the displacement height and roughness length for momentum are respectively 68% and 9.4% of the average height of the tree canopy, which are similar to percentages found in the literature. The calculated roughness length for sensible heat is 6.4% of the average height of the tree canopy, a little higher than the percentage documented in the literature. When wind direction was aligned within 5 degrees of the row direction of the trees, the average displacement height calculated was about 0.5 m smaller than when the wind blew across the row direction. This difference was statistically significant at the 0.0005 probability level. This implies that when the wind blows parallel to the row direction, the logarithmic profile of wind speed is shifted lower to the ground, so that at a given height the wind speeds are faster than when the wind blows perpendicular to the row direction.

H13B CC: 520 C Monday 1330h

Tracers in Hydrology I

Presiding: **B L McGlynn,** Montana State University; **M Weiler,** University of British Columbia

H13B-01 1330h

Can the Paradox of Pre-event Water Domination in Subsurface Flow Despite Rapid Flow Response and Solute Transport in Preferential Flow Pathways be Solved?

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Despite numerous hillslope experiments at different sites around the world, the influence of lateral preferential flow in the subsurface on runoff generation is still unresolved. Many experiments have shown a paradox of fast transport of artificially applied tracers and a rapid subsurface runoff response with an associated contribution of predominantly pre-event water in the chemically separated hydrographs. Using the recently introduced virtual experiment approach we aim to provide a theoretical, but experimentally driven solution to this paradox. The two main causes for lateral preferential flow on hillslopes are macropores/pipes and bedrock topography. We explore the effect of both features using the Hill-Vi model, which focuses on lateral subsurface flow simulation within the matrix and macropores including solute transport. The simulations show how observed bedrock topography and macropore properties in combination with measured soil properties will alter the response characteristics of flow and transport at the hillslope scale. Compared to a hillslope without preferential flow, subsurface runoff at the base of the hillslope responds quicker, artificially applied tracers are transported much faster, but the event/pre-event water ratio remains the same. The simulated patterns of preferential flow networks within the hillslope show how the interconnection of certain regions within the hillslope due to preferential flow will enhance the flow and transport response, but doesn't change the mixing behaviour of event and pre-event water.

URL: http://marrkus.2hydros.de

H13B-02 1345h

Quantifying New Water Contributions to Stormflow in an Urban Watershed Using Electrical Conductivity and Isotopic Tracers

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Decreased permeability associated with urbanization is known to alter the hydrologic response of streams and rivers to rainfall. We suggest that electrical conductivity (EC) is a simple and cost-effective tracer for determining the direct contribution of precipitation and surface runoff (e.g. new water) to urban streams during rainfall events. Urban watersheds may be ideally suited for EC-based hydrograph separations because (1) storm runoff is often dominated by two sources of water (groundwater and surface runoff) and (2) end-members are typically characterized by large differences in EC values. We therefore evaluate the use of EC as a tracer for two-component hydrograph separation during 13 rainfall events (2001 and 2002) in a 3.9 km2 urban catchment in Massachusetts (25% impervious). EC-based results are compared against isotopic (deuterium) hydrograph separation results for two storms as validation. Precipitation EC values for our 13 rainfall events were significantly lower (12-46 uS/cm) than stream baseflow EC values (520-1297 uS/cm), contributing to less than 8% uncertainty in our hydrograph separations. The direct input of new water, presumably as direct runoff from impervious surfaces, accounts for 70-90% of the elevated discharge during most storms. Since using EC allows for characterization of a large number of storms, we were also able to assess the role of precipitation characteristics and watershed moisture on new water runoff variability between events. Total rainfall volume explains 72% of the variability in new water runoff volumes and is only slightly improved by including an indicator of antecedent moisture in a multiple regression (r2=0.77). In all but one event, 4-11% of the total storm rainfall volume appeared as new water in the stream, suggesting that less than half of the watershed impervious area is hydrologically connected to the stream. The remaining impervious surface runoff either infiltrates pervious surfaces or is exported out of the watershed via the storm drainage network. Understanding the role of impervious surfaces in delivering rapid runoff to streams is critical for hydrologic modeling in urban areas, as well as for assessing the fate of urban pollutants.

H13B-03 1400h

Validation of Hydrological Models Using Stable Isotope Tracers.

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The delineation of source areas for groundwater recharge is the first step in protecting groundwater resources as a source of water for human consumption and ecological preservation. To accomplish this task, a thorough understanding of water pathways from precipitation to streamflow is required. The rainfall-runoff process can be modelled using hydrological models, in which conservative tracers can be incorporated and used to disaggregate streamflow into its various origins and pathways. The measurement of naturally occurring isotopes in streamflow can then provide a relatively simplistic and inexpensive validation tool by verifying that flow paths and residence times are being correctly modelled. The objective of this research is to validate flowpaths in hydrological models by comparing modelled conservative tracers to measured isotopic data, where it is available. A tracer module has been integrated with the WATFLOOD model; a fully distributed, physically based, meso-scale hydrologic model for watersheds having response times larger than one hour. Conservative tracers are used to track water through the model by quantifying and segregating the various contributions to the total streamflow. Groundwater flow separation is accomplished using simplified storage routing of groundwater through the subsurface and into the stream. A specified concentration of tracer is added to the groundwater at its origin and upon reaching the stream; a mass balance is performed to determine the concentration of tracer in the stream, allowing for a separation of groundwater from streamflow. Other flow tracers have also been modelled, including ones for surface water, interflow, flows from different landcovers, and flows from different sub-basins. Validation of the WATFLOOD models flowpaths will be made using the flow separation tracers and measured isotope data from the lower Liard River Basin near Fort Simpson, Northwest Territories. Examples of flow separations using additional tracers will be presented for the Grand River watershed, where isotope data is not yet available for validation purposes, but other baseflow separation techniques have been applied and can be used for comparison.

H13B-04 1415h

Contribution of Tracers in an Interdisciplinary Characterization of Hard Rock Aquifers in a Complex Middle Mountain Environment: the Ringelbach Research Catchment (High-Vosges, France)

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In the granite Vosges massif, affected by tectonic fracturing, water is mainly supplied by small aquifers in weathered and fissured hard rocks, whose geometry and hydrodynamic properties control water pathways but are still little known. An interdisciplinary characterization of the structure and functioning of these complex aquifers has been implemented in the small Ringelbach research catchment (36 ha; 1000-750 m a.s.l.; weathered granite partly covered by Triassic sandstone), which is studied since 1975 and is well representative of this type of environment. In addition to climato-hydrological monitoring, geological surveys and geophysical prospecting (electrical and magnetic resonance soundings, resistivity imaging profiles), the time and space variability of hydrogeochemical data has provided useful tracers: (1) pluri-annual isotopic (^{18}O, ^{2}H) signals in precipitation, main springs and stream, to estimate residence times and reservoir volumes; (2) hydrochemical surveys (major and trace elements) in springs and streams within and nearby the catchment in low and high water conditions, to identify the different reservoirs from their hydrochemical fingerprints. Preliminary results using these tracers show: (1) no influence of evaporation on isotopic signals in this densely vegetated catchment, and rather long mean residence times (more than one year) and large mixing reservoirs even within such small aquifers, whose contrasted dynamics combine fast and slow components and involve only one part of these reservoirs; (2) a clear hydrochemical differenciation according to lithology (granite waters being more concentrated than sandstone waters), and rather large variations between 2 end-members within each lithology (especially, increasing mineralization with decreasing spring altitude along granitic hillslopes). Combined with geophysical results, tracers results seem to confirm the weathering and structural model suggested by geological surveys: a stratified vertical profile of ante-Triassic granite weathering, which has been more or less eroded within the catchment depending on the relative elevations of its several fault-separated blocks. This new geological model, which could be transposed at the massif scale, will be useful to improve catchment hydrological modeling and water resource management tools.

H13B-05 1430h

Application of a Two-Storage Zone Model to Characterize Transport and Reaction of Solutes and Solute Tracers in Streams and Wetlands

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Natural streams and wetlands exchange water and solutes between the main flow zone and a complex assemblage of "transient storage" zones that include stagnant water in pools, areas of flow recirculation, and subsurface flow paths through bed sediments and deeper alluvial sediments. Exchange between faster moving waters of the main flow zone and the slowly

moving waters in storage zones results in delayed downstream transport of solutes, relative to what would be predicted from velocity measurements in the main flow zone. The transient storage concept is useful particularly for understanding the fate and transport of contaminants in streams, such as nutrients and metals, because solutes transported into storage zones come in close contact with reactive substrates such as sediment, periphyton, and macrophyte leaves. Delayed transport and characterization of transient storage zones can be quantified with solute tracer injections and modeling. Many of the widely used stream transport models that consider transient storage, such as the OTIS-P model (Runkel, *USGS WRIR 98-4018*, 1998), use only a single storage zone (i.e., linear reservoir with exponential residence time distribution) to account for transient storage. Choi et al. (*WRR*, 36:1511, 2000) showed that a model with two independent storage zones improved the characterization of transient storage in systems having both slow' and fast' exchange zones while retaining an appropriate level of model simplicity. We modified the OTIS-P model to include the option of simulating transport by allowing for exchange with two independent storage zones. The new model package, called OTIS-2Stor, also incorporates new options for weighting tracer concentration measurements while estimating the parameters of the model using the same non-linear least squares regression routine that is included in OTIS-P. Our experiences in headwater channels of Indiana and in the Florida Everglades demonstrate that, if used in conjunction with high quality tracer data sets, the OTIS-2Stor model package can reliably identify the sizes and fluid residence times of two storage zones in complex natural channels and wetland environments.

H13B-06 1445h INVITED

Watershed Residence Time and the Role of Topography

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In the past few decades, tracers have provided some of the most important insights into hydrological processes; from definition of groundwater and surface water age, to hydrograph source components, to descriptions of water flow pathways at the watershed scale. The age, or residence time of water is an integrated descriptor of watershed hydrology, revealing information about the storage, flow pathways and source of water in a single measure. Residence time offers a linkage to water quality, since the contact time in the subsurface largely controls stream chemical composition. While there has been tremendous recent interest in residence time estimation to characterize watersheds, there are relatively few studies that have quantified residence time at the watershed scale, and fewer still that have extended those results beyond single watersheds to larger landscape scales. We examined topographic controls on residence time for seven watersheds that range in basin area from 10 ha to 6200 ha and represent diverse geologic and geomorphic conditions in the western Cascade Mountains of Oregon. We found that baseflow mean residence time, estimated using stable isotope tracers, ranged from 0.8 to 3.6 years. Like in our previous work in other watersheds, there was no relationship with basin area. We then developed relationships between mean residence time and simple watershed terrain indices and found that mean residence time is highly correlated (r = 0.96) to the flow path distance and gradient. This illustrates that landscape organization (i.e., topography), as opposed to watershed size controls transport. Results from this study may provide a framework for describing scale invariant transport across climatic and geologic conditions, whereby the internal form and structure of the basin defines the first order control on baseflow residence time. These findings may present new opportunities for watershed classification and regionalization based on seemingly simple internal topographic descriptors.

H14A CC: 520 A Monday 1530h

Merging Soil Physics With Geophysics and Remote Sensing: Spatial and Temporal Variations in Shallow Soil Processes and Properties

Presiding: **R M Holt,** University of Mississippi**; C J Hickey,** University of Mississippi**; B Mohanty,** Texas A&M University

H14A-01 1530h

Soil Variability Measurements Via Acoustic to Seismic Coupling

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We use acoustic to seismic (A/S) coupling to study soil variability at the field scale with particular attention on delineating the depth to the fragipan, a shallow high strength layer which has important consequences for soil productivity. Acoustic waves from a loudspeaker are used to excite the ground in the form of seismic energy. These seismic waves (recorded by a geophone at the air-earth interface) contain information, via reflected waves, about the underlying subsurface layer boundaries. In theory, seismic resonances can be set up between the soil and the onset of the fragipan, a soil layer with very high strength and low water conductivity. By recording the A/S coupling versus frequency at many points within an agricultural field, we show how these resonance compare to actual measurements of the fragipan depth, and discuss how this technique can be used to quickly measure fragipan depth.

H14A-02 1545h

Impact of Soil Hydraulic Parameter Distributions on Upscaling for Steady State Flow in Heterogeneous Soils

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In this study, we investigate effective soil hydraulic parameter averaging schemes for steady state flow in heterogeneous soils. Our focus is on the impact of hydraulic parameter distributions and domain scales on the effective hydraulic parameters. “Effective” soil hydraulic parameters of the heterogeneous soil formation are obtained by conceptualizing the soil as an equivalent homogeneous medium. It requires that the “effective” homogeneous soil will discharge the same ensemble-mean surface flux. Using Gardner's unsaturated hydraulic conductivity model, we derive the effective value for the parameter α. Skewness is found to be important in determining the averaging schemes. Negative skewness greatly enhances heterogeneity effects, which make the optimal averaging schemes for the α parameter deviate more from the arithmetic mean. Scale impact on the averaging schemes is more significant as the fractal dimension increases.

H14A-03 1600h

Radiometric Sensitivity to Soil Moisture at 1.4 GHz Through a Corn Crop at Maximum Biomass

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It is generally assumed that brightness at 1.4 GHz is usefully sensitive to soil moisture only up to a certain level of canopy biomass. We have found that this is not true for a corn canopy. We accomplished this by analyzing time-series measurements of 1.4 GHz brightness, soil moisture, and relevant micrometeorology, all of high temporal resolution, made on the plot-scale for a corn canopy at maximum biomass. Our approach was unique: remote sensing studies typically replicate satellite measurements, in which discrete measurements are made at isolated points in time. Our method of integrating nearly continuous observations of brightness, micrometeorology, and soil state revealed how these variables change together as a result of their interdependencies. This method can be used to identify subtle physical processes that might otherwise be hard to find, much like using the context of a sentence to decipher an unknown word as opposed to only examining the word itself. One of the notable features of our experiment was our measurement of surface soil moisture. Buried TDR instruments, calibrated in-situ with periodic, hand-held impedance probe measurements, produced continuous observations of 0-3 cm and 3-6 cm soil water content. The impedance probe measurements themselves were calibrated with gravimetric samples and bulk density measurements. Two different temperature corrections were applied to the TDR measurements. Each method fit the data well and it was impossible to determine the true temperature correction. Both temperature corrections were considered in the final analysis. We found that there is useful radiometric sensitivity to soil moisture at 1.4 GHz through a corn canopy of vegetation column density 8 kg m-2 (water column density of 6.3 kg m-2). The magnitude of the measured sensitivity of horizontally-polarized brightness temperature to the 0-3 cm volumetric soil water content was at least 1.5 K per 0.01 m3 m-3, and could have been as high as 2.5 K per 0.01 m3 m-3. Vertically-polarized brightness temperature was 0.5 K per 0.01 m3 m-3 less sensitive than horizontally-polarized brightness temperature. A widely-used radiative transfer model underestimated this soil moisture sensitivity at horizontal polarization by over 1 K per 0.01 m3 m-3. We hypothesize this is because the water in a corn canopy is concentrated in stems and ears and not spread evenly over the canopy volume as assumed by the model, and as it effectively is in vegetation with electrically small components like grass. Enhanced backscatter from such scattering canopies has been observed in radar experiments. There may be a similar effect in radiometry. It is also possible that this “backscatter effect” could itself be enhanced when the vegetation canopy constituents are wet, and hence more reflective, when intercepted precipitation or dew is present. Given an appropriate emission model that correctly accounts for the differences in transparency between corn and grass-like canopies and/or an enhancement of soil moisture sensitivity through volume scattering, it appears that there will be practical sensitivity to soil moisture through corn (and most, if not all row crops) throughout the growing season.

URL: http://www.public.iastate.edu/~bkh/

H14A-04 1615h

The Use of Multispectral Imagery to Detect Variations in Soil Moisture Associated Shallow Soil Slumps

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Spatial variations in soil moisture have previously been linked to the process of soil aging and can contribute to mass wasting in slopes rich in clay. We use remote sensing imagery to assess variation in soil moisture. Our investigation includes compacted clay soils of the levees along the Mississippi River maintained by the Mississippi Levee Board. Shallow soil slumps are associated with aging of levee soils composed of clay of high plasticity. Continued exposure to seasonal fluctuations in groundwater conditions has contributed to this aging process, causing the soils to become increasingly fissured and stiff. This aging process also alters the moisture retention characteristics of the soil, providing a property contrast that we identified using multispectral imagery. Airborne multispectral imagery was collected along sites with limited vegetation cover (almost bare soil) along with direct measurements of soil water

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