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MODELING SOIL MOISTURE PROCESSES AND RECHARGE UNDER A MELTING SNOWPACK

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ABSTRACT

Recharge into bedrock under a melting snowpack is being investigated as part of a study designed to understand hydrologic processes involving snow at Yosemite National Park in the Sierra Nevada Mountains of California. Snowpack measurements, accompanied by water content and matric potential measurements of the soil under the snowpack, allowed for estimates of infiltration into the soil during snowmelt, and percolation into the bedrock. Infiltration rates into the soil exceeded the permeability of the bedrock and caused ponding to be sustained at the soil-bedrock interface during the snow melt period. During a 7-day period with no measured snowmelt, drainage of the ponded water into the underlying fractured granitic bedrock was estimated to be 16 mm/day. The numerical simulator, TOUGH2, was used to reproduce the field data and evaluate the potential for vertical flow into the fractured bedrock or lateral flow at the bedrock/soil interface. The field data and model results support the notion that although most snowmelt on shallow soils overlying relatively impermeable upland bedrock tends to run off and contribute directly to streamflow, at least some of the snowmelt can infiltrate and potentially provide recharge to local or regional aquifers.

INTRODUCTON

Infiltration of water into bedrock in mountainous terrain represents a significant portion of recharge in the western United States, especially under conditions of a melting snowpack. Under anticipated increases in air temperature associated with global warming, snowmelt processes and the associated runoff in the Sierra Nevada Mountains are likely to occur earlier in the springtime (Dettinger et al., 2004), with uncertain implications regarding recharge. Developing a better understanding of the processes contributing to mountain block recharge under these conditions is deemed prudent.

The conceptual model of infiltration into bedrock is described by Flint et al. (2004) as resulting from water percolating through a shallow soil column at a rate exceeding that of the underlying bedrock permeability, ponding at the bedrock interface, and penetrating the bedrock at a rate equivalent to the saturated hydraulic conductivity of the fractures. Use of a basin-scale water-balance model that accounts for melting snow, the physical characteristics of a location dominated by the granitic bedrock present throughout much of the Sierra Nevada, and shallow soils, generally results in calculations indicating a higher potential for runoff than in-place recharge into the bedrock. This process is strongly controlled by the bedrock permeability and the nature of the matrix and fracture properties reflected in the bedrock moisture retention characteristics. Measurements of the various processes in the field allow for estimation of the bulk bedrock permeability, and when accompanied by detailed numerical investigations provide a means to glean additional understanding of how the processes of snowmelt, soil moisture flow,

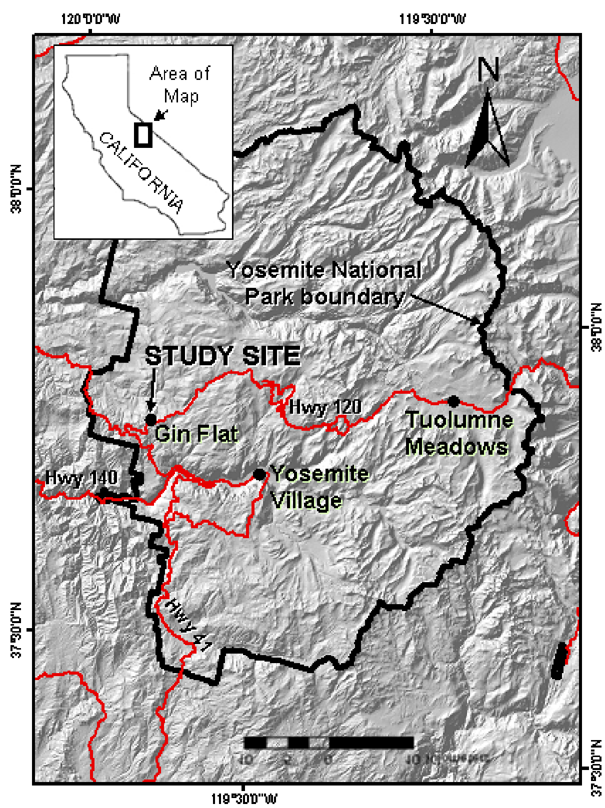

Figure 1. Map of study location in Yosemite National Park, central Sierra Nevada Mountains.

ponding, bedrock flow, and redistribution operate in this complex system. In a small headwater catchment, Kosugi et al. (2006) also showed saturated flow from overlying soil into weathered granite to the dominant hydrologic process at the soil-bedrock interface.

The U.S. Geological Survey, working with the Scripps Institution of Oceanography, has established a research field site located in Yosemite National Park at a Department of Water Resources SNO-TEL station on the western boundary of the park at Gin Flat (*Figure 1*) to study soil moisture processes under the accumulation and melting of snow. This research is part of the California Climate Change Center's research program to understand how climate change will influence California future economic, social, and natural systems.

Study Objectives

The established field site hosts a variety of instruments to measure turbulent heat and vapor fluxes, soil moisture and temperature, and snow pack temperatures. Specifically the soil measurements of matric potential, water content, and temperature are used to develop conceptual models of the interaction between the soil and snowpack. The measurements are accompanied by calculations of snowmelt to provide properties and boundary conditions for a numerical model to elucidate the relative importance of the processes and test hypotheses regarding soil moisture drainage and bedrock infiltration. Overall, the study will help develop an understanding of the water balance between the atmosphere, snowpack, soil moisture, drainage, recharge, and runoff.

METHODS

For the purposes of investigating the processes occurring in the snowpack, instruments were installed to measure the temperature and volume of the snow, as well as all of the associated meteorological components (solar radiation, net radiation, evapo-transpiration, sublimation, etc.). Snowmelt rates were calculated from an adjacent snow pillow. Adjacent to the aboveground instrumentation, soil instrumentation was installed (*Figure 2*) in the 30-inch deep, loamy sand, overlying fractured granite. Measurements were made at 4 hour intervals from the fall of 2002 to March, 2004, then changed to hourly intervals until the fall of 2004, and are used to illustrate the subsurface processes associated with the 2004 springtime snowmelt.

A series of time domain reflectometry (TDR) probes were installed at 4, 14, and 28 inches below the surface to measure soil water content. Alongside the TDR probes were heat dissipation probes (HDP; Flint, et al., 2002) that measure soil matric potential and soil temperature (*Figure 2*).

Field Data Collection

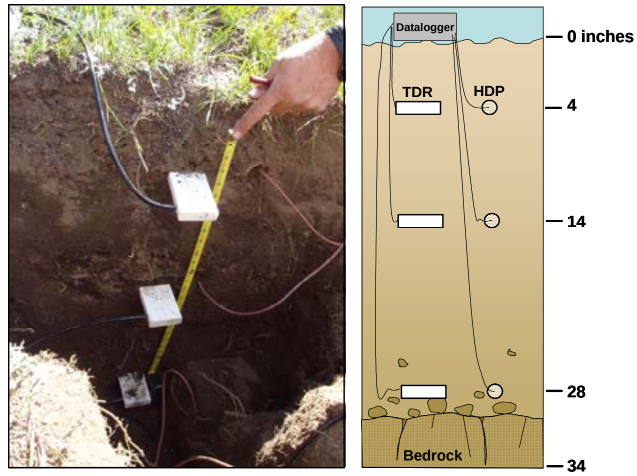

Figure 2. Time domain reflectometry (TDR) and heat dissipation probes (HDP) at 3 depths in shallow soil above granitic bedrock.

Laboratory Data Collection

During instrument installation soil samples were taken for measurement of physical and hydrologic properties. Laboratory measurements of porosity, bulk density, grain density, and moisture retention characteristics were measured.

Model Development

Using the numerical simulator TOUGH2 (*Pruess et al., 1999*) 1-D and 2-D models were developed using measured soil properties with 3 soil layers, 2 bedrock layers, and upper boundary conditions consisting of early melting initiation, sustained melting, and no melt during periods of freezing conditions. Lower boundary conditions were bedrock with a specified potential beginning in equilibrium with the soil prior to the onset of snow melt. Grids consisted of 5-cm thick layers with the model domain being 1-m deep for the 1-D model, and 1-m deep x 10-m wide for the 2-D model. Three scenarios were investigated: large-scale seasonal processes at 3 depths for 3 months during the snowmelt period, hourly melt and drain processes at the beginning of snowmelt, and a 2-D investigation with a 5% slope to evaluate the potential for lateral flow and if it is likely to be influencing one-dimensional conclusions.

RESULTS AND DISCUSSION

Laboratory measurements

Soil core samples were measured and resulted in average hydrologic and thermal properties (*Table 1*). Soil water content measurements were made periodically to help develop field specific calibration equations for the TDR probes, however site access problems (snow closed roads) only allowed for measurements during the relatively dry periods.

Table 1. Results of laboratory measurements on bulk soil samples.

Hydrologic properties	
Bulk density (g/cm^3)	1.12
Porosity (cm^3/cm^3)	0.55
Grain density (g/cm^3)	2.66
Gravel (percent of total soil)	22
Organic matter (percent of total soil)	5
Sand (percent of fines)	86
Silt (percent of fines)	9
Clay (percent of fines)	5
Van Genuchten alpha (1/Pa)	1.6E-4
Van Genuchten n	1.44
Thermal properties	
Thermal conductivity (W/m ^{o}K)	1.17
Heat capacity (MJ/m^3)	1.75

Field Data

Volumetric soil water content is shown in *Figure 3* for 3 depths. Water content is the highest for the 28-in depth where it reaches saturation under ponded conditions in early April. Initial evaluation of the data suggested that the water content at 4 inches depth seemed low but could possibly be explained as a soil under steady state conditions with melting snow. Numerical modeling suggests possible measurement errors that will be discussed later.

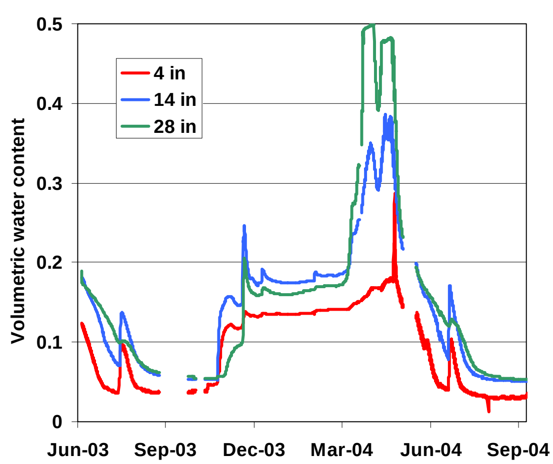

Figure 3. Volumetric soil water content for June 2003 through September 2004 at 3 depths.

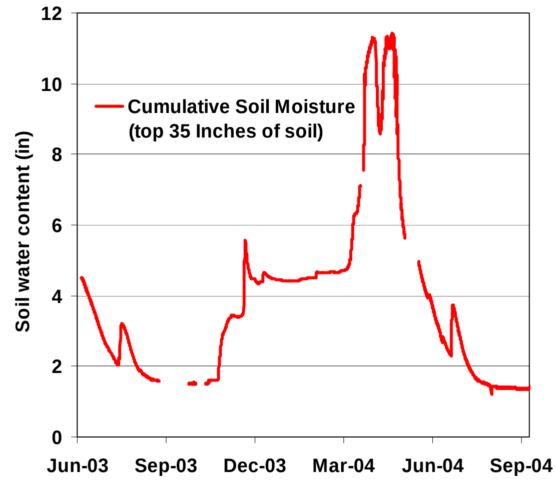

Figure 4. Cumulative water content for entire soil profile for June 2003 through September 2004.

Cumulative water content for the whole soil profile is shown in *Figure 4* with over 11 inches of water at the maximum following snow melt in April, and a low of just over an inch during September.

A detail of the soil moisture measurements for 6 weeks in April and May (Figure 5a) illustrates daily fluctuations that are a result of nightly freezing of the snow pack, followed by subsequent snow melt. The soil continues to drain, regardless of snow processes, but the water content fluctuates according to the melting and drainage each day into the soil.

Changes in water content in the soil profile also illustrate infiltration into the bedrock. This can be seen when the 28-in depth is saturated (Figure 5a) and fluctuations in the 14-in depth reflect soil water content changing as the water ponds and then drains into the bedrock. There was a snow storm and freezing event on April 18th that is reflected as a discontinuation of snow melt that then allows the soil water to drain for several days and reduce in water content at the 14-in and 28-in depths. Snow began melting again the 23rd, with a resulting rise in water content that then ponded again until the second week of May. In this period of time, with no snowmelt, it was calculated that 16 mm per day of water infiltrated into the saturated bedrock. In Figure 5b, it is shown that the 28-in depth becomes ponded from April 7 on. The time frame for the meltwater to penetrate through the soil column is 1-2 hours.

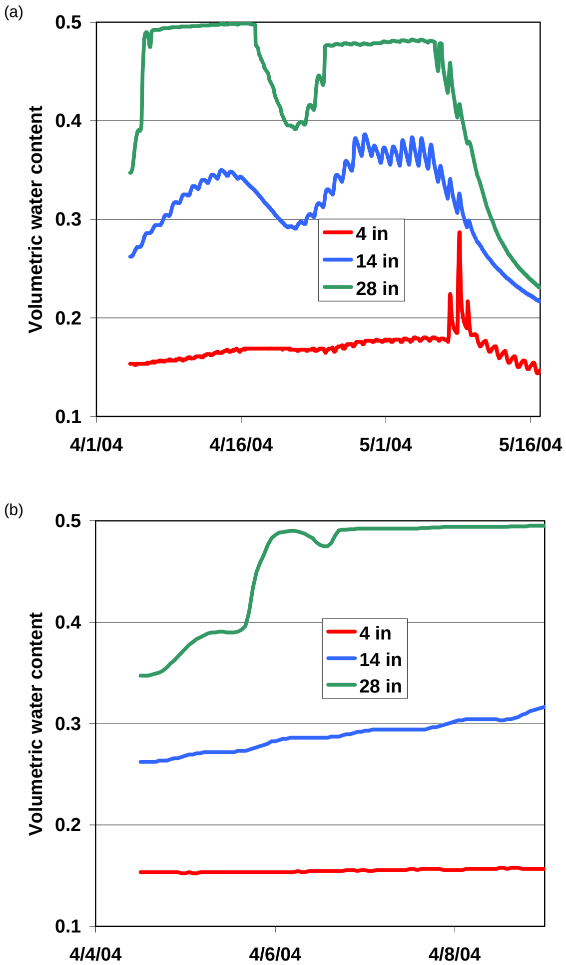

Figure 5. Detailed soil water content for springtime snowmelt for (a) the month of April 2004, and (b) for April 4-8, 2004.

Soil matric potential is shown for the same 3 depths and supports the interpretation of saturated conditions as the bottom 2 depths reach -0.01 bars. The 14-in depth likely had hysteretic conditions and air entrapment resulting in less than full saturation.

Soil water retention characteristics are shown in *Figure 7* for laboratory measurements and field measurements, illustrating possible hysteresis in the field observations, but also providing relative confirmation of laboratory measurements. The 3 soil depths are very similar in their retention characteristics with the exception of the 4-inch field data. It appears that the TDR data at 4 inches may be too low causing a shift in the field water retention curve, which also suggests possible errors in the TDR measurement. The laboratory derived water retention curves were used in the numerical simulation.

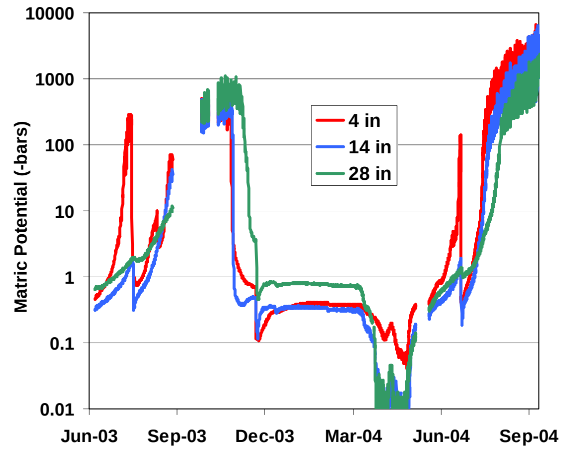

Figure 6. Soil water potential for June 2003 through September 2004 at 3 depths.

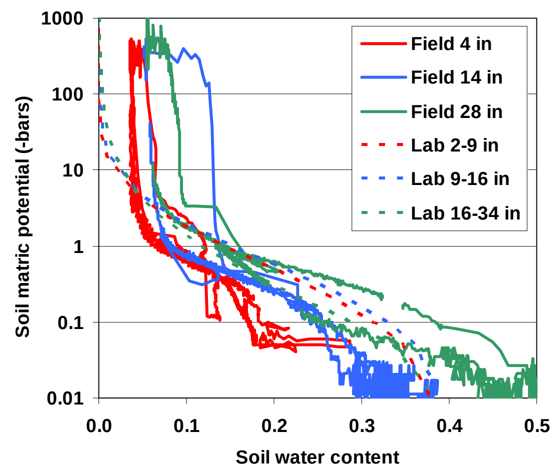

Figure 7. Laboratory and field water retention curves for soil at 3 depths.

Soil temperature measurements at the 3 depths (*Figure 8*) illustrate when the site was snow covered as exemplified by the drop in temperature and lack of daily fluctuations. The onset of spring snowmelt can be seen as a sharp rise in temperature accompanied by distinct daily fluctuations, indicating lack of snowcover.

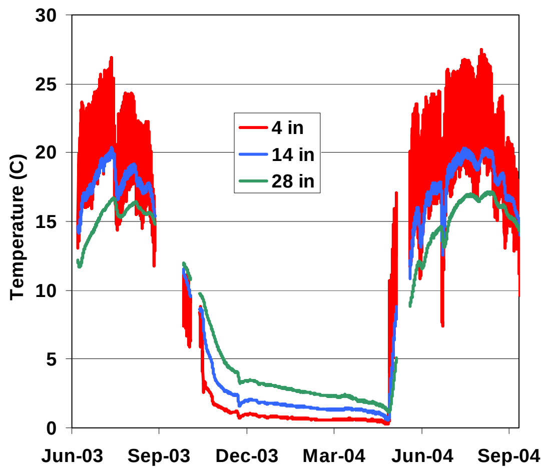

Figure 8. Soil temperature for June 2003 through September 2004 at 3 depths.

To test the hypothesis that the soil heat flux was contributing to the melting snowpack from below, soil heat flux was calculated from soil temperature measurements between the 4-in and 14-in depths and between the 14-in and 28-in depth (*Figure 9*). Flux of heat moving upward from the ground into the snowpack, shown for the November to May period where the flux has no diurnal fluctuations, is approximately 5-10 W/m^2. This small heat flux is considered to be an insignificant contributor to snowmelt at this location.

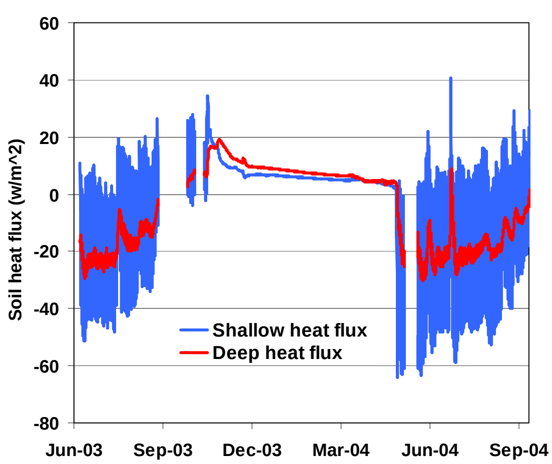

Figure 9. Soil heat flux calculated from soil temperature measurements for shallow soil (4-14 inches), and deep soil (14-28 inches).

Calculations of changes in soil moisture indicated that there was approximately 14 inches of soil water storage capacity, and approximately 12 inches of water stored at the maximum wetness during the study period. It appeared that the soil moisture input remained stable under frozen snow and allowed for drainage, and that melting snow percolated through the coarse textured soil at the soil field capacity.

During the period of April 7-14, 2004, when snowmelt had ensued, the infiltration from snowmelt into the 30-cm deep loamy sand was calculated to be approximately 35 mm/day, which exceeded the permeability of the bedrock and caused ponding to be sustained at the soil-bedrock interface during the snowmelt period. During a subsequent 7-day period with no measured snowmelt, drainage into the underlying fractured granitic bedrock was estimated to be 16 mm/day.

Uncertainties in calculations of bedrock infiltration are a result of the uncertainty in local slope conditions that could impact heterogeneities in lateral flow at the soil-bedrock interface. If the site had a slight but consistent slope, lateral flow occurring would enter the measurement domain at the same rate that it left, resulting in no net changes in water content and more accuracy in the estimate of bedrock infiltration, assuming enough upslope water availability.

Model Results

The 1-D model was run for 3 months, March 14 – May 14, 2004 to simulate the snowmelt period (*Figure 10*). The model shows reasonable agreement at the 28-inch depth but shows higher than measured water contents at 4 and 14 inches. It should be noted that the measured 4-inch data in *Figure 10* is not the same as that in *Figure 7*. The measured HDP data for the 4-inch depth were converted to water content using the laboratory measured water retention curve to replace the assumed bad TDR data from that depth. It can be seen that model simulations mimic the slow melt, followed by fast melt, then no melt (refreezing conditions, the continued melt for the 3 soil layers for this period of time). Although the match is not as good was we would like we believe the process of ponding and draining at the bedrock interface is in reasonable agreement with the field data.

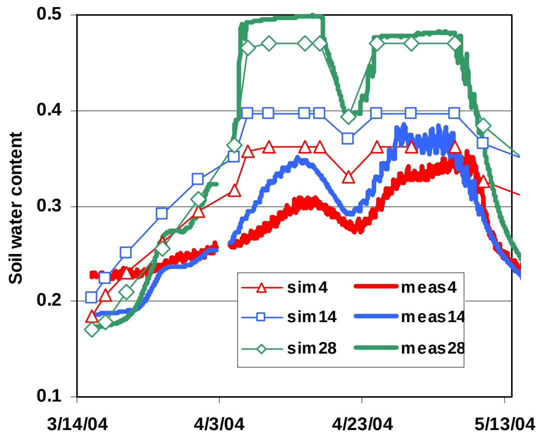

Figure 10. Measured and simulated soil water content for 3 months during springtime snowmelt for 3 soil layers.

To better understand the melt/pond/drain process, hourly simulation output was evaluated for the 4 days representing the initiation of the melt sequence, April 5-8, 2004 (*Figure 11*). The simulation does a reasonable job of reproducing the diurnal signature of the melt/pond/drain process, however, we never attain full saturation. This preliminary model result will be further tested with more rigorous modeling when the field data from this year (2006) become available.

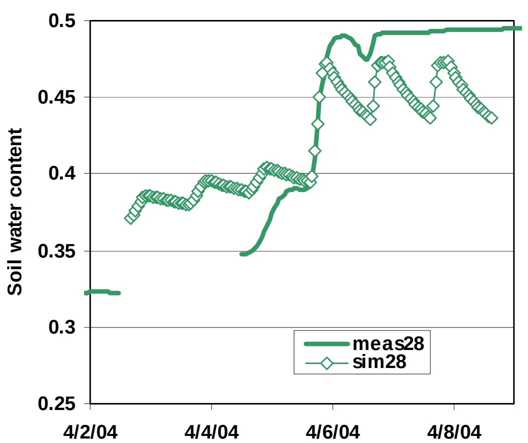

Figure 11. Measured and simulated soil water content for the 28-in soil depth for April 5-8, 2003 during the initiation of the snow melt sequence.

One hypothesis tested was the possibility that lateral flow was actually causing the drop in water content at the bedrock interface and that no infiltration into the bedrock was occurring. To test this hypothesis a scenario investigating the effect of sloping bedrock on soil water content fluctuations was done and is illustrated in *Figure 12* for a 2-D model simulation with a 5% slope.

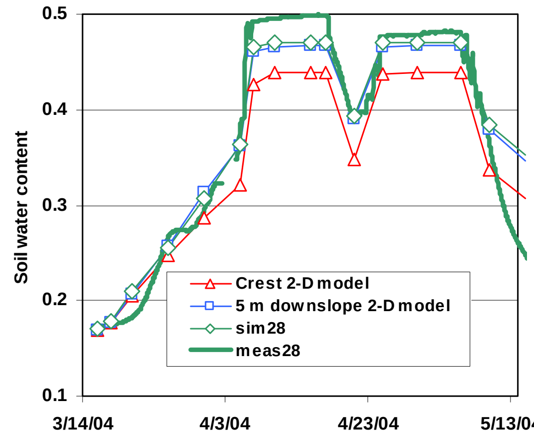

Figure 12. Results from a 2-D simulation with a 5% slope.

One assumption in this analysis was that the instruments were on the "crest" of a local subsurface bedrock divide and that all infiltrating water was moving away from the instruments with no inflow from up gradient. Even under this assumption there is a small drop in water content under the melting condition that is far exceeded by the no-melt drainage seen on the 20th of April. This supports the contention that field observations of local slope were not this heterogeneous. The second scenario of lateral flow away from the measurement site resulting in the decline in the soil water content (interpreted as bedrock infiltration), indicates no such result. With only 5 m of up-gradient contributing area, the amount of inflow equaled the amount of outflow along the soil-bedrock interface. Field observations, including ground penetrating radar measurements (not presented in this paper) could not identify a possible bedrock divide further supporting the hypothesis that infiltration into the bedrock was occurring under the snowpack at the instrumented site. A 2-dimensional representation of the model domain illustrating volumetric water content results for the 2-D simulation is shown in *Figure 13*, including flux vector direction. Vertical flow still dominates at the soil/bedrock contact, however, the no-flow boundary condition at the downslope boundary is influencing the flux direction from 7 to 10 m.

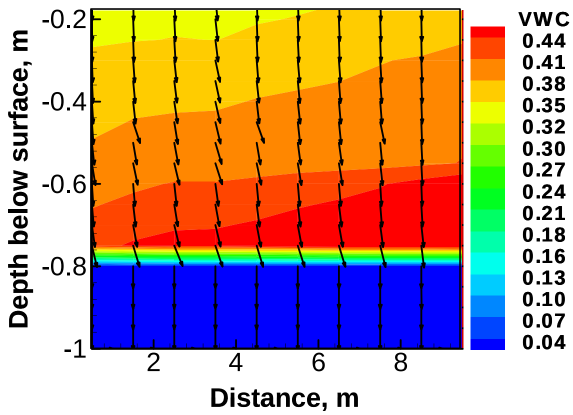

Figure 13. Two-dimensional representation of 2-D simulation showing volumetric water content (VWC) and flux vector direction on 4/17/2006 (horizontal to vertical was compressed 10:1, however flux direction vectors remained 1:1).

SUMMARY

Soil moisture field data were collected under a melting snowpack at Gin Flat in Yosemite National Park. A conceptual model was developed that suggests that as the snow melts it infiltrates into the soil and percolates vertically downward until it contacts the soil-bedrock interface. As the snow melt and soil infiltration rate exceed the bulk bedrock permeability, the soil-bedrock interface eventually becomes saturated, ponds, and starts to infiltrate into the bedrock fracture system. As the snow pack refreezes at night the soil water continues to drain at the bedrock permeability rate until the next morning when the snowpack again begins to melt, resulting in diurnal changes in soil water content. This cycling continues until the snowpack is gone. There is the potential for some lateral flow to be occurring during this time but the flow away from the instruments is replaced by snowmelt from up gradient. Numerical modeling in 1- and 2-dimensions supports this hypothesis and generally reproduces the diurnal and seasonal signatures. Further data collection in 2006, along with additional refinement of the numerical model will be used to refine and support the conceptual model of snowmelt and soil processes.

FUTURE WORK

The preliminary modeling analysis provides insight into further field efforts and additional modeling analysis. The results of the model are sensitive to the fracture properties of the underlying bedrock and the timing and duration of snow melt. Additional analysis of snow pack measurements is required to better define the snowmelt and refreezing. This upper boundary condition is the least known and may require an independent numerical model of snow accumulation, melt, and refreezing. In addition, the hydrologic properties of the bedrock are not well defined and additional field measurements or observations are needed to provide a better rationale for the properties used in the model. The 2006 water year is providing a very heavy snow pack and will undoubtedly provide a wealth of soil moisture data that will allow for a more rigorous modeling exercise and testing of additional conceptual models.

CITATIONS

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