PROCEEDINGS OF THE TWENTY-EIGHTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Holli Frey
Symposium Convener
Union College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Christina Kelly
Symposium Proceedings Layout & Design
Office of Communication & Marketing
Scripps College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

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KECK GEOLOGY CONSORTIUM
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Robert J. Varga
Editor and Keck Director
Pomona College

Keck Geology Consortium
Pomona College
185 E 6th St., Claremont, CA 91711

Christina Kelly
Proceedings Layout & Design
Scripps College

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VICTOR W. MAJOR, Williams College
Research Advisor: David P. Dethier

INTRODUCTION

Alpine and subalpine areas of the Colorado Rocky Mountains form the headwater catchments that supply important water resources to the western United States. Snowmelt runoff dominates the hydrology of these headwater catchments (Serreze et al., 1999) and in Colorado, the 3100 to 3700 m elevation range is the most important for generating snowmelt (Segura and Pitlick, 2010). This elevation range, which dissects the alpine and subalpine zones, generally accumulates snow from October through April, forming deep seasonal snowpacks that melt out from May to July. The water temporarily stored as snow and ice is released progressively by melt that flows through surface and groundwater pathways that are complex, connected, and spatially and temporally variable.

Understanding the hydrological significance of the surface/groundwater interface in headwater catchments is important, but challenging. The interface has implications for both water quality and quantity, yet traditional techniques for hydrological measurements are less suitable for in mountain areas. Furthermore, the combined effects of elevated terrain and geologic history result in hydrologic systems characterized by high rates of flow, preferential (?) fluid pathways in periglacial and glacial deposits and underlying bedrock, and steep slopes with extreme head gradients. The significant contribution of headwater catchments to regional water balance makes accurate and quantifiable models of alpine and subalpine hydrology invaluable.

A common hydrologic assumption is that most alpine and subalpine zones have little groundwater storage capacity. In areas dominated by glacially deposited till, the relatively low hydraulic conductivity of till limits groundwater infiltration and tends to "plug" fractures in bedrock, forming mainly watertight catchments (D. Dethier, personal communication). Conversely, in unglaciated zones with coarse-grained surficial deposits and steep slopes, it was assumed that water moved rapidly through the subsurface with little physical or chemical interaction (Liu et al., 2004). However, studies of alpine and subalpine catchments in the Front Range suggest that groundwater provides significant contributions to streamflow (Williams et al., 1997; Clow et al., 2003) and that the relative contribution of groundwater increases during the latter stages of melt (Liu et al., 2004). Locally thick and layered surficial deposits above the glacial limit and fractured bedrock provide both water storage and shallow subsurface pathways. As our understanding of hydrologic flux (Knowles et al., submitted) and the water balance disparity on Niwot Ridge increases, there is a need for hydrogeologic information that can connect the variables between shallow subsurface geology and 'leaky' headwater catchments on Niwot Ridge and similar areas.

RESEARCH AREA

The headwater catchments in this study are in the Niwot Ridge/Green Lakes Valley area of the Colorado Front Range, Boulder County, Colorado, within the Boulder Creek Critical Zone Observatory (CZO). I focused on four basins (total area ~2 km^2) on Niwot Ridge: Martinelli, Saddle, Upper Como, and Upper Fourmile; and I include the Upper Green Lakes Valley basin (area ~2.2 km^2) as a counterexample. These basins lie east of the Continental Divide in the alpine and subalpine zone of the Boulder Creek watershed, ranging in elevation from approximately 4087 m at the top of Navajo Peak to 3036 m at the outlet of the upper Fourmile Creek basin (Fig. 1).

The Niwot Ridge/Green Lakes Valley area has been tectonically quiescent since the end of the Laramide orogeny (~40 Ma), but the retreat of the most recent glaciers 14,000 years ago has revealed two distinct geomorphic landscapes. The Green Lakes Valley represents a textbook, U-shaped glacial valley with headwalls and cirques carved into the spine of the Continental Divide, till deposits, and fresh bedrock surfaces exposed throughout the valley walls and trough (Dühnforth and Anderson, 2011). The Niwot Ridge interfluve, however, which extends approximately 9 km eastward from the Continental Divide, remained mainly above the glacial limit and therefore avoided glacial erosion (Fig. 1) (Gable and Madole, 1976). Instead, the cold temperatures and moisture that enabled adjacent glacier formation produced extended periods of periglacial activity on the Niwot Ridge and resulted in a thick mantle of surficial deposits that reflect long-term physical weathering and mass wasting of the underlying bedrock (Benedict, 1970).

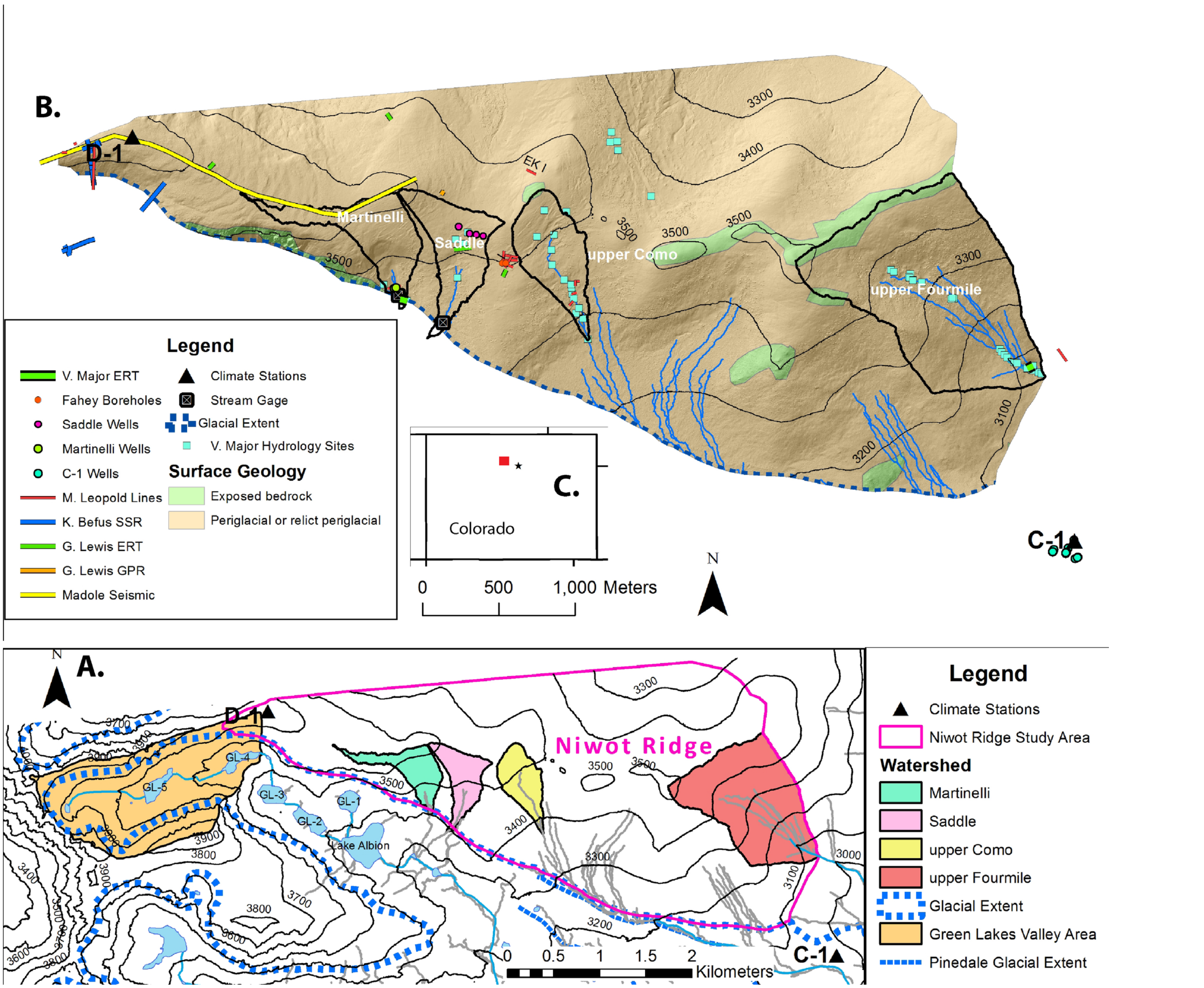

Figure 1. A. Location map identifying the four main catchments that I worked in as well as the upper Green Lakes Valley basin and the glacial maximum. The southwestern border of the Green Lakes Valley basin is the Continental Divide. B. Image of my primary study area, entirely above the glacial limit, showing the surficial geology, locations of geophysical lines, well or borehole locations, and the sites where I made hydrologic measurements. C. Red box indicates the approximate location of (A.).

Niwot Ridge is a broad and topographically smooth alpine zone with several knolls and saddles surrounded by subalpine and montane zones. On top, vegetation is sparse, with krummholtz, grasses, sedges, and low perennial herbs, but gradually increases in size and extent at lower elevations to include willows, Englemann spruce (*Picea engelmanni*), subalpine fir (*Albies lasiocarpa*), and limber pine (*Pinus flexillus*) (Benedict, 1970). Above treeline, soils are Cryepts with A/Bw/C profiles (Burns, 1984). The mean annual temperature (MAT) on the Niwot Ridge is -3.71°C at D-1 (3743 m) and is 1.30°C at C-1 (3048 m) (Greenland, 1989). The mean annual precipitation (MAP) ranges from 800-1000 mm per year, and is generally 80% snow (Caine, 1995), which is easily transported by wind, increasing the effective precipitation in lee and protected areas (Benedict, 1970). Elevation, consistent high winds and low temperatures, and spatially and temporally variable precipitation control the land cover of Niwot Ridge.

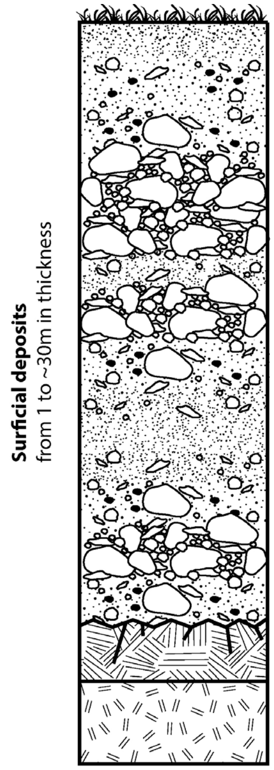

Figure 2. Schematic or idealized stratigraphic column of the surficial geology of Niwot Ridge. The most important hydrological features are the clast-supported, open-work gravel or boulder layers that would serve as preferential fluid pathways. These well-sorted layers form from the same frost action that produces blockslope deposits or stone-banked gelifluction lobes seen on the Niwot Ridge today (see Benedict, 1970). Columns at higher elevations would be shallower and have less soil development, whereas columns at lower elevations would be deeper and have more soil development. One could imagine the surface intersecting with this column at any level, producing varied surface exposures and subsurface profiles.

HYDROGEOMORPHIC SETTING

The hydrologic potential of Niwot Ridge reflects its geologic and geomorphic history. The absence of middle (?) and late Pleistocene glacial erosion and persistent frost action formed a thick mantle of surficial deposits on top of a structurally complicated igneous and metamorphic basement. These two suites (bedrock and surficial deposits), form the principal water storage reservoirs on Niwot Ridge.

Bedrock on Niwot Ridge is composed mainly of igneous and metamorphic Precambrian basement rocks with various younger intrusives (Gable and Madole, 1976; Cole and Braddock, 2009). Precambrian rocks show structural features from deep-crustal faulting and there are inferred structures from the Ancestral Rocky Mountains, but these are overprinted and dominated by structural complexity and pervasive fracturing from the Laramide orogeny (Cole and Braddock, 2009). Groundwater flow in bedrock is primarily through a network of fractures near the upper surface of the bedrock. Geophysical data from both Niwot Ridge and Green Lakes Valley indicate a weathered bedrock zone of variable thickness overlying fractured and jointed bedrock (Fig. 2). Bedrock may be exposed or greater than 30m below the surface on Niwot Ridge (Madole, 1982; Leopold et al., 2010). Exposed bedrock constitutes only 4.4% (0.48 km^2) of the Niwot Ridge area (Dethier, unpublished data), but underlying bedrock geometry influences water movement though the subsurface. King (2012) estimated the hydrologic properties of bedrock aquifers using several shallow and deep wells in the Saddle and Martinelli basins. Hydraulic conductivities from slug tests ranged from 8.74×10^{-4} m/s in Tertiary syenite to 8.42×10^{-6} m/s in Precambrian Granite of Long's Peak. King (2012) attributed the range in values to the geology of the screened interval and nonuniform distribution of fractures resulting in aquifer heterogeneity.

The surficial deposits on Niwot Ridge reflect a history of long-term topographic decay and climate influence (Anderson et al., 2006), resulting in a thick mantle of surficial deposits affected by periglacial processes. Periglacial activity is driven by frost action from the expansion of water as it freezes, resulting in the ratchet-like movement of particles heaving perpendicular to slope and subsequent vertical settling upon thawing (Washburn, 1973). Niwot Ridge is covered by a number of periglacial features such as patterned ground, blockslopes, and turf-banked and stone-banked terraces and lobes. Current periglacial activity is limited to certain microenvironments that are saturated with meltwater in the fall (Benedict, 1970; Leopold et al., 2011). However, in times of colder climate and glacier advances, periglacial processes were much more active, effective, and extended much lower (Benedict, 1970). Periglacial deposits on Niwot Ridge have been transported up to 100m and have modified deposits from ancient valley systems (Gable and Madole, 1976). Völkel (2011) found that Pleistocene age periglacial solifluction processes explain soil profiles on the adjacent Gold Hill (2710m).

Geophysical investigations of the subsurface show that layered periglacial slope deposits compose the majority of surficial deposits on Niwot Ridge, Figure 1.B. These deposits underlie a thin (1-3m) layer of colluvium, soils, and unconsolidated sediment and range in thickness from 3 to >30m over weathered and fractured bedrock. Periglacial slope deposits are generally coarse and well sorted, making them ideal conduits for shallow groundwater, and appear to accumulate in layers (Fig. 2). Drill logs from Niwot Ridge showed that there were multiple water-filled pockets of high permeability (referred to as *little aquifers*) that support the layered model of the slope deposits (King, 2012). Still, deposits show variability in geophysical properties. The range in resistivity and seismic velocities is reasonable and can be attributed to local differences in compaction, layering, water saturation, degree of sorting, and presence of fines. Fines, either generated from frost-action or from aeolian sedimentation, reduce both the electrical resistivity and the hydraulic conductivity of the deposits as well as the infiltration capacity in the surface material.

Additionally, periglacial deposits, unless they are sheet deposits like blockslopes, are laterally discontinuous and may exhibit dramatic anisotropy. Consequently, the preferential fluid pathways in the layered openwork gravel deposits are also discontinuous. The hydraulic conductivity within these layers is likely much greater than the entire surficial profile, so estimates of hydraulic conductivity represent the bulk properties of a heterogeneous shallow subsurface.

METHODS

This study focuses on constructing an accurate picture of the hydrogeology of Niwot Ridge and critical to this understanding is the nature of the shallow subsurface. A number of geophysical investigations and holes have probed the subsurface on Niwot Ridge, but all for different reasons. I gathered and compiled this information to assemble a representative model of the subsurface. The data compiled include: geophysical information from Madole (1982), Davinroy (2000), Leopold et al. (2008, 2010, 2013, and unpublished data), Befus (2009), Völkel et al., (2011), and Lewis

Material Type	Material	Range of thickness (m)	Area of unit (km^2)	Hydraulic Conductivity (ms^{-1})	Porosity	Seismic Velocity (m/s)[6]	Resistivity (Ωm)
Shallow fractured bedrock	Syenite and quartz syenite[1]	5 to 10	0.80	$8.74x10^{-4}$	0.04%	4,400	3,000 to ≥4,500
	Biotite schist and gneiss	5 to 10	5.88		0.04%	2,908 to 3,920	≥ 3,000
	Granite of Long's Peak[1]	5 to 10	1.08	$8.42x10^{-6}$	0.04%	3,500 to >5000	
Surficial material[7]	Colluvium[2,4]	2 to 3	1.94	$4.07x10^{-5}$		233 to 368	
	Diamicton[1,2]	3 to 36	1.04	$4.31x10^{-4}$ to $1.92x10^{-4}$		~1,400 to >2500	
	Wetlands	0 to 2		$3.9x10^{-6}$	20%		
Slope deposits	Periglacial or relict periglacial	3 to >22	10.54	$3.16x10^{-3}$ to $3.07x10^{-5}$		567 to 777	350 to 1400
	Talus slopes[5]	8.5 to 26.5		$6.5x10^{-3}$ to $9.4x10^{-3}$	43 to 60%	400 to 1,600	
	Till[8]	7 to 10		$4x10^{-3}$ to $6x10^{-3}$	20%	850 to 1400	
	Blockslopes[3]	1 to 3		$1.1x10^{-3}$ to $3.9x10^{-3}$	50%		

[1] Hydraulic conductivity estimates are means from slug tests in King (2012)
[2] Hydraulic conductivity estimates are means from double-ring infiltrometer tests in King (2012)
[3] Hydraulic conductivity from constant-head permeameter, thickness, and porosity in Davinroy (2000)
[4] Thickness from shallow seismic refraction (Leopold, 2008)
[5] Estimates from Clow et al. (2004)
[6] Seismic velocities and depths compiled from Befus (2009), Leopold et al. (2008), and Madole (1982)
[7] Mapped by Cole and Braddock (2009) and Burns (1984)
[8] Hydraulic conductivity estimated from grain-size analysis in Clow et al. (2004)

Table 1. Compilation of some of the hydrogeologic and geophysical information related to Niwot Ridge and Green Lakes Valley. Colluvium and diamicton units are considered surficial material, as opposed to slope deposits, as they are marked on the geologic map (Cole and Braddock, 2009). Hydraulic conductivity estimates for till seem high and may be an artifact of the estimation method, but seem reasonable because mountain glaciers tend to deposit very coarse material (Clow et al., 2004).

(2013); borehole or well-log data from King (2012) and Tingjun Zhang; soil, permafrost, and periglacial investigations from Burns (1984), Fahey and Ives (1971), and Benedict (1970); and finally, geologic maps from Gable and Madole (1976) and Cole and Braddock (2009). Lines and boreholes are indicated in Figure 1.B. and essential data are summarized in Table 1. Comparison of geophysical properties, drill sections, shallow trenches, and my own measurements allows characterization of the shallow subsurface geology on Niwot Ridge. Additionally, I calculated total potential ground water storage using depth to bedrock, porosity estimates and measurements, and areas calculated from GIS.

There have been a number of hydrological studies on the Niwot Ridge including Liu et al. (2004), King (2012), and Nesbitt (2013). I lean heavily on the data collected by King, the conceptual model developed by Liu et al., and the data and methods pioneered by Nesbitt. Hydrogeologic data derived from these studies, mostly infiltration rates and hydraulic conductivities, are included in Table 1.

Geophysical data I collected in July 2014 compliments previous work on Niwot Ridge. Working with Dr. Matthias Leopold (University of Western Australia), two ~50m Electrical Resistivity Tomography (ERT) lines were completed above major seep zones: one in Martinelli and one in upper Fourmile. Two-dimensional direct current resistivity tomography profiles were measured to investigate the depth and lateral extent of the saturated zone. A multimode SYSCAL JUNIOR Switch-48 system was used. Conductive metal stakes were hammered into the ground with 2m spacing and resistivity was measured in a Wenner array with a frequency of 5 Hz and a current of 0.1-10 mA. Apparent resistivity values were inverted using the software RES2DINV 3.55.18. I used the cross-sectional area of the saturated zone (A in m^2), the instantaneous discharge of the seep (Q in m^3s^{-1}), the slope (dh/dl) calculated with GIS, and Darcy's law (*Eq.1*) and was able to calculate the hydraulic conductivity (K in ms^{-1}) of the deposits above the seep zone.

Eq. 1 $$K = \frac{q}{A \times {}^{dh}/_{dl}}$$

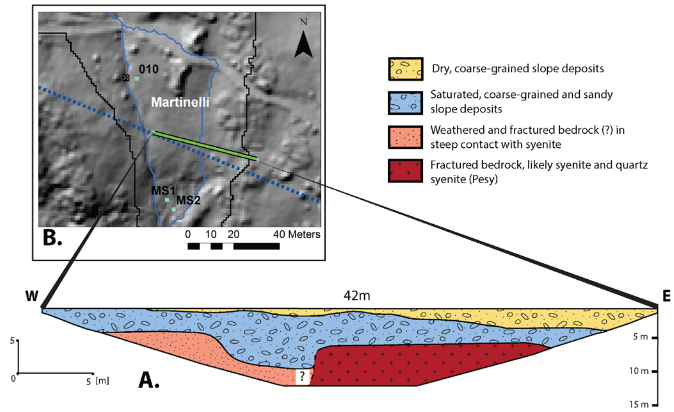

Figure 3. A. Interpretation of ERT Line above Martinelli seep zone. The illustration reflects a low resistivity saturated zone (light blue) underneath a higher resistivity, coarse and dry layer (yellow) and perched above higher resistivity bedrock (red) and weathered bedrock layer (pink). The question mark is due to the uncertainty when interpreting vertical boundaries in ERT profiles. The area of the saturated zone is ~146.0 m^2. B. The location of the line (A.) in the Martinelli catchment. No stream channel crossing the line as shown from the DEM flowpath (blue), but there must be subsurface flow here because of the large seep just below the line.

Stream and spring discharge was measured repeatedly in July 2014 at multiple locations marked with GPS along each stream profile, supplementing and expanding measurements reported by Nesbitt and Dethier (2013). Discharge was measured using a bag-capture method over a period of seconds to a minute to calculate the instantaneous discharge in Ls^{-1}. This method was flexible, consistent, and very successful at capturing low rates of discharge. In upper Fourmile, where discharge was too high for this method, a measured channel profile and adjusted float velocities were used to make repeated measurements of discharge. Infiltration rates of the upper Como and Saddle stream channels were calculated from the losses in instantaneous discharge over the stream channel area (e.g. from point 004 to point 003 assuming a channel width of 0.1 m).

RESULTS

Potential water storage and hydraulic conductivity of headwater catchments are informative properties about the nature of headwater catchment hydrogeology. To calculate the potential water storage in bedrock on Niwot Ridge, I assumed porosity of 0.04% and open fracture depths of 5 to 10 m (Clow et al., 2003). Spatial distribution and areas of the bedrock units were determined from Cole and Braddock (2009) and GIS analysis. Results indicate a storage capacity of 1.4×10^4 to 3.1×10^4 m^3 in shallow bedrock on Niwot Ridge. Groundwater flow rates in fractured bedrock are likely slow and decrease with depth and increasing fracture spacing.

To calculate the total potential storage of the surficial deposits on Niwot Ridge, I assumed there was mantle of periglacial deposits (Area=10.48 km^2) in places where there is no exposed bedrock. Assuming porosity from 25 to 35% (from comparison with properties of till and blockslopes) and thickness from 3 to 10m, the potential water storage capacity of surficial deposits on Niwot Ridge is 7.9×10^6 to 3.69×10^7 m^3. This value seems large when considering that wind scoured portions of Niwot Ridge do not accumulate snow and the storage in these areas may never be filled to capacity. However, the mantle of surficial deposits is shallower near the summit surfaces and in other places deposit depths may be greater than 30m, therefore balancing this estimate of storage capacity.

Hydraulic conductivities decrease and storage capacities increase as the proportion of fine material in the deposit increases (Clow et al., 2003). Using *Eq. 1* I was able to estimate hydraulic conductivity of subsurface deposits (Table 1). The coarse and sandy saturated material had a calculated hydraulic conductivity of 3.16×10^{-3} m/s in Fourmile (Fig. 4) and 8.63×10^{-5} m/s in Martinelli (Fig. 3). The lower conductivity in Martinelli is attributable to compaction from the deep snowfield and discharge bypass because of the presence of local openwork gravels. Estimates of the infiltration capacity along stream profiles using the losing characteristics of Upper Como and Saddle streams fall with the range of these values (Table 1).

The upper Fourmile basin (area=1.3 km^2) forms the headwater catchment of Fourmile Creek (area=64 km^2). While it only forms 2% of the area of the total watershed, upper Fourmile basin contributed from 18% to 60% of the total output of Fourmile Creek at Orodell, Colorado. More importantly, as the stream channel is consistently dry above the seep zone, all of of the meltwater from upper Fourmile travels as groundwater from the persistent late-lying snowfields in the basin's upper reaches, a distance of at least 300 m. Downstream, where the bedrock surface shallows (Fig. 4), the saturated zone intersects the surface, demonstrating that the subsurface is capable of discharging at substantial rates long after peak snowmelt (Q=151.7 Ls^{-1} on July 2, 2014). This catchment exemplifies the significance of subsurface

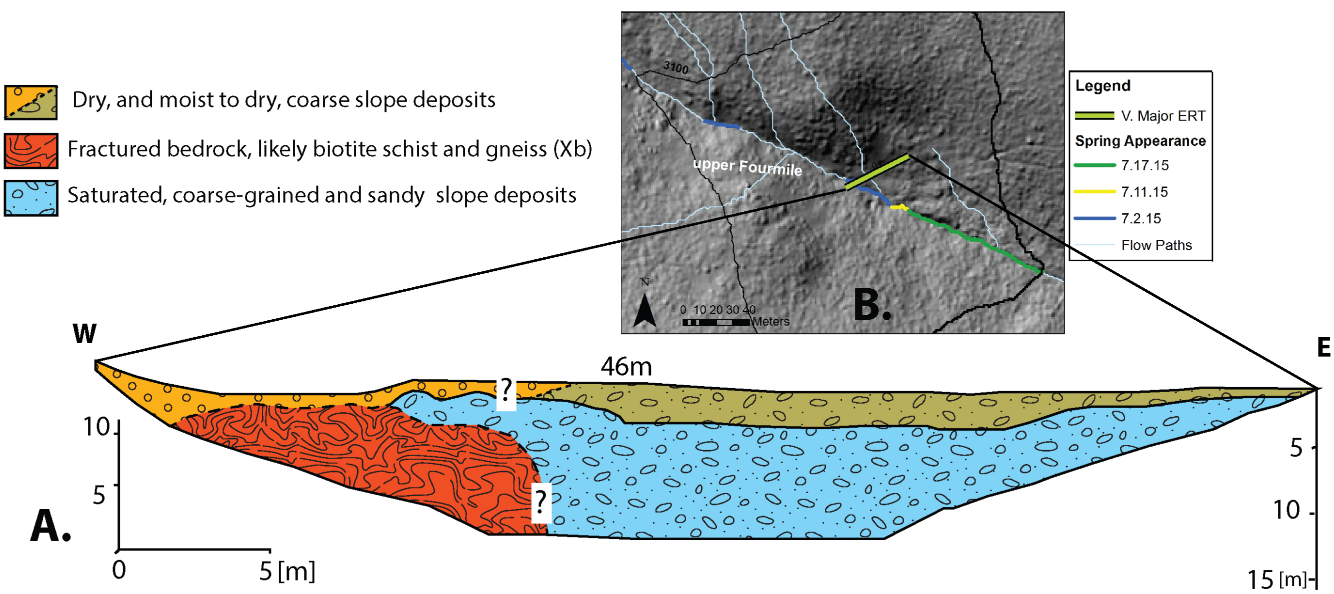

Figure 4. A. Interpretation of the ERT line above the Fourmile seep zone. Area of the saturated zone is ~180.0 m^2. B. Location of the line within the Fourmile watershed. Colored lines in the stream channel show the first appearance of water in the as the height of the water table decreases from 7/2/15 to 7/17/15.

flow in alpine catchments mantled by thick and layered surficial slope deposits.

CONCLUSIONS

The total potential for groundwater storage on Niwot Ridge is large, mainly in periglacial slope deposits, because of their extensive distribution and thickness. Hydraulic properties of surficial deposits are variable depending on the degree of compaction and percentage of fines, but are easily capable of storing and transmitting large volumes of water. Results indicate that there is a close relationship between the expression of surface water and the lateral and vertical extent of the saturated zone. Little water is lost into bedrock, but there may be significant bypass where discharge measurements are made in thick surficial deposits. The hydrologic importance of headwater catchments is therefore, not only their ability to accumulate and store water as snow, but to retain large volumes of water in shallow aquifers, truly making headwater catchments the water towers of the west.

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