rocks, and surficial sediments. The structure of hydrostratigraphic units in the study area can be inferred from the geological cross section of Figure 3a using the information contained in Table 1. Because few in situ or laboratory measurements of hydraulic conductivity are available, we used estimates based on the cumulative experience of the authors and published values of hydraulic conductivity obtained for similar rock types (i.e., Freeze and Cherry 1979). Hydrostratigraphic units are shown in the vertical cross section of Figure 3b. We used plausible conductivity contrasts to provide a qualitative concept of the influence of topography and geological influences on ground water flow in Big Cottonwood Canyon.

Water moving through limestones and dolomites tends to dissolve and enlarge fractures to produce a suite of relatively high permeability rocks in the study area. Caverns are well known in some parts of the Wasatch Mountains. Low permeability quartzite and igneous rocks can have a comparatively high permeability that depends on the degree of fracturing. For example, fractured Weber Quartzite is reported to be the principal source of water in mines of the Park City Mining District on the east side of the Wasatch Range (Holmes et al. 1986). Fracturing plays a lesser role in controlling the permeability of consolidated clastic sedimentary rocks where high values of hydraulic conductivity are associated with sandstone and low values are associated with shale. Mixtures of fine- and coarse-grained surficial sediments, such as the glacial moraine that fills the upper part of Big Cottonwood Canyon, are relatively permeable.

Faults have a permeability structure that depends on several factors, including host lithology, magnitude of displacement, and depth of formation (Caine et al. 1996). The major faults found in the study area (e.g., Silver Fork and Superior faults shown in Figure 2) have a similar character with a core of fine-grained fault gouge and several outer layers of highly fractured host rock. The low-permeability gouge causes reduced flow across the fault while flow along the fault is enhanced by the higher-permeability fracture network that runs parallel to the fault plane. Thus, major faults found in the study area are likely to act as dams that restrict flow across the fault while also forcing ground water to flow up or down along the fault plane. As a consequence, the major faults create ground water compartments that restrict ground water flow between different regions of the watershed. The K-U, Alta, and Wasatch Drain Tunnels were each constructed to release water encountered during mining within these compartments. The extensive network of mining-related tunnels found within the study area (Calkins and Butler 1943) yield a complex pattern of enhanced permeability that has depressed the water table in the highlands between Big and Little Cottonwood canyons. The absence of monitoring wells, however, precludes mapping the modified water table configuration. The higher permeability sedimentary rocks above each tunnel may reasonably be assumed to have been largely dewatered over the 50-plus years following tunnel construction. The impact of the tunnels on the ground water flow system is outlined in greater detail in the next section.

Patterns of Ground Water Flow

Ground water flow in the Wasatch Mountains is primarily controlled by the topography of the land surface and the underlying geologic structure. Inspecting the topography, therefore, provides a rough guide to the general directions of horizontal components of ground water flow. In the absence of permeability variations caused by geologic structure, ground water within the Big Cottonwood watershed would generally flow from the watershed divides shown in Figure 2 to Big Cottonwood Creek. The results of a two-dimensional, steady-state ground water flow simulation (Figure 3c) illustrate how the topography given in the vertical cross section of Figure 3a would cause water recharging on the ridge south of the K-U Tunnel to flow in a local flow system to Big Cottonwood Creek. A homogeneous and isotropic permeability structure was modeled to enable us to focus on the way that topography controls flow in the vicinity of the K-U Tunnel.

The finite-element code and background for modeling ground water flow systems in mountainous terrain was described by Forster and Smith (1989). Impermeable basal and vertical model boundaries were set at large distances from the region of primary interest to minimize their impact on the simulation results. Computed patterns of flow near the K-U tunnel were largely unaffected when a high permeability basal aquifer was modeled (not shown) to test the sensitivity of the results to the basal boundary. The top boundary (water table) was assigned a distribution of fixed head values that mimic the form of the surface topography. The K-U Tunnel was not included in the model so that the patterns of ground water flow in the absence of the tunnel could be evaluated.

Permeability variations caused by geologic structure can shift ground water divides from the topographically defined watershed divides and modify the patterns of ground water flow inferred for the simple system shown in Figure 3c. The impact of a plausible permeability structure on ground water flow was modeled by assigning homogeneous and isotropic hydraulic conductivity values to each hydrostratigraphic unit shown in Figure 3b. The resulting patterns of ground water flow (Figure 3d) are clearly influenced by the geologic structure. The geologic structure allows the local flow system operating near the K-U Tunnel to transmit water from the nearby ridge to Big Cottonwood Creek.

Ground water divides on the north side of Big Cottonwood Creek are likely shifted to the south (to the right in Figure 3) because northeasterly dipping permeable rocks transfer water to the Mill Creek and Weber River drainages (Figure 2). The modeling results shown in Figure 3d suggest that the ground water divide beneath the north ridge is likely shifted to the south (to the right in Figure 3) because the northeasterly dipping shales inhibit southward flow to Big Cottonwood Creek. This shift of the divide has little impact on topographically controlled patterns of ground water flow near the K-U Tunnel.

Ground water flow south of Big Cottonwood Creek is compartmentalized by low permeability shale, faults, and the low permeability igneous rocks that underlie the southern ridge of the watershed (Figure 2). For example, the Wasatch Drain Tunnel is positioned to drain the sedimentary, ore-bearing rocks that lie within a compartment bounded on the west by the Superior Fault, on the east by the Silver Fork Fault, and below and to the south by igneous rocks (Figures 2 and 3). Although the Wasatch Drain Tunnel depresses the water table in the compartment and transfers water from Big to Little Cottonwood watersheds, the ground water flow system near the K-U Tunnel is likely little affected. If the earlier construction of the Wasatch Drain Tunnel had dewatered the area of the K-U Tunnel, then the K-U Tunnel would not have been constructed.

The Alta and K-U Tunnels were constructed to drain a compartment bounded on the west by the Silver Fork Fault and on the south, east, and below by igneous rocks (Figures 2 and 3). Although the Alta Tunnel drained the ore-bearing sedimentary rock and depressed water table elevations in the western portion of the compartment, southward propagation of the tunnel influence is restricted by the igneous rocks. The K-U drain tunnel was constructed because shale, faults, and dikes to the east of the Alta Tunnel inhibit eastward propagation of the Alta Tunnel influence. The Alta Tunnel discharges approximately 10 times the flow of the K-U Tunnel (Figure 4), yet was unable to drain the mine workings overlying the terminus of the K-U Tunnel.

Primary inflows to the K-U Tunnel occur at the terminus of the tunnel in a high permeability fracture zone at the contact between sedimentary and igneous rocks. When the tunnel first encountered the primary inflow zone, the water level fell in a small lake located above the tunnel terminus and several hundred meters along the contact. The lake, however, still exists because precipitation rates are high (in excess of 150 cm per year) and the water table in the igneous rocks has suffered little decline in the 50 years since the K-U Tunnel was constructed. The relatively small volume of water yielded by the K-U Tunnel suggests that the high elevation recharge area that encompasses the lake and supplies the tunnel must be relatively small. Rough calculations suggest that a recharge area of less than 5 km^2 is sufficient to supply the K-U Tunnel discharge if only 10% of the incoming precipitation actually reaches the tunnel. The small recharge area is bounded to the south by igneous rocks so that the influence of the K-U Tunnel is unlikely to have propagated southward across the topographic divide that likely coincides with the location of the ground water divide.

The K-U Tunnel appears to be collecting water from a northeast-southwest trending fracture zone found at the contact of the igneous rock. In the absence of the tunnel, the fracture zone likely transmitted water falling on the tunnel recharge area to Big Cottonwood Creek. The need to construct the K-U Tunnel indicates that natural southward drainage, combined with water transfers to Little Cottonwood Canyon through higher elevation mine workings, was unable to depressurize the fracture zone sufficiently to enable mining to proceed. Although the K-U Tunnel lowered the water levels in mines operating in the overlying sedimentary rocks, the tunnel appears to have had little impact on water levels in the adjacent, low permeability igneous rocks. Thus, the compartmentalized and localized flow system computed near the K-U Tunnel (Figure 3d) seems to yield a plausible, yet idealized, representation of the patterns of flow that might operate today if the K-U Tunnel had not been constructed. In the absence of the K-U Tunnel, water currently recharging the K-U Tunnel is unlikely to have flowed anywhere other than to Big Cottonwood Creek.

Alternate Flowpaths

Ground water recharging the K-U Tunnel is unlikely to have flowed to the Park City watershed (Weber River drainage). Flow to the Weber River drainage would require ground water to travel from the mountain slope above K-U Tunnel, under Big Cottonwood Creek and beneath the drainage divide on the next ridge to the north. Computed flow patterns shown in Figures 3c and 3d suggest that the Weber River drainage is unlikley to capture flow from the ridge south of the K-U Tunnel.

The three-dimensional character of the surface topography is not fully captured in the simulation results discussed previously. Examination of the geological structure in Figure 2 suggests that westward ground water flow toward Salt Lake Valley is unlikely. For example, the dam-like character of the north-trending Silver Fork and Superior faults likely forces northward flow of ground water toward Big Cottonwood Creek, rather than allowing westward flow toward the Salt Lake Valley. Significant transfer of ground water from the vicinity of the K-U Tunnel to the Salt Lake Valley is also inhibited by a number of semi-permeable barriers, such as 4900 m of lower permeability Big Cottonwood Formation quartzite and shale and 120 m of Ophir shale (Figure 2; Table 1). These geological features tend to divert any subsurface flow moving beneath the creek bed to discharge into the creek. Net gains, rather than losses, of water by the creek are further enhanced by contributions from local ground water flow systems moving water along bedding planes and fault-related features from adjacent high-elevation ridges toward the valley floor.

Southward transfer of ground water from the vicinity of the K-U Tunnel to the Provo and Little Cottonwood watersheds is prohibited by the low permeability igneous rocks that form the backbone and underlie the intervening ridge. The necessity of constructing the K-U Tunnel implies that the pre-existing mining tunnels were unable to transfer water from the K-U Tunnel recharge area to the Little Cottonwood watershed.

Water Chemistry

Previous studies of the geochemical and isotopic character of ground water in the Wasatch Mountains (Mayo and Loucks 1992) provide a foundation for interpreting the water chemistry. Mayo and Loucks (1992) used rock type and structure to identify six types of ground water systems in the Wasatch Mountains: granitic, alluvial, consolidated sedimentary bedrock, fault controlled, thermal, and mine drainage. Water from each system is distinguished by differences in total dissolved solids, magnesium, sulfate, and chloride concentrations, Ca/Mg ratios, and calcite and dolomite saturation indices. Most nonthermal ground water is dominated by Ca, Mg, HCO_3, whereas the thermal ground water has higher sulfate concentrations. Bulk water chemistries of ground water other than those from granitic terrains are generally consistent with the dissolution of carbonate rocks. Heavy metal concentrations Cu, Fe, and Zn are greatest in discharge from mine tunnels.

Compositions of 15 water samples collected for the present study are shown in Table 2. All of the water samples collected are calcium-magnesium-bicarbonate-sulfate water types. Calcium (13.1 to 96.4 mg/L), magnesium (4.8 to 29.5 mg/L), and bicarbonate (43 to 173 mg/L) originate in the water through dissolution of the limestone and dolomite sediments through which the water circulates. The sulfate (11 to 402 mg/L) is a result of oxidation of sulfide minerals in the mining areas. Dissolved silica (3.1 to 11.1 mg/L) is derived from dissolution of quartz and other silicates in the rocks through which the water flows. The sodium (1.7 to 16.5 mg/L) and potassium (0.5 to 2.0 mg/L) content of all of the water samples is low, reflecting the low sodium and potassium contents of carbonate rocks and the low solubility of the sodium and potassium bearing minerals in the igneous rocks. The chloride content of the water is generally low, ranging from 1 to 10 mg/L. The highest value of 20 mg/L is in Big Cottonwood Creek at Silver Fork and may be due to cultural contamination of the water. Significantly, the chloride value at Argenta (sample 1) is lower indicating dilution of chloride concentrations in Big Cottonwood Creek by low chloride water contributed from sources such as Days Fork Spring (sample 2). The pH of the water varies from 7.9 to 9.05. These pH values indicate that the hydrogen ion content of the water is controlled by interaction of water with atmospheric carbon dioxide and carbonate minerals in the subsurface.

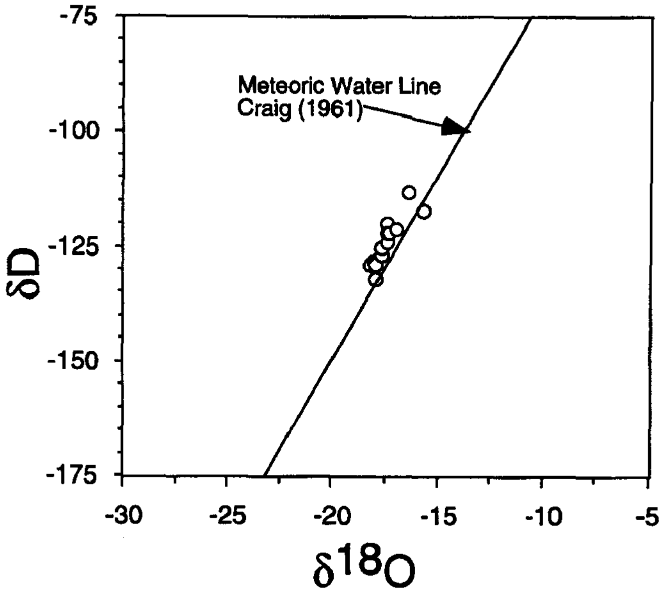

Figure 5. Plot of δD versus $\delta^{18}O$ compositions of water analyzed in this study. The global meteoric water line of Craig (1961) is shown for reference.

Water sample temperatures range from 0.68° to 10.6°C. This range in temperature is consistent with the range in mean annual air temperature from 10°C in the Salt Lake Valley to near zero at the highest peaks of the watershed (Hely et al. 1971). This similarity in mean annual temperatures reflects the close association between ground water and the atmosphere.

The chemical composition, pH, and temperature of ground water samples collected by Mayo and Loucks (1992) and the authors all indicate shallow circulation of ground water through rocks found in the immediate vicinity of the K-U Tunnel. This result is consistent with the generalized patterns of flow discussed in the previous section and shown in Figure 3.

Hydrogen and Oxygen Isotopes

Water samples collected by Mayo and Loucks (1992) and in this study have been analyzed for three isotopes of hydrogen and two isotopes of oxygen. Because the values of δD and $\delta^{18}O$ cluster around the global meteoric water line shown in Figure 5 (Craig 1961), all samples clearly originated as water falling from the atmosphere as precipitation (meteoric water). The variation between sample results is relatively small and likely reflects seasonal variations in the isotopic signatures of moisture traveling in the atmosphere. There is no evidence of high temperature exchange of isotopes between rock and water. Thus, circulation of the water sampled in these studies to any significant depth is unlikely.

Tritium concentrations in samples collected in the Wasatch Mountains by ourselves (Table 2) and by Mayo and Loucks (1992) are less than 100 TU and greater than 15 TU, indicating that ground water in this region moves rapidly through the hydrologic system with transit times less than 30 years. Tritium concentrations found for all samples collected in this study are representative of post-1963 ground water recharge. Relatively low tritium concentrations found in samples collected in the upper reaches of Big and Little Cottonwood creeks and in both the Spiro and Alta tunnels indicate relatively recent exposure to the atmosphere and little delay in moving through the hydrologic system. The relatively high tritium concentrations of samples collected from the remaining tunnels and from Big Cottonwood Creek at Argenta indicate longer transit times. These results support the interpretation that ground water flowing from the K-U, and other, tunnels is moving rapidly through a shallow ground water flow system. Furthermore, the elevated tritium concentration noted in the sample obtained from Big Cottonwood Creek at Argenta confirms that water moving in the creek at this location is comprised mostly of young ground water.

Chlorofluorocarbon (CFC) Estimates of Ground Water Age

Samples for CFC analyses were collected in clean ⅜-inch O.D. copper tubing that was sealed by cold welding the ends (Wilkowske 1998). At least three analyses were performed, at the University of Utah, on samples from each site. The analytical system is similar to that described by Wisegarver and Cline (1985). The results of CFC analyses are shown in Table 2.

The apparent recharge years shown in Table 2 were determined by computing the atmospheric concentration of CFCs that would be in equilibrium with the measured values at a temperature of 2°C and at a total pressure of 0.737 Atm (i.e., an elevation of 2500 m.) These atmospheric concentrations were then compared with the observed atmospheric values in order to assign a recharge year to each sample.

Recharge years have been computed using measurements of both CFC-11 and CFC-12. While CFC-11 and CFC-12 recharge years are highly correlated, CFC-12 ages are systematically younger. Biodegradation of CFC-11 has been observed in other systems (Cook et al. 1995), which leads to apparent CFC-11 ages being older than CFC-12 ages. The difference between CFC-11 and CFC-12 ages increases with increasing age, which is the expected trend if a small amount of biodegradation of CFC-11 is occurring. In contrast, CFC-12 has been shown to be geochemically conservative in a variety of hydrogeologic systems (Busenberg and Plummer 1992; Cook et al. 1995). Thus, CFC-12 ages are considered more representative of actual fluid travel times and are used in this report for hydrologic interpretations.

To compare the CFC-12 ages with tritium results, a decay-corrected tritium concentration was computed using travel times as given by the CFC-12 recharge year. Because the tritium measurements were made in 1993 while the CFC-12 measurements were

Table 2
Composition of Surface and Ground Water from the Kentucky-Utah Area[1]

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Type	Strm	Sprg	Strm	Tnnl	Sprg	Sprg	Strm	Tnnl	Sprg	Tnnl	Tnnl	Tnnl	Tnnl	Tnnl	Tnnl
Temp °C	7	6	5	6	3	4	1	5	8	11	8	6	4	4	3
pH	8.63	7.84	8.68	9.05	8.31	7.90	8.37	8.38	7.99	8.01	7.91	7.85	8.21	8.4	8.53
O_2	9	10	9	7	7	7	10	9	8	6	8	5	8	10	8
Ca	62	39	22	44	13	34	30	35	44	19	96	45	36	60	30
Mg-	9	6	8		3	5	8	15	9	29	7	7	19	14	14
Na	8	2	17	3	2	4	2	2	3	5	5	4	2	2	2
K	1	1	1	2	1	2	1	1	1	1	2	1	1	1	1
HCO_3	173	171	80	101	43	66	84	118	156	107	138	114	173	131	121
Cl	10	1	22	2	1	2	3	1	2	2	3	6	2	1	2
SO_4	70	11	34	21	67	21	74	32	21	49	390	402	223	14	108
NO_3	0.5	0.4	0.2	0.5	1.5	0.2	0.1	0.1	0.3	0.0	0.1	0.4	0.4	0.5	0.2
SiO_2	4.9	3.3	3.3	6	3.6	11.1	4.1	4.1	8.7	7.6	8.6	3.6	3.1	4.2	6.3
^3H (TU)	28.9	42.1	21.3	32.4	29.2	47.3	17.6	31.5	32.5	30.6	17.6	30.5	29.5	17.6	35.6
			21.6												33.0
δD‰	−120	−129	−117	−128	−121	−129	−112	−127	−131	−128	−129	−120	−124	−122	−125
	−124		−117				−113		−132				−124		−125
$\delta^{18}O$‰	−17.4	−17.9	−15.8	−18.0	−17.0	−18.0	−16.4	−17.7	−17.9	−17.9	−18.2	−17.4	−17.4	−17.3	−17.6
			−15.6			−17.8									−17.8
CFC-12	84	80			88	85	85	85		74	76	92	82	86	88
Age	82	81			87	85	85	85		73	75	91	82	85	87
	84	81			87	84	86	86		73	76	88	82	85	88

[1]**Measurement units:** temperature in °C, dissolved constituents in mg/L, ^3H in tritium units, δD and $\delta^{18}O$ in per mil, and CFC-12 age in calendar date.

Index to Sites: 1. Big Cottonwood Creek at Argenta; 2. Spring in Days Fork; 3. Big Cottonwood Creek at Silver Fork; 4. Discharge from New York Tunnel; 5. Spring near Twin Lakes Dam; 6. Spring Silver Lake Water Co., Brighton; 7. Little Cottonwood Stream at Alta; 8. Discharge from Steamboat Tunnel; 9. Spring in Lavina Creek; 10. Discharge from Snake Creek Tunnel; 11. Discharge from Spiro Tunnel; 12. Discharge from Wasatch Tunnel; 13. Discharge from Bay City Tunnel; 14. Discharge from Alta Tunnel; 15. Discharge from Kentucky-Utah Tunnel.

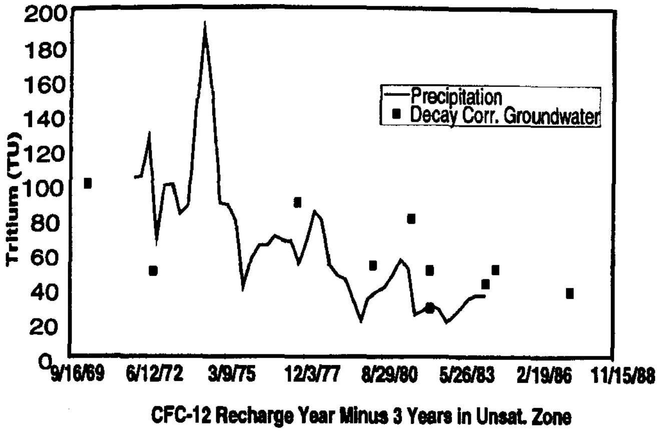

Figure 6. Tritium in precipitation (weighted by assuming 90% of precipitation occurs between October and June), and decay corrected tritium in ground water collected from streams at base flow, springs, and tunnels. The decay correction was done using the CFC-12 recharge year minus three years. Tritium values from unpublished data of S. Thiros, U.S. Geological Survey.

made in 1996, it was necessary to assume that if CFC-12 recharge years had been measured in 1993 they would simply be three years younger than those measured in 1996 (i.e., this assumes that average fluid velocities and travel times are temporally invariant). Because the CFC dating method does not account for travel times in the unsaturated zone where gas-water exchange occurs, it was also necessary to assume a travel time (three years) for the unsaturated zone. Thus, the CFC-12 age (which gives the travel time in the saturated zone) plus the assumed travel time in the unsaturated zone represents the elapsed time in which radioactive decay of tritium has reduced the initial tritium activity in precipitation.

Decay-corrected tritium values are shown in Figure 6. Also shown are observed tritium activities in precipitation that have been weighted by assuming that 90% of precipitation occurs between October and June (Figure 4). A weight was used because tritium activities in winter are higher than summer and most precipitation/recharge occurs during the winter resulting in the tritium activity of recharge being highly skewed toward the winter value. The decay-corrected values of water samples agree reasonably well with atmospheric measurements, indicating that the tritium measurements and the CFC-12 ages are consistent.

Conclusions

In our study of the hydrogeology of the K-U Tunnel and vicinity, we first establish the subsurface geological conditions that govern water flow. These geological conditions are first a sequence of continental-shelf sedimentary rocks. These rocks were then folded, fractured, and thrust faulted. The rocks were then intruded by igneous rocks that altered the sedimentary rocks in the vicinity of the intrusions. Then normal faulting introduced additional fractures and water flowpaths into the brittle rocks.

We next establish the source, age, and depth of circulation of ground water in the area by examining the chemical and isotopic composition of surface flow in Big Cottonwood Creek, ground water in the K-U Tunnel, and ground water in nearby springs and other similar tunnels in the Central Wasatch Mountains. All of these water samples are dominantly calcium bicarbonate water with small amounts of sodium, potassium, and chloride and variable amounts of sulfate. Calcium and bicarbonate are derived by dissolution of the limestone sedimentary rocks through which ground water flows. The similarity of chemical composition among tunnel discharge, spring discharge, and base flow of Big Cottonwood Creek indicates that the creek is fed by ground water that has circulated through the limestone sedimentary rocks, similar to the ground water that is present in spring and tunnel discharge.

Stable hydrogen and oxygen isotopes indicate that the ground water and surface water is meteoric in origin, derived from water falling as precipitation in the high Wasatch Mountains. Measured water temperatures and temperatures calculated from water composition indicate that the water has never been warm and therefore has not circulated to great depths. The concentrations of tritium indicate that the surface and ground water fell as precipitation since the 1950s when atmospheric nuclear testing introduced substantial tritium into the atmosphere.

The results of CFC measurements indicate ground water travel times through the saturated zone ranging from four to 23 years. Uncertainty in these travel times results from uncertainties in recharge temperature and pressure, and the amount of gas-water exchange that occurs prior to sample collection. The maximum uncertainty in travel time is estimated to be five years. The CFC analyses support the conclusion that water discharging from the K-U and other tunnels in the vicinity is recharged on the adjacent slopes and circulates in a shallow ground water flow system.

Finally, we outline the way that ground water might flow near the K-U Tunnel in the absence of the tunnel. Numerical simulations aid in visualizing the influence of geologic structure on ground water flow systems near the K-U Tunnel but in the absence of the tunnel. In the absence of the K-U Tunnel, water infiltrating on adjacent high ridges would most likely travel through the subsurface and discharge into Big Cottonwood Creek. The K-U Tunnel has intercepted ground water that would otherwise have appeared as springs and seeps along Big Cottonwood Creek and become a part of the base flow of the creek. Subsurface flow to adjacent watersheds along alternate flowpaths are prohibited by the combined effect of rugged surface topography and a complex distribution of igneous, sedimentary, and fault-related low-permeability structures.

The Judge's Decision

Placement of our conclusions in the legal context that initiated the study is valuable. Although technical data are sparse and methods are lacking for fully quantifying three-dimensional patterns of ground water flow associated with tunnels in complex geology and rugged mountainous terrain, the judge concluded that sufficient technical information was available to rule on the case. The decision rendered in the District Court of the Third Judicial District in and for Salt Lake County, State of Utah, was issued in Memorandum for Case No. 920904952PR: ". . . the evidence at trial clearly established that the water emanating from the K-U Tunnel recharges at an area near the Alta Stock, flows through the subsurface, and ultimately, in the absence of the K-U Tunnel, would have contributed to the Creek."

We do not suggest that the judge's decision ratifies the results of our technical study. Rather, we show that legal disputes must often be resolved with unambiguous legal decisions even though technical ambiguities may remain.

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