Millimeter- to Kilometer-Scale Variations in Vadose-Zone Bedrock Solutes: Implications for Estimating Recharge in Arid Settings

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Unsaturated-zone solute concentrations from vertical boreholes have been used in many arid-zone studies to estimate recharge rates under past and current climates. However, such sampling may not adequately represent lateral variability in solute distributions caused by either local features that focus infiltration or preferential flow along macropores. Kilometer-length excavations in a desert basin in southwestern Utah provided a unique opportunity to investigate the spatial distribution of vadose-zone solutes and factors controlling infiltration and recharge. Specific-conductance measurements of leachates from sandstone samples collected along 3,350 linear meters of excavations show great lateral and vertical heterogeneity. Specific conductance values of the leachates ranged from 28 to 13,800 microsiemens per centimeter. The most extensive zones of low solute accumulation were observed beneath exposed sandstone, coarse-grained soils, and a buried relict wash channel. Large solute accumulations generally were observed beneath thicker deposits of fine-grained soils. The distribution of soil moisture at the bedrock contact after a large precipitation event indicated that soil coarseness and focused runoff are important factors controlling the horizontal variability of solute distributions. At depths greater than 3 meters below the bedrock surface, solute accumulations were generally lower along near-vertical fractures than in the adjacent non-fractured sandstone matrix. This is consistent with the widely-held belief that in areas where infiltration penetrates the overlying soil cover, vadose-zone preferential flow is associated with sandstone fractures. The spatial variability of vadose-zone solute concentrations illustrates the difficulty in characterizing recharge in desert basins underlain by shallow bedrock using a limited number of vertical cores.

1. INTRODUCTION

Accumulations of unsaturated-zone solutes such as chloride have often been used in arid settings to evaluate rates of natural recharge [*Allison et al.*, 1994; *Phillips*, 1994;

Scanlon et al., 2002]. Vertical profiles often show little solute accumulation beneath areas of focused runoff and infiltration, such as along active washes and playas. In contrast, high solute accumulations typically occur in areas of diffuse recharge where infiltration of precipitation is not enhanced by runoff [*Izbicki et al.*, 2002, Stonestrom et al., this issue]. The correlation between low unsaturated-zone solute concentrations and active recharge has been supported by soil-moisture measurements and concentrations of other environmental tracers, including ^{3}H, ^{36}Cl, ^{2}H, and ^{18}O [*Allison and Hughes*, 1978; *Allison*, 1988; *Allison et al.*, 1994; *Phillips et al.*, 1988; *Cook et al.*, 1989, 1992, 1994; *Scanlon*, 1991; *Edmunds et al.*, 2002]. Boreholes in areas with high solute accumulation generally have a shallow chloride bulge within the first 10 to 20 meters (m) below land surface [*Allison et al.*, 1985; *Sharma and Hughes*, 1985; *Cook et al.*, 1989; *Prudic*, 1994; *Izbicki et al.*, 2002]. These chloride bulges are attributed either to (1) preferential flow where rapid infiltration along higher permeability macropores (features with larger pore-throat diameters) can bypass evaporative concentration in the root zone, (2) diffusion of chloride to the water table, or (3) a transition to drier climatic conditions causing decreased recharge [*Allison et al.*, 1994; *Walvoord and Scanlon* (this issue)].

In many arid-zone studies, one-dimensional interstitial (matrix) flow has often been assumed and recharge rate estimates were based on environmental tracer concentrations from one or more vertical boreholes. Because of the limited number of boreholes that are typically drilled, localized sites of focused infiltration may be overlooked, such as areas of slightly coarser sediments, small depressions, exposed or shallowly buried bedrock, or along secondary washes and rivulets receiving runoff from exposed bedrock [*Allison*, 1988; *Scanlon et al.*, 2002]. Borehole sites spanning the complete range of topographic, morphologic, and geologic conditions may result in a reasonable estimate of basin-scale recharge rates. However, such extensive drilling is generally not feasible. Furthermore, preferential flow along macropores (fractures, desiccation cracks, coarse sediment lenses, root tubes, burrows, solution cavities) may not be accurately represented by vertical borehole sampling, which can completely miss or be overly biased by such features. Preferential flow along macropores has been reported in a variety of vadose-zone settings including unconsolidated sand deposits [*Cook et al.*, 1989; *Komor and Emerson*, 1994], loess deposits [*O'Brien et al.*, 1996], fissured basin-fill sediments [*Scanlon*, 1992; *Scanlon et al.*, 1997], calcrete dissolution and sinkholes [*Stone*, 1985; *Wood and Sanford*, 1995, *Wood et al.*, 1997], fractured chalk [*Nativ and Nissim*, 1992; *Nativ et al.*, 1995; *Dahan et al.*, 2000], fractured basalt [*Faybishenko et al.*, 2000] and fractured tuff [*Fabryka-Martin et al.*, 1993; *Rasmussen and Evans*, 1993; *Wolfsberg et al.*, 2000; *Flint et al.*, 2001].

In this study, we use detailed solute distributions along kilometer-scale excavations for evaluating arid-zone infiltration and recharge processes. This report describes the most-detailed investigation, to date, of lateral variability in shallow vadose-zone solute accumulations. The objectives of this investigation were to: (1) determine the extent of shallow unsaturated-zone bedrock solute heterogeneity within a small drainage basin and its implications regarding estimates of recharge based only on vertical borehole data; (2) examine potential factors controlling variations in infiltration; and (3) evaluate the timing and spatial extent of natural recharge events in Sand Hollow basin. A more-complete documentation of vadose-zone data collected from both excavations and boreholes in Sand Hollow basin can be found in *Heilweil* [2003]. The report includes hydraulic and physical properties data for unconsolidated soils and bedrock, as well as pore-water chemical concentrations (Cl, Br, ^{2}H, ^{3}H, ^{18}O) from vertical and high-angle boreholes.

1.1. Site Description

Sand Hollow is a 50-square kilometer (km^{2}) basin located southwest of Hurricane, Utah (fig. 1). The basin is underlain by the Navajo Sandstone, which is at least 300 m thick and is part of the Hurricane Bench Syncline [*Hurlow*, 1998]. The Navajo Sandstone was deposited during the Jurassic Period as an eolian deposit and is prominently cross-bedded. The sandstone is well sorted and consists of fine-to-medium arenite held together with variable amounts of calcite cement. The top 0.5 m of sandstone is weathered and poorly cemented. Within Sand Hollow basin, the sandstone is generally either exposed or covered by a thin (generally less than 3 m) layer of unconsolidated soils including loam and fine sand (fig. 2). A narrow exposure of a thin fractured basalt flow (about 3 m thick) occurs along the edge of the East Ridge. The unconsolidated material along the East Ridge slope beneath the exposed basalt flow consists of basalt boulder colluvium.

Sand Hollow basin is in the upper Mojave Desert ecosystem and is considered arid; average annual precipitation is about 0.20 m. As in many other basins in the region, the Navajo Sandstone aquifer beneath Sand Hollow is unconfined and receives most of its recharge from the infiltration of precipitation [*Heilweil et al.,* 2000]. Depth to the water table in the lower part of the basin varies from about 20 to 65 m. Sand Hollow is essentially a closed basin under present climatic conditions. An ephemeral wash flows during

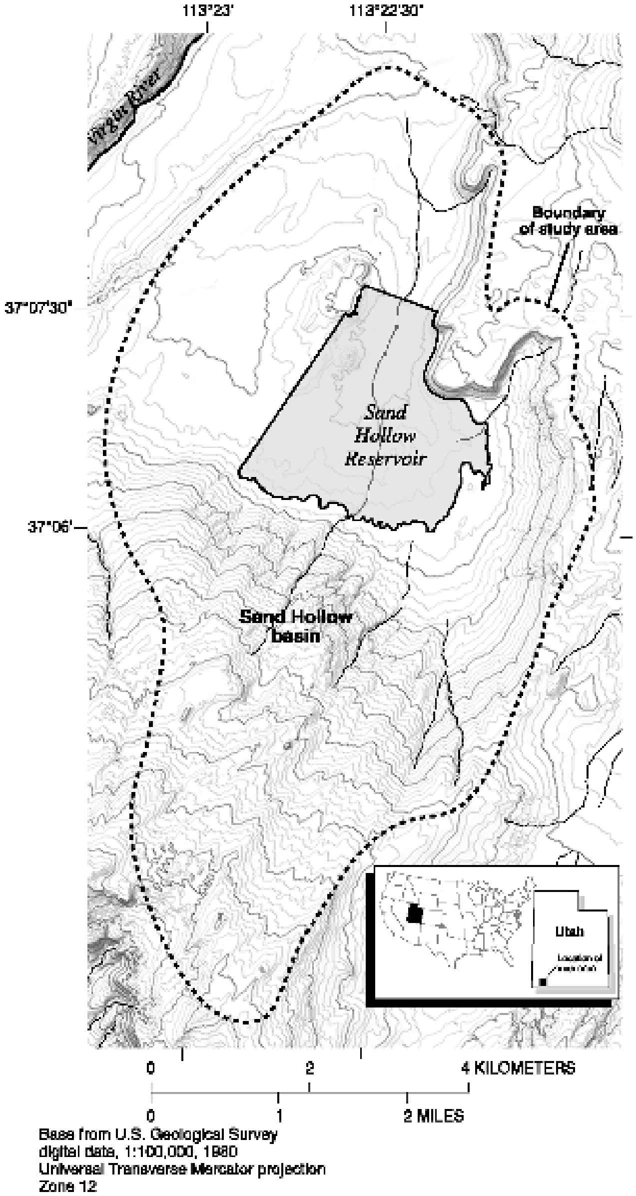

Figure 1. Location of Sand Hollow basin, Washington County, Utah.

the largest precipitation events. However, at the lower end of the wash where the topographic slope decreases, surface water spreads out and infiltrates the permeable soils rather than leaving the basin [L. Jessup, Washington County Water Conservancy District, personal communication, 2001].

A surface-water reservoir was recently constructed (2002) in Sand Hollow basin for recharging the underlying ground-water aquifer with Virgin River water during periods of high flow. The water is impounded by two long dams at perpendicular orientations ~~and~~ separated by an exposed sandstone outcrop. Beneath the footprints of the two dams, surficial soils and weathered sandstone were removed along a 60-m wide swath and 1-m-wide trenches were cut into the Navajo Sandstone (fig. 2). These trenches were subsequently sealed with concrete as an impermeable barrier to prevent underflow. Trench 1, about 1,000 m long and as deep as 6 m, spanned the lower part of the basin from the flank of the West Ridge (fig. 3a) to the flank of the East Ridge and provided a cross section of the shallow unsaturated zone perpendicular to the topographic gradient of the basin, along a strike of 115º. Trench 2, about 1,900 m long and as deep as 3 m, was oriented along a strike of 35º. This is parallel to the surface-water divide and provided a cross section of the shallow unsaturated zone from the southern to the northern part of the basin. In addition to the two trenches, the 450-m-long East Ridge road cut, between 3 and 7 m deep, is located on the shoulder of the East Ridge and provides access to the unsaturated zone beneath both basalt boulder colluvium and exposed basalt-flow deposits. As much as 3 m of soils and weathered sandstone were removed prior to the excavation of the trenches and road cut. Measured specific-conductance values of leachates mixed from the soils generally were low. Pedogenic carbonate (calcrete) layers and coatings, as much as 1 m thick, were observed at several locations in the soil profile but are most abundant at the contact between soil/weathered sandstone and underlying non-weathered sandstone (fig. 3b). Solute concentration from plant transpiration and evaporation are the primary mechanisms for carbonate supersaturation and the precipitation of calcrete [*Cerling*, 1984; *Quade et al.*, 1989]. Roots are commonly observed within calcrete deposits both in Sand Hollow (fig. 3d) and elsewhere in the Mojave Desert [*Schlesinger*, 1985].

Both bedding-plane and near-vertical fractures were observed in the sandstone trenches and road cut (fig. 3). The dip of these near-vertical fractures in Sand Hollow basin varies between 55º and 85º [RBG Engineering, Inc., personal communication, 1999]. The predominant regional strike of these near-vertical fractures is 40º [EWP Engineering, Inc., personal communication, 1999]. The apparent spacing between near-vertical fractures in Trench 1 was 5 m. When this apparent fracture spacing is corrected for the 75º angle between Trench 1 and the predominant fracture orientation, the actual fracture spacing is 4.8 m. The spacing of near-vertical fractures along Trench 2 was larger, consistent with the small angle (5º) between this trench and the predominant fracture orientation. Apertures of the near-vertical fractures were either open or filled with precipitates at shallow depths (fig. 3). Apertures generally decreased

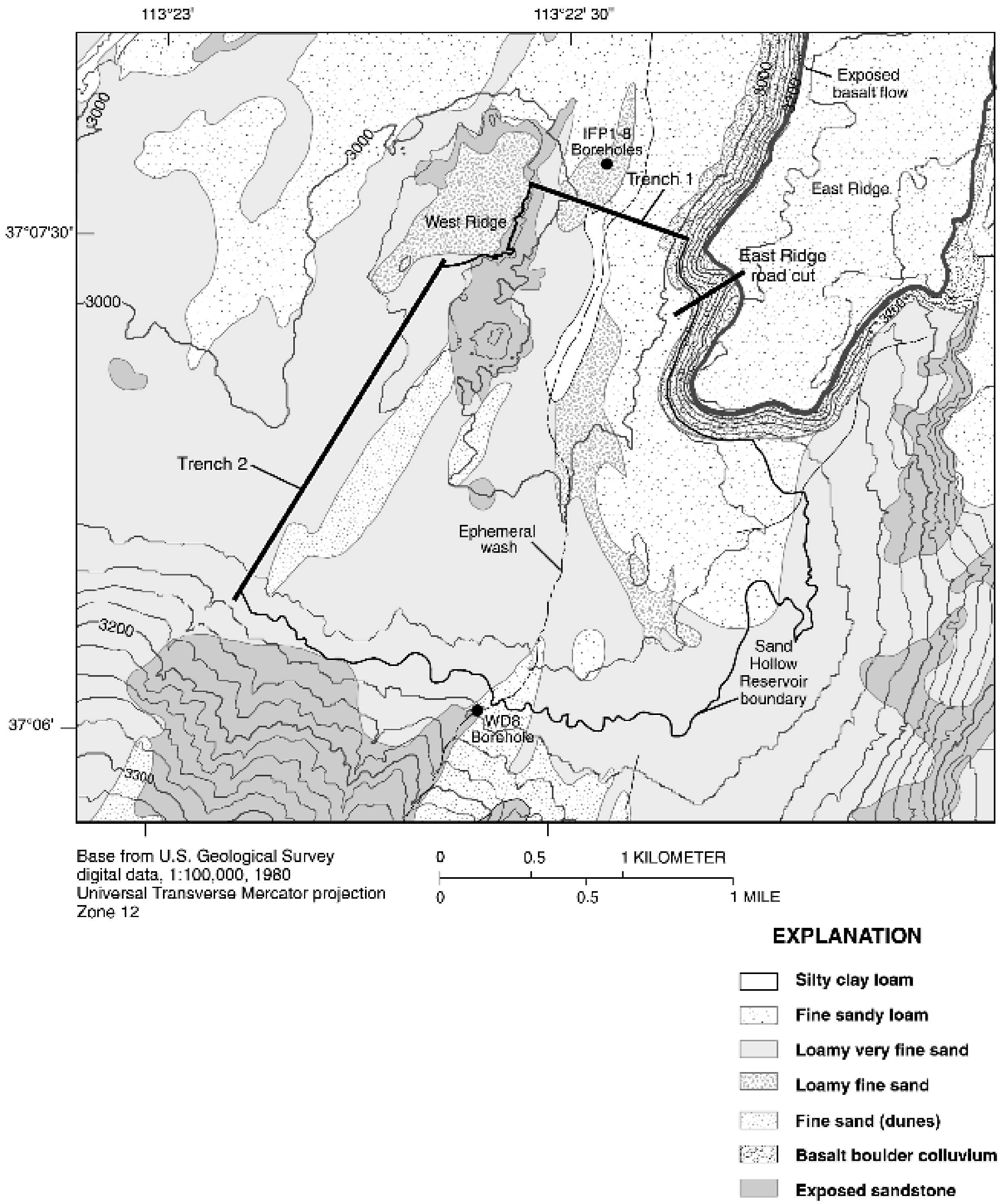

Figure 2. Soils map with location of trenches, road cut, and boreholes in Sand Hollow basin, Utah.

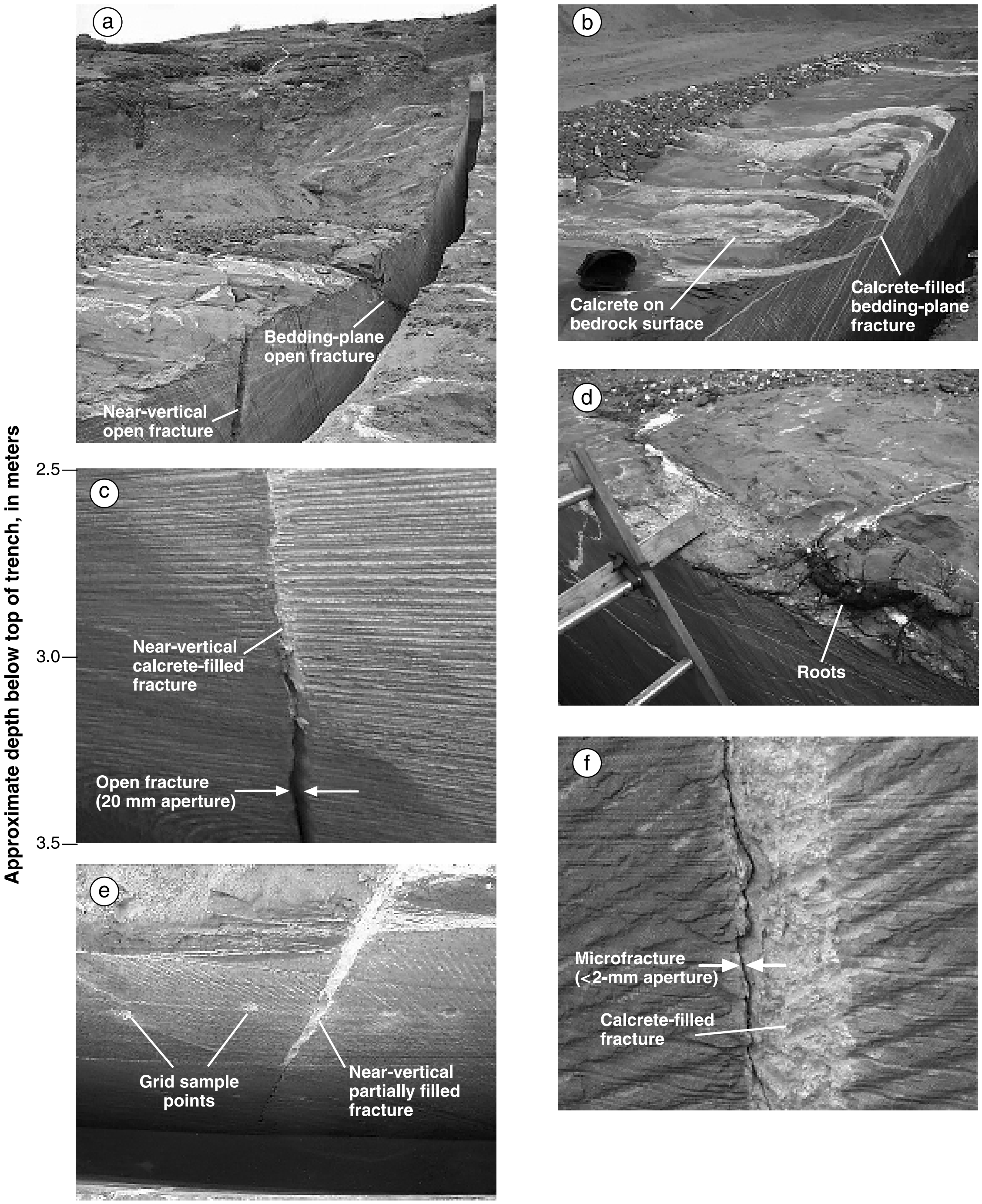

Figure 3. Photographs of the sandstone trenches in Sand Hollow basin, Utah. (A) West end of Trench 1 showing bedrock outcrop and fractures; (B) Calcrete on bedrock surface and in bedding-plane fractures in Trench 2; (C) Transition from calcrete-filled to open fracture in Trench 1; (D) Roots and calcrete on the upper bedrock surface along Trench 1; (E) Partially filled fracture at 313 m from the west end of Trench 1; (F) Microfracture with a 2-mm aperture in the shallow part of a calcrete-filled fracture.

with depth. The apertures of the shallow precipitate-filled fractures were as large as 70 ~~mm~~. The apertures of open fractures were generally less than 20 ~~millimeters (~~mm~~)~~. *Weisbrod et al.* [2000] demonstrated that transpiration in the unsaturated zone caused the accumulation of salts and precipitates on shallow fracture surfaces. The predominant precipitate mineral is assumed to be pedogenic carbonate (calcrete), although x-ray diffraction also indicates the presence of kaolinite and sepiolite within the fracture filling. The calcrete fill in fractures is generally thickest in the uppermost 3 m of the fracture. Beneath about 3 m (the maximum root depth), this calcrete fill rapidly decreases, resulting in an open or sand-filled fracture. Vertically continuous microfractures were observed in many of the calcrete fracture fillings. These small fractures generally have apertures of less than 2 mm (fig. 3) and were often observed to contain small roots. Roots were not observed in nonweathered or nonfractured sandstone, nor deeper than about 3 m in fractures.

2. METHODS

Sandstone samples for solute analysis were collected from the excavations with either a rock-coring drill or rock hammer. A total of 780 sandstone samples were collected along 3,350 m of trench and road-cut walls shortly after excavation. Samples were collected along horizontal transects along the bottom of the two trenches and the road cut to examine regional-scale variations in solute concentrations. The regional transect along Trench 1 had a maximum 8-m spacing between sample points; 15-m and 30-m sample intervals were used along the bottom of the East Ridge road cut and Trench 2, respectively. To evaluate the effects of fracturing on infiltration, 42 sets of samples were also collected at a depth of 5 m in Trench 1 on and adjacent to near-vertical fractures. Samples were collected along 15 vertical profiles in Trench 1 to look at vertical variations in solute concentration, both along and away from fractures. Samples were collected on two-dimensional grid patterns in the vicinity of three near-vertical fractures in Trench 1 to examine solute patterns associated with bedrock fractures in more detail. The first grid included a set of open fractures located 583 to 585 m from the west end of the trench. The other two grids, at 313 and 490 m from the west end of Trench 1, were associated with single fractures having thick calcrete fill in the upper 3 m. Detailed millimeter-scale samples were collected along horizontal transects in the vicinity of two microfractures (313 m and 490 m from the west end of Trench 1) in shallow calcrete fill of near-vertical fractures to evaluate their role in preferential flow.

Leachates were made by mixing 50 grams (g) of deionized water with 25 g of dry sandstone, resulting in a 2:1 water-to-rock ratio. The sandstone was crushed, resulting in samples consisting of fine- to medium-grained sand. The samples were shaken periodically throughout a 24-hour period, after which specific conductance was measured with a specific-conductance meter. To evaluate the use of specific conductance as a proxy for chloride, a subset of 76 leachate samples were analyzed for chloride concentration with ion chromatography done by the Bureau of Reclamation Lower Colorado Region Soils Laboratory. The chloride concentration and the specific-conductance value of these samples were well correlated (R^2 of 0.99), such that

$$Cl = 0.2696xSC \qquad (1)$$

where *Cl* is the chloride concentration, in mg/L and *SC* is the leachate specific conductance value, in microsiemens per centimeter at 25º C (µS/cm). Specific-conductance measurements, therefore, are considered a good surrogate for chloride concentrations in the vadose zone of the Navajo Sandstone within the Sand Hollow basin.

Two types of replicate samples were prepared to evaluate the precision of specific-conductance values determined from leachates. First, replicate samples were collected at the same sample location. The average difference between 10 pairs of replicate leachate samples collected at the same location was 20 percent. The second type of replicate involved preparing two separate leachate mixtures from the same rock sample. This was done for four pairs of replicate samples, with an average difference of 7 percent.

In order to evaluate the role of surficial soils on the variability of solute distributions in the underlying sandstone, soil samples were collected for analysis of gravimetric moisture content after a precipitation event. Soil samples were also collected to investigate variations in physical and hydraulic properties. Samples for moisture content were collected from transects parallel to the two trenches at a 30-m offset in undisturbed soils. Sampling was done at multiple depths down to the bedrock contact in order to determine the depth of moisture penetration. About 200 samples were collected for moisture analysis at 98 locations parallel to Trench 1; 44 samples were collected at 16 locations parallel to Trench 2. Soil samples were collected at widely spaced intervals along Trench 1 and Trench 2 during March 13 to 17, 2000 (about 4 days after the precipitation period); a more detailed sampling along Trench 1 was completed on March 26th (about 17 days after the precipitation period). Duplicate samples collected from 7 sites at the bedrock contact along Trench 1 during the two sampling periods showed less than 1 percent difference in moisture content. The samples were collected with a 7.5 cm diameter hand auger and immediately sealed in airtight bags.

Gravimetric moisture content was analyzed within 2 weeks of sample collection. The method consisted of measuring wet weights of the soils, drying in an oven for 24 hours at 105 degrees Celsius (º C), and reweighing.

Soil samples for analysis of physical and hydraulic properties were collected with both a percussion-coring bit on a CME 55 drill rig, as well as with a hand-driven piston-coring device. They were collected in 5-centimeter (cm) diameter brass sleeves, which were used as the sample containers during hydraulic testing to minimize soil disturbance. Physical and hydraulic properties of the soils were measured at the U.S. Geological Survey Unsaturated Zone Flow Laboratory in Menlo Park, California. The porosity of soil-core samples was estimated by dividing the difference between particle and bulk densities by the particle density. Measurements of saturated hydraulic conductivity were performed on soil samples with the falling head method [*Reynolds et al.*, 2002]. In order to determine the retention characteristics of soils during infiltration events, moisture-characteristic curves were determined for three types of unconsolidated soil-core samples: a loam, a fine sandy loam, and a dune deposit fine sand. The controlled liquid volume method [*Winfield and Nimmo*, 2002] was used for making these measurements. The technique uses a tensiometer to measure matric potentials at varying degrees of water content.

Sandstone samples for laboratory analysis of physical and hydraulic properties were collected with a continuous HQ-size triple-tube core barrel system. Air was used as the drilling fluid to avoid potential calcite dissolution. Calcrete samples were collected by hand along the exposed sandstone of Trench 1. Both sandstone and calcrete samples were subcored to a 3-cm diameter. Physical and hydraulic properties of the sandstone samples were determined by the U.S. Geological Survey Hydrologic Research Laboratory in Sacramento, California. The porosity of sandstone core samples was determined by dividing the difference between saturated and oven-dry mass by the sample volume. Measurements of saturated hydraulic conductivity were taken on sandstone core samples with a flexible wall permeameter [*American Society for Testing and Materials*, 1998].

3. RESULTS

3.1. Observed Distribution of Solutes in Bedrock

Leachates from samples collected on a regional horizontal transect along the bottom of Trench 1 showed a large variation in specific conductance, with values ranging from 31 to 7,920 µS/cm (fig. 4). Although this horizontal transect shows much random scatter, seven clearly defined areas have specific-conductance values of less than 2,000 µS/cm. These low-solute zones are separated by areas with high or variable specific-conductance values. The widest zone of low solutes is along or down slope of the exposed bedrock of the West Ridge (0 to 175 m from the west end). In contrast, the other side of the trench along the slope of the East Ridge (900 to 1,000 m from the west end) is covered with basalt boulder colluvium (fig. 2) and horizontal variations were much larger, ranging from 325 to 6,600 µS/cm. Another wide zone of low specific-conductance values (48 to 1,510 µS/cm) occurs between 690 and 810 m from the west end of Trench 1, an area that appears to be a relict wash on the basis of the topography of the bedrock surface.

Because of the similar topography and soil cover (basalt boulder colluvium) at the east end of Trench 1 and along the lower end of the East Ridge road cut, the specific-conductance profile of the road cut can be considered an approximate extension of the Trench 1 transect. The specific-conductance values of samples collected in bedrock along the base of the East Ridge road cut ranged from 40 to 1,120 µS/cm (fig. 5a). These values were generally lower than those at the east end of Trench 1, particularly beneath the fractured basalt flow outcrop near the top of the East Ridge (fig. 2).

The regional horizontal transect along the bottom of Trench 2 had specific-conductance values that were generally lower than those along the bottom of Trench 1. The specific-conductance values along Trench 2 ranged from 30 to 1,670 µS/cm but generally were less than 500 µS/cm (fig. 5b). Solute concentrations were lowest along the north end of the trench where it intersects exposed sandstone of the West Ridge. This is consistent with low specific-conductance values measured along the west end of Trench 1, which intersects the same ridge (fig. 2).

A second-order characteristic of the horizontal bedrock solute distribution was the lower specific-conductance values generally measured on near-vertical fractures, compared with adjacent nonfractured sandstone. A typical symmetric pattern of solute distribution associated with a near-vertical fracture at a depth of 5 m below the bedrock surface is shown in the inset of figure 4. This pattern was confirmed by the 42 sets of samples collected along the bottom of Trench 1. Three samples were collected within 3 m of each fracture: west of the fracture, on the fracture, and east of the fracture. The percent difference between fracture and matrix specific conductance was calculated with the following formula:

$$n = \left[\frac{S_m - S_f}{S_m} \right] x100 \qquad (2)$$

where n is the percent difference, S_m is the matrix specific conductance value, S_f and is the fracture specific conductance value. Of the 42 sample groups, 14 had differences in

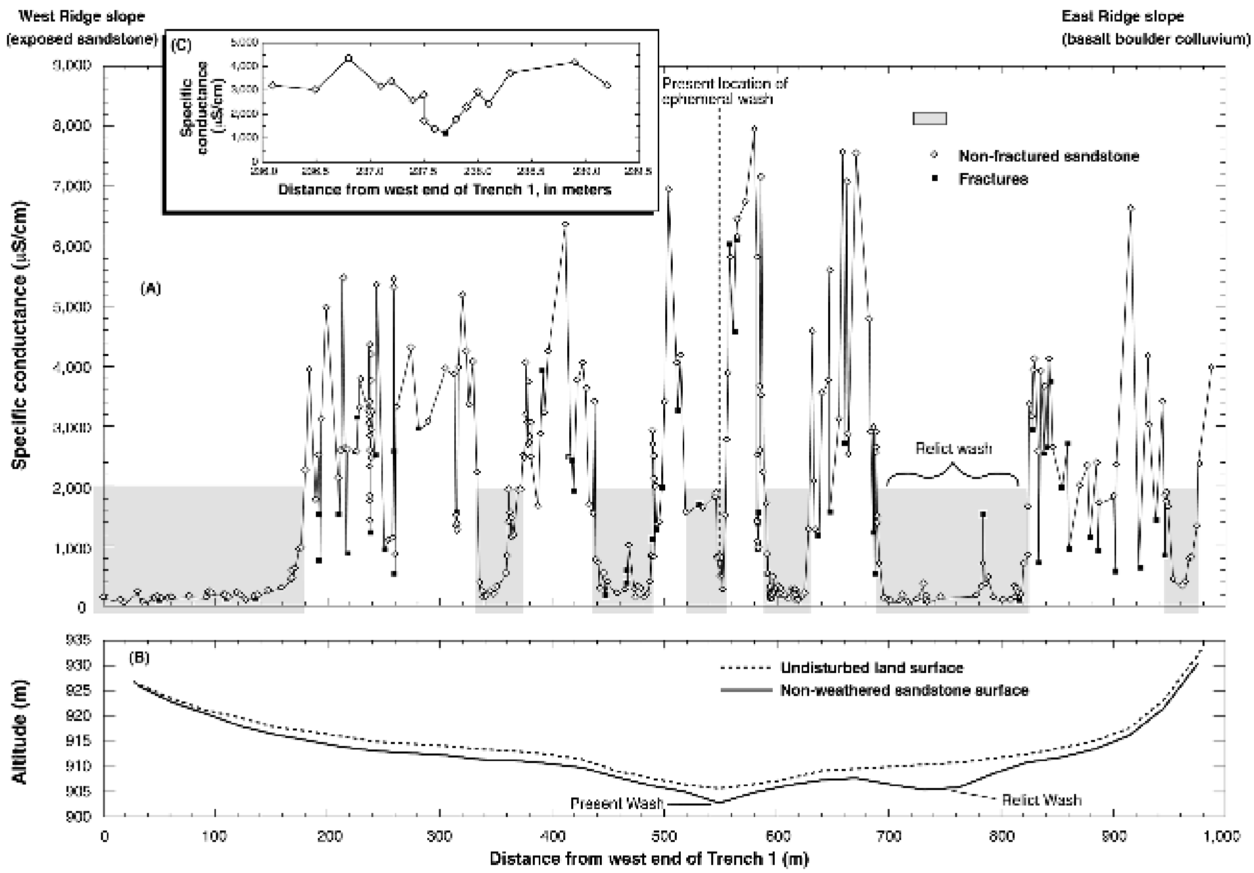

Figure 4. Horizontal transect along Trench 1 in Sand Hollow basin, Utah, showing: (A) Specific-conductance values of leachates from sandstone samples at a depth of 5 m; (B) Altitude of land surface and underlying non-weathered sandstone. Inset (C) shows specific-conductance values of leachates across a near-vertical fracture located about 238 m from the west end of Trench 1.

specific-conductance values of less than 20 percent, which is the approximate measurement precision based on analyses of replicate samples. Of the remaining 28 sample groups with statistically significant differences, 24 (86 percent) had lower specific-conductance values on fractures than in the surrounding nonfractured sandstone on both sides, 2 (7 percent) had higher specific-conductance values on fractures than in the adjacent sandstone, and 2 (7 percent) were located in regional transition zones from low to high specific-conductance values, masking any variations caused by the fractures.

Leachates from vertical profiles collected in Trench 1, both along fractures and in nonfractured sandstone, had specific-conductance values ranging from 28 to 13,800 µS/cm. In general, the highest measured values occurred in the upper 3 m of calcrete-filled fractures (fig. 6a). Lower specific-conductance values were measured in sandstone near filled fractures (fig. 6b) and along nonfractured sandstone (fig. 6c). This indicates that roots in some fractures may extract most of the infiltrating moisture, resulting in mineral precipitation and higher solute accumulation than in nonfractured sandstone, where roots cannot penetrate. The lowest specific-conductance values were measured on open-fracture profiles, where infiltration is able to bypass the root zone more quickly (fig. 6d). Specific-conductance values along all 15 vertical profiles decreased to less than 4,000 µS/cm around a depth of 5 m, consistent with the chloride-bulge pattern observed in vertical boreholes at Sand Hollow and in other arid settings.

Two-dimensional grid patterns along high-solute regions of Trench 1 showed interesting patterns associated with high-angle fractures. The solute pattern in the vicinity of the open fracture set at 583-585 m from the west end of Trench 1 shows a 2- to 3-m-wide zone of low specific-conductance values (less than 2,000 µS/cm) centered on the fractures

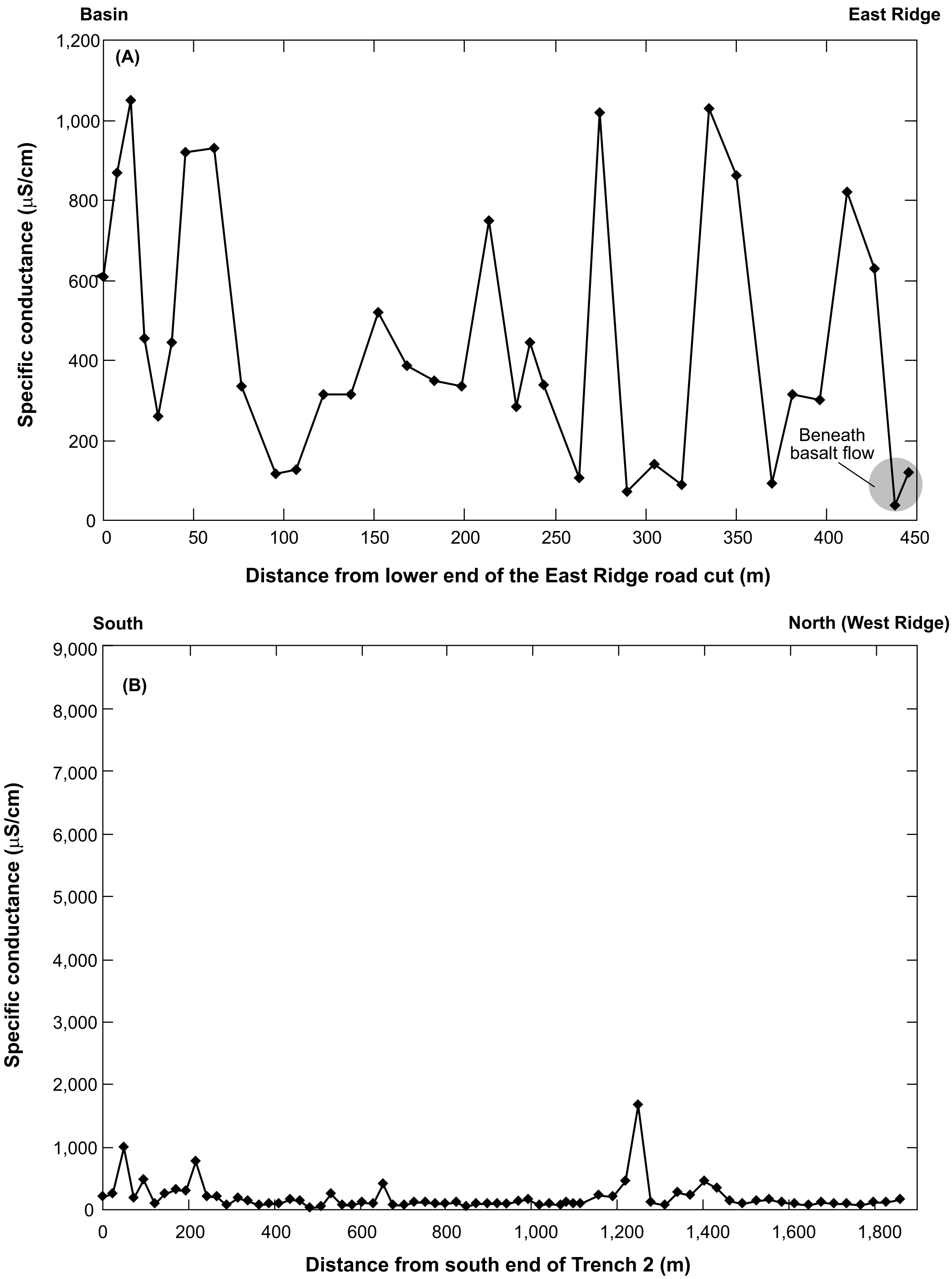

Figure 5. Specific-conductance values of leachates from sandstone samples along the bottom of (A) the East Ridge road cut; and (B) Trench 2, in Sand Hollow basin, Utah.

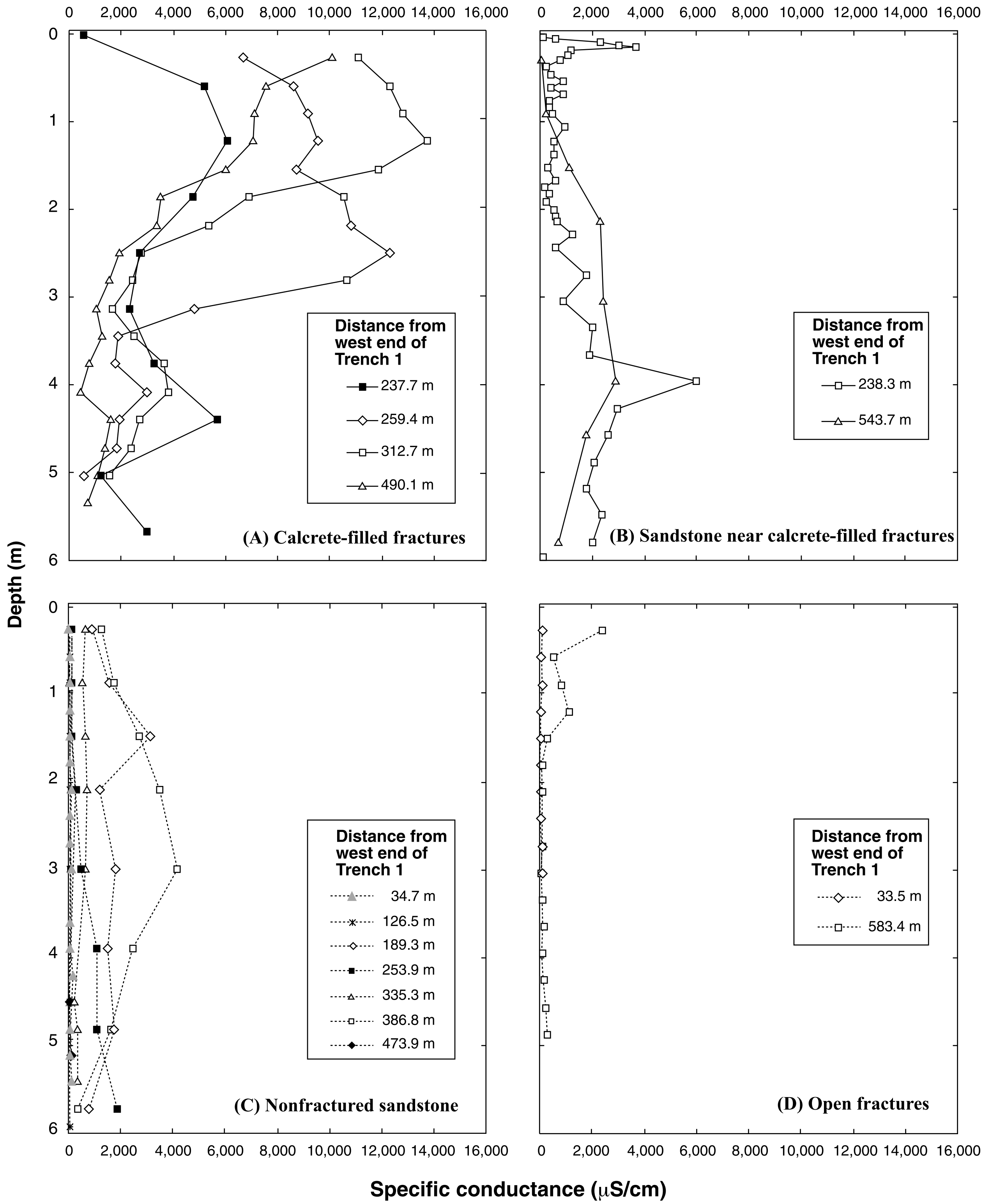

Figure 6. Specific-conductance values of leachates from sandstone samples on vertical profiles along Trench 1, Sand Hollow basin, Utah: (A) Calcrete-filled fractures; (B) Sandstone near calcrete-filled fractures; (C) Nonfractured sandstone; and (D) Open fractures. See figure 4 for location of vertical profiles.

between depths of 0.5 to 5 m below the bedrock surface (fig. 7). The solute patterns in the vicinity of the two calcrete-filled fractures at 313 m (not shown) and 490 m (fig. 8) had higher specific-conductance values on the fracture than in the nearby nonfractured sandstone at depths less than 2.4 m. These solute patterns reverse with depth, with lower specific-conductance values on fractures than those in the surrounding matrix below 2.4 m. Even though specific-conductance values are lower in the deeper part of these calcrete-filled fractures than in the adjacent nonfractured sandstone, the widths of these low-solute zones are much narrower than that of the open fracture set at 583-585 m.

The specific-conductance values of detailed millimeter-scale samples collected along horizontal transects in the vicinity of two microfractures in shallow calcrete fill-fractures showed contrasting patterns. Samples collected at a

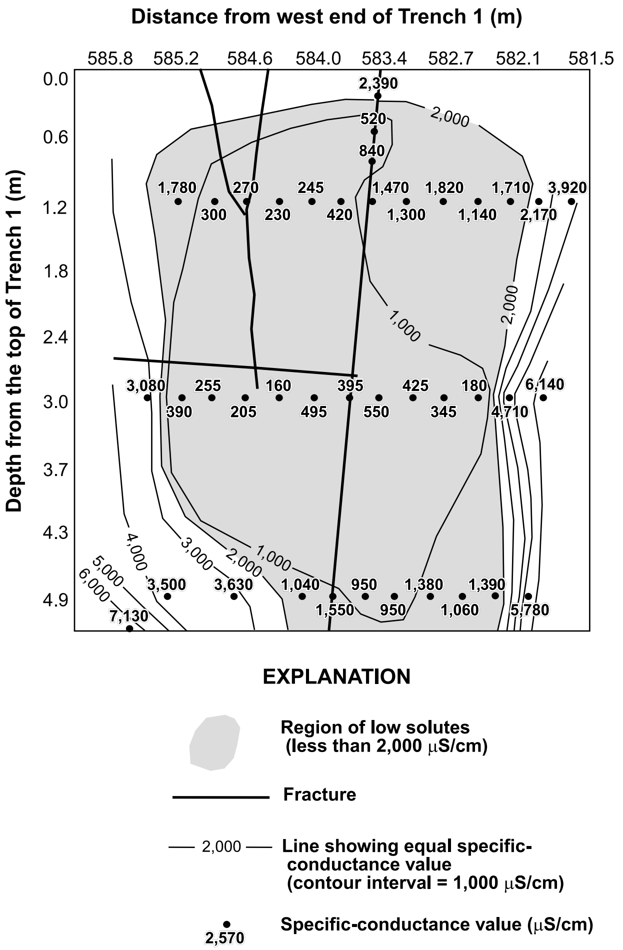

Figure 7. Specific-conductance values of leachates from sandstone samples in the vicinity of a near-vertical fracture set located between 583 and 585 m from the west end of Trench 1, Sand Hollow basin, Utah.

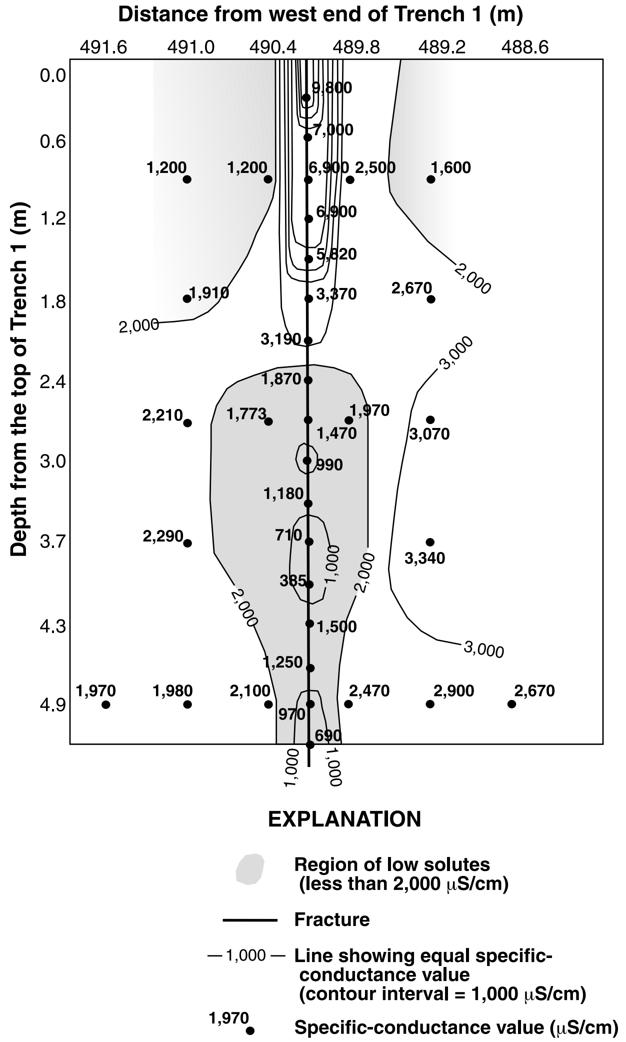

Figure 8. Specific-conductance values of leachates from sandstone samples in the vicinity of a vertical fracture located 490 m from the west end of Trench 1, Sand Hollow basin, Utah.

depth of 0.8 m below the bedrock surface in a fracture located 490 m from the west end of Trench 1 show lower solute concentrations on the microfracture than elsewhere in the calcrete fill (fig. 9a). Conversely, samples collected at a depth of 0.9 m below the bedrock surface in a fracture located 313 m from the west end of Trench 1 show higher specific-conductance values on the microfracture than elsewhere in the calcrete fill (fig. 9b).

3.2. Physical and Hydraulic Properties of Soils, Sandstone, And Calcrete

Laboratory tests of physical and hydraulic properties were conducted on three different soil types: a loam (46

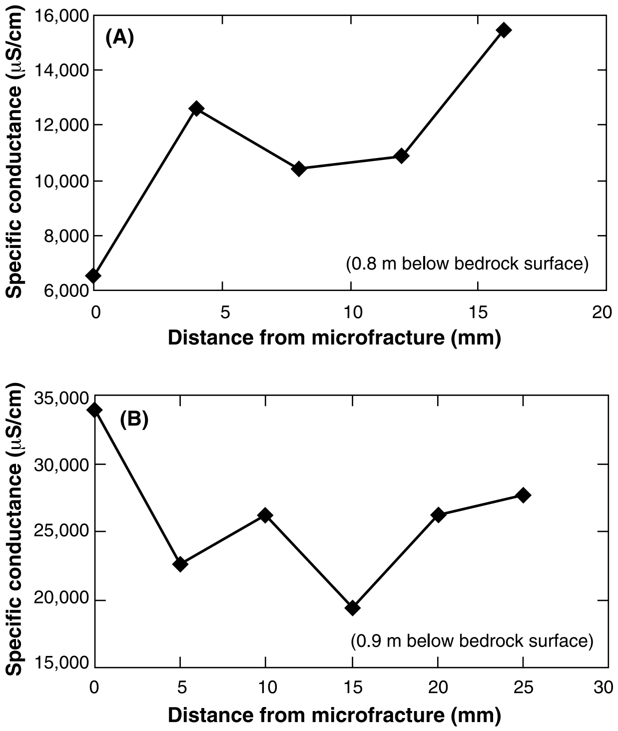

Figure 9. Specific-conductance values of leachates from samples along horizontal transects across microfractures in the shallow part of calcrete-filled fractures at: 490 m (A); and 313 m (B) from the west end of Trench 1, Sand Hollow basin, Utah.

percent sand, 44 percent silt, 10 percent clay) from the IFP6 borehole site, a fine sandy loam (55 percent sand, 37 percent silt, 8 percent clay) from the IFP5 borehole site, and a fine sand (98.7 percent sand, 0.7 percent silt, 0.6 percent clay) from a dune deposit at the WD8 borehole site (fig. 2). The loam had a porosity of 0.40 and a saturated hydraulic conductivity of 6.0 meters per day (m/d); the fine sandy loam had a porosity of 0.36 and a saturated hydraulic conductivity of 0.03 m/d; the fine sand had a porosity of 0.30 and a saturated hydraulic conductivity of 0.10 m/d (table 1). Moisture characteristic curves show a large range in moisture retention values at –330-cm of water (-1/3 bar) matric potential, a commonly used field capacity definition for medium-textured soils [*Cassel and Nielson, 1986*]. Volumetric water content at –330 cm of water was 22 percent for the silty loam, 17 percent for the sandy loam, and 9 percent for the sand (fig. 10).

Laboratory testing of shallow weathered sandstone samples collected from boreholes near Trench 1 show porosity values ranging from 0.20 to 0.26, with an arithmetic mean of 0.22 (table 1). An arithmetic mean is used to describe multiple porosity values because it is assumed that they are normally distributed. Porosity values of deeper sandstone samples had a similar range and an arithmetic mean of 0.24. Saturated hydraulic-conductivity values of the weathered and non-weathered sandstone samples were similar and ranged from 0.01 to 0.42 m/d, with geometric means of 0.17 and 0.10 m/d, respectively. A geometric mean is used to describe multiple hydraulic-conductivity values because it is assumed that they are log-normally distributed.

Laboratory testing of calcrete samples collected along Trench 1 shows a much wider range of saturated hydraulic-conductivity values than the sandstone samples, ranging from 0.0005 m/d to 1.1 m/d, with a geometric mean of 0.02 m/d (table 1). The porosity of the calcrete samples also had a wider range of from 0.11 to 0.32, with an arithmetic mean of 0.21. The lower-porosity samples have lower saturated hydraulic-conductivity values; the higher-porosity samples have higher hydraulic-conductivity values.

3.3. Observed Soil Moisture After a Large Precipitation Event

Gravimetric moisture content of the samples collected in undisturbed soils adjacent to the trenches ranged from 2 to 11 percent by weight. The soil-moisture survey showed that infiltration from the February/March 2002 precipitation event was able to reach bedrock where the surficial soils were either coarser grained or thinner. Lower soil-moisture content (2 to 4 percent by weight) at the bedrock contact was observed beneath thicker and finer-grained overlying soils; higher moisture content (5 to 11 percent by weight) was observed beneath thinner and coarser-grained overlying soils. The moisture penetrated to depths of about 1.5 m in the areas of fine sand along Trench 2 and the western part of Trench 1, whereas moisture only penetrated to depths of about 0.6 m in the finer-grained loams elsewhere along Trench 1.

4. DISCUSSION

Low specific-conductance values of bedrock leachate samples may either indicate (1) impermeable conditions and no infiltration, such that all precipitation runs off or is evaporated and solutes never enter the vadose zone; or (2) relatively high infiltration rates and little evaporation or transpiration in the shallow root zone. The latter explanation is indicated by the analysis of the moisture content and pore water chemistry (Cl, ^{3}H, ^{2}H, ^{18}O) of vertical borehole samples collected from the unsaturated zone of Sand Hollow basin. Boreholes with small accumulations of unsaturated-zone chloride generally have higher moisture contents, LOW RES

Table 1. Physical and hydraulic properties of soil, calcrete and sandstone samples from Sand Hollow basin, Utah.

Sample type	Site identification	Depth of sample below land surface, meters	Saturated hydraulic vonductivity, meters per day	Porosity
Silty loam	Soil at IFP6 borehole	1.4	6.00	0.40
Sandy loam	Soil at IFP6 borehole	0.9	7.23	0.42
Sandy loam	Soil at IFP5 borehole	0.9	0.03	0.36
Sandy loam	Soil at IFP5 borehole	1.8	0.08	0.30
Sand (dune deposit)	Soil at WD8 borehole	0.2	0.09	0.35
Low-porosity calcrete[a]	Sample 1a in Trench 1	1.0[b]	0.025	0.1
	Sample 1b in Trench 1	1.0[b]	0.0005	0.11
	Sample 1c in Trench 1	1.0[b]	0.0007	0.11
	Sample 1d in Trench 1	1.0[b]	0.027	0.17
High-porosity calcrete[c]	Sample 2a in Trench 1	1.0[b]	1.1	0.29
	Sample 2b in Trench 1	1.0[b]	1.1	0.28
	Sample 3a in Trench 1	1.0[b]	1.1	0.30
	Sample 3b in Trench 1	1.0[b]	0.48	0.32
	Sample 4a in Trench 1	1.0[b]	0.22	0.31
	Sample 4b in Trench 1	1.0[b]	0.54	0.26
Weathered sandstone[d]	IFP6 borehole	1.2	0.23	0.26
	IFP7 borehole	1.5	0.18	0.22
	IFP8 borehole	1.4	0.10	0.20
	IFP3 borehole	1.2	0.20	0.21
Sandstone[e]	IFP1 borehole	2.1	0.04	0.21
	IFP1 borehole	3.5	0.10	0.26
	IFP1 borehole	5.5	0.03	0.26
	IFP1 borehole	7.6	0.31	0.26
	IFP1 borehole	8.9	0.11	0.26
	IFP1 borehole	9.6	0.42	0.27
	IFP1 borehole	11.4	0.18	0.22
	IFP1 borehole	13	0.19	0.20
	IFP1 borehole	13.1	0.01	0.20
	IFP1 borehole	14.5	0.06	0.20
	IFP1 borehole	15.7	0.18	0.27
	IFP1 borehole	17.5	0.11	0.26
	IFP1 borehole	18.7	0.12	0.27

[a]Geometric mean hydraulic conductivity is 0.004 meters per day; arithmetic mean porosity is 0.13.
[b]Estimated depth below land surface.
[c]Geometric mean hydraulic conductivity is 0.64 meters per day; arithmetic mean porosity is 0.29.
[d]Geometric mean hydraulic conductivity is 0.17 meters per day; arithmetic mean porosity is 0.22.
[e]Geometric mean hydraulic conductivity is 0.10 meters per day; arithmetic mean porosity is 0.24.

deeper penetration of anthropogenic ^{3}H, and non-enriched ^{18}O [*Heilweil*, 2003]. Therefore, it is assumed that active recharge is occurring in areas of Sand Hollow basin where leachates from bedrock samples have small specific-conductance values. These recharge areas are where moisture regularly penetrates bedrock, either by diffuse infiltration of precipitation or as focused infiltration from runoff. Conversely, little or no active recharge likely occurs in areas of the basin where solutes are accumulating and leachate samples have high values of specific conductance. These low recharge areas are places where roots, either in soils or the shallow part of sandstone fractures, are able to effectively intercept most infiltration.

Areas without any soil cover, such as the exposed sandstone at the west end of Trench 1 and the north end of Trench 2, as well as the exposed basalt flow at the upper end of the East Ridge road cut, had the lowest bedrock solute concentrations. Plant density and root penetration along these outcrop locations was also very low, indicating that transpiration is minimal and net infiltration is higher in the

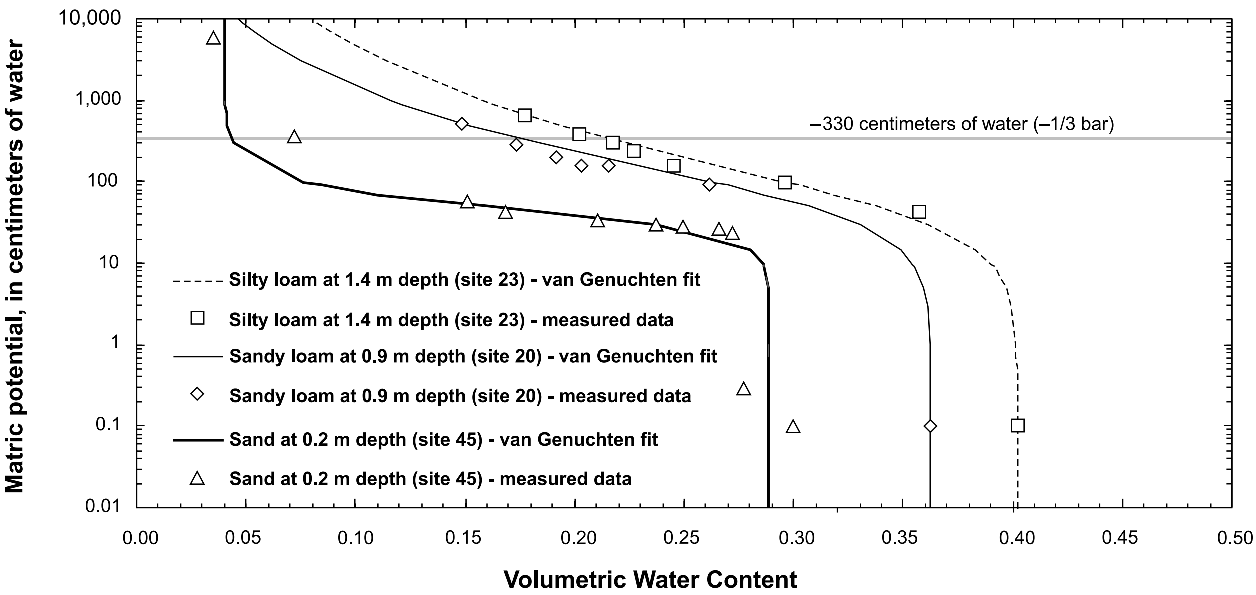

Figure 10. Measured and computed moisture characteristic curves for silty loam, loam, and sand samples, Sand Hollow basin, Utah.

absence of soils. It was observed that bedrock solute concentrations were generally higher beneath thicker deposits of fine-grained soils than in areas covered either by thinner deposits of fine-grained soils or coarser soils of any thickness. The variation in moisture retention determined by laboratory testing of soil core samples under typical gravity drainage pressures (fig. 10) shows that finer-textured soils are generally able to intercept and store a larger percent of infiltration than coarser-textured soils. Therefore, coarse-grained soils are more likely to allow infiltrating precipitation to reach the underlying sandstone than fine-grained soils. Exceptions to this may occur due to preferential flow in finer soils along observed desiccation cracks, root casts, and animal burrows. Such macropore structures were not observed in the coarser sand-dune deposits. ~~The~~ higher laboratory saturated hydraulic-conductivity value of the loam sample (6.0 m/d) compared to the sand-dune sample (0.1 m/d) ~~is evidence of the potential for macropore flow in the finer sediments. The~~ wide range in ~~laboratory saturated~~ hydraulic-conductivity values of the silty and sandy loam samples (0.03 to 7.23 m/d; table 1) ~~is~~ evidence of the potential for macropore flow in the finer sediments.

4.1. Relation Among Precipitation, Soil Moisture, and Solute Concentrations

The 70 mm rainfall event recorded at the Sand Hollow weather station from February 10 to March 9, 2000, was the largest monthly precipitation event of the year. Monthly precipitation events of this magnitude occur about once per year. The amount of soil moisture at the bedrock contact after this precipitation event is inversely correlated with solute concentration in sandstone along the bottom of the trenches (fig. 11). The relation would likely have been even clearer if soil samples had been collected directly over the trench, rather than at a 30-m offset. In fact, 22 of 23 15-m-wide low-solute intervals (having average specific-conductance values of less than 2,000 µS/cm) along Trench 1 were within 15 m of soils with 5 percent or higher gravimetric moisture content. A similar relation was observed along Trench 2, where 12 of 16 soil samples at the bedrock contact had gravimetric moisture contents of 5 percent or higher and leachate solute concentrations along the bottom of Trench 2 were always less than 2,000 µS/cm. The four drier soil samples, ranging between 1 and 2 percent gravimetric moisture content, were located between 150 and 300 m from the south end of Trench 2 where the overlying soils are coarse yet thicker (as thick as 3.0 m) than elsewhere along Trench 2. The low solute concentrations of underlying bedrock indicate that net infiltration occurs at this location but possibly only during monthly precipitation events larger than 70 mm.

Meteorological records from St. George indicate that larger precipitation events do occur at Sand Hollow. Monthly precipitation events exceeding 100 mm occurred 15 times during the 20th century, or about every 7 years [Precipitation data are available from the World Wide Web server for the *Desert Research Institute's Western* Region

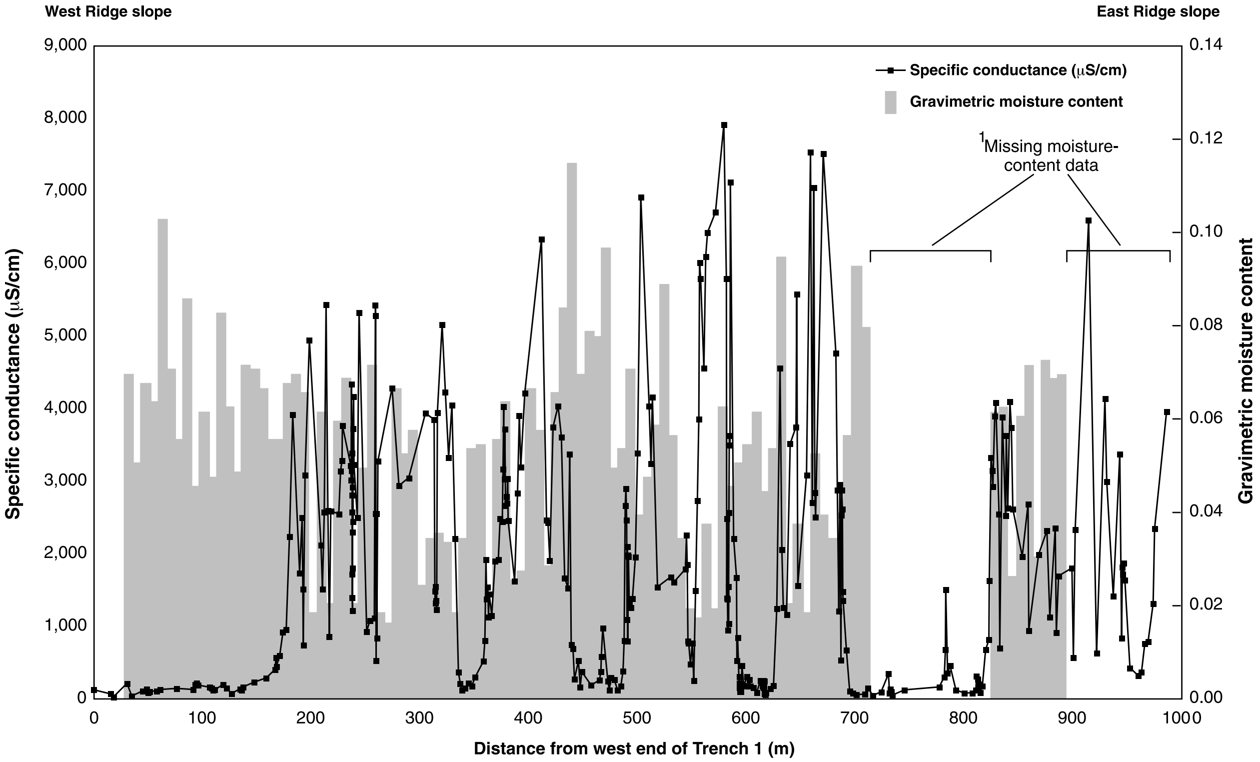

Figure 11. Relation between specific-conductance values along the bottom of Trench 1 and gravimetric moisture content in adjacent soils at the bedrock contact, Sand Hollow basin, Utah.

Climate Center at http://www.wrcc.sage.dri.edu]. It is hypothesized that infiltration occurs over larger areas of Sand Hollow basin during such events, especially in regions with thicker sand deposits. In addition to total precipitation, time of year and storm intensity likely affect the amount and location of bedrock infiltration. If the precipitation event comes during warmer months when evaporation and transpiration losses are higher, net infiltration may occur less frequently or in smaller areas of the basin that have the thinnest soil cover. It is expected that more-intense storms, such as the 60-mm 24-hour precipitation events that occurred on August 31, 1909, and January 3, 1997, would generate substantial runoff and little infiltration along sloping portions of exposed bedrock. This runoff would cause focused infiltration and recharge in areas of coarser soils immediately below outcrops. Such high-intensity storms also would cause substantial recharge beneath the coarser sand-dune deposits where rapid infiltration can occur, minimizing loss as runoff.

4.2. Focused Infiltration Along a Relict Wash

The wide zone of solutes at a depth of 5 m below the bedrock surface between 690 and 810 m from the west end of Trench 1, in combination with the thicker (3 m) fine-grained, semi-consolidated, poorly-sorted sand and calcrete deposits, is unique. This is inconsistent with the general relation of high bedrock solute concentrations beneath thick, fine-grained soils. The topography of the bedrock surface (fig. 4b) indicates that it was previously the site of a large wash. One possibility is that the low solute concentrations are a paleosignature of past recharge along this preexisting wash. Subsequent rapid deposition of fine-grained soil, possibly as mudlfow or landslide deposits from the nearby slope of the East Ridge, may have caused the wash to migrate westward from that site towards its present location, abruptly shutting off recharge and preserving the low solute concentrations. Similar vadose-zone relict solute signatures, formed under different recharge conditions in the past that were caused by the migration of an active stream channel, have been observed in the Armagosa Desert, Nevada [*Stonestrom et al.*, this issue]. The zone of low solutes beneath the relict wash is much wider than that underneath the present-day wash (fig. 4a). A possible explanation is that more infiltration had occurred beneath the relict wash, either over a longer period of time or during wetter climatic conditions. Pollen, plant macrofossil records, and clastic deposits from sediment cores beneath two lakes on the Kaibab Plateau of northern Arizona, about 100 km southeast of Sand Hollow Basin, indicate a much wetter period from about 11,000 to 8,000 years ago [*Weng et al.*, 1999].

4.3. Preferential Flow Associated With Fractures

Lower solute concentrations in and around fractures than in adjacent nonfractured matrix at depths greater than 3 meters below the bedrock surface (figs. 4, 6, 7, 8) indicate that preferential flow of infiltration is associated with these unsaturated-zone features. The wide zone of low solutes on both sides of the fracture set at 583 to 585 m indicates that even in this region of generally high solute concentrations, preferential flow associated with this fracture set has been imbibed into the surrounding matrix (fig. 7). Similarly, low solute concentrations deeper than 3 m on fractures with shallow calcrete fill, such as the fracture at 490 m (fig. 8) indicate that these fractures can also be active conduits for recharge. However, the narrower regions of low solute concentration indicate that less infiltration and matrix imbibition has occurred beneath these calcrete-filled fractures as compared to the open fracture set at 583 to 585 m.

Because of the larger pore-throat diameter of open fractures compared to that of sandstone matrix, such features are barriers to flow under unsaturated conditions. Therefore, ponding of water above the bedrock surface associated with larger precipitation events may be necessary for substantial infiltration to occur along open fractures. It is not clear how water moves preferentially down the calcrete-filled fractures, but two sets of hypotheses are proposed: one for high-permeability calcrete fill and another for low-permeability calcrete fill. Laboratory testing of calcrete samples collected along Trench 1 (table 1) shows a wide range of saturated hydraulic-conductivity values from 0.0005 m/d (lower than the surrounding sandstone) to 1.1 m/d (higher than the sandstone). If the calcrete fill in a fracture is of higher permeability than the adjacent sandstone, either: (1) saturated downward preferential flow could episodically occur during periods of high precipitation when ponding occurs above the bedrock surface; or (2) surface-zone flow (a type of film flow) may occur under unsaturated conditions, as reported by *Tokunaga and Wan* [2001] for high-permeability mineral coatings on a lower-permeability consolidated rock (welded tuff).

If the calcrete fill in a fracture is of lower permeability than the adjacent sandstone, preferential flow may occur along the microfractures commonly observed in shallow calcrete-filled fractures. For a high-porosity dry matrix, such as sandstone, flow along an unlined fracture would be readily imbibed into the unsaturated matrix, thus preventing preferential flow. However, imbibition into the sandstone matrix would be minimal along microfractures lined with low-permeability calcrete, allowing either saturated flow or unsaturated-zone film flow, surface-zone flow, fingering, and flow channeling along these fractures [*Tokunga and Wan*, 1997; *Tokunga et al.*, 2000; *Dahan et al.*, 2000; *Tokunga and Wan*, 2001]. The lower specific-conductance values measured on the microfracture at 490 m from the west end of Trench 1, relative to the rest of the calcrete fill (fig. 9a), indicate that some microfractures may be conduits for recharge through low-permeability calcrete fracture fill. The hard, well-cemented sandstone generally observed adjacent to the calcrete-filled shallow parts of the fractures indicates that little matrix imbibition and dissolution of the calcite cement has occurred, supporting the interpretation of preferential flow along microfractures. Below the zone of calcrete fracture fill, the sandstone next to the fractures is often softer, likely as a result of dissolution of the cement holding the sand grains together by infiltrating water imbibed into the sandstone matrix.

4.4. Limitations of Vertical Borehole Data for Characterizing Recharge

The variability in vadose-zone solute concentrations observed in excavations at Sand Hollow indicates that a large number of vertical cores are necessary to characterize recharge at the kilometer scale. Sampling would need to include the full range of surface morphology and geology present within the basin. To adequately represent the variety in surface morphology, this would include ridge, slope, and basin settings, as well as rivulets and larger ephemeral washes that receive runoff during precipitation events. To investigate variations in surface geology, sites would be needed on exposed fractured sandstone and basalt outcrops, basalt boulder colluvium, sand dunes, fine sand, and loams.

Vertical cores in areas of high solute accumulation may underestimate actual recharge rates due to their inability to accurately represent preferential flow associated with near-vertical fractures. Based on the estimated 4-m spacing between near-vertical fractures and an average fracture dip of 70 degrees, a vertical borehole would only intersect, on average, one near-vertical fracture per 10 m of core. Although this may cause a localized decrease in the pore-water chloride content of the core at that depth, it will not substantially reduce the cumulative chloride calculated for that drill site. Unless a borehole happened to be drilled directly along a vertical fracture (a very small probability), recharge rates calculated from borehole cumulative chloride mass would under-represent macropore flow occurring along fractures.

The observed solute distributions in the excavations at Sand Hollow were not sufficient for evaluating whether enhanced recharge along fractures occurs in areas of low solute accumulation. Four near-vertical fractures along the bottom of Trench 1 on the west end (at 50, 94, 110, and 136 m) did not show any significant difference between specific-conductance values of leachates from nonfractured and fractured sandstone. The low solutes in both the matrix and fractures of this area only indicate that net infiltration is moving through both interstitial pore spaces and fractures. Further investigation using environmental tracers (^{3}H, ^{36}Cl) is needed to determine if recharge rates are much higher in the fractures as compared to the surrounding sandstone matrix. Therefore, the results of this study cannot be used to evaluate whether vertical core data in areas of low solute accumulation will yield representative recharge rates.

4.5. Implications for Evaluating Recharge in Other Desert Basins

The findings of this study should be directly applicable to other desert basins in the southwestern United States with exposed or shallowly buried fractured bedrock. This would include much of the Colorado Plateau region, as well as smaller upland basins of the Mojave and Sonoran deserts with similar surface morphology, geology, and rainfall patterns. Additional research in other geomorphologic settings is needed to determine if the large heterogeneity in solute distribution and net infiltration observed at Sand Hollow is limited to shallow fractured bedrock environments. Variations in soil type and surface morphology, vegetation, and macropore features such as animal burrows, root casts, and fissures, may result in similarly heterogeneous infiltration processes in other arid environments, such as larger alluvial basins.

5. SUMMARY

Unsaturated-zone bedrock solute distributions from trenches and a road cut indicate that net infiltration at Sand Hollow is spatially variable. Such variability would be difficult to characterize on the basis of solute concentration data from a limited number of vertical cores. Important factors affecting basin-wide variability in net infiltration include runoff from exposed sandstone, coarseness of surficial soils, bedrock fracturing, and intensity of precipitation. Bedrock infiltration primarily occurs beneath exposed sandstone and along areas of coarse-grained soils in the upland parts of the basin, rather than lower in the basin where the sandstone is covered by fine-grained soils. Once moisture penetrates beneath the root zone, either in nonfractured sandstone or beneath the maximum root depth in fractures, this water becomes net infiltration and eventually recharges the underlying aquifer. The thick deposits of fine-grained soil and the limited extent of low solutes in the underlying sandstone beneath the present ephemeral wash indicate that little recharge is presently occurring there. In contrast, a wide zone of low solutes beneath a nearby topographic low, inferred to be a relict wash, implies that more recharge had occurred beneath the wash in the past during wetter conditions. In high-solute areas, localized patterns of lower solute concentration around fractures were observed at depths greater than 3 m below the bedrock contact, indicating preferential flow along these features. However, at depths less than 3 m, many of these same fractures had higher solute accumulations than the adjacent matrix. The high solute accumulations in bedrock beneath finer-grained soils and in shallow calcrete-filled fractures indicate that most infiltration in these areas is recycled back into the atmosphere by way of evaporation and plant transpiration.

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