New Method Developed for Studying Flow on Hillslopes

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Hillslope hydrologists have long assumed that the downslope movement of water and solutes can best be described by surface topography since gravitational potential largely dominates hydraulic gradients in steep terrain. Hence with the increased availability of Digital Terrain Maps (DTMs), surface topography is driving many popular hydrological models and is being used to estimate flow pathways in hydrological and geochemical models. This method may suffice at the catchment scale, but at the hillslope scale, flow pathways are not always determined by surface topography.

It is at this critical scale (100–10,000 m^2) that water flux and the chemical composition of soil water and groundwater can be measured as they move downslope. The complex interactions between water and solutes along hillslope subsurface flow paths have not been well documented. New evidence suggests that for steep hillslopes with thin soils, the fundamental control on hillslope flow paths is the bedrock surface.

The bedrock surface often characterizes the impeding layer at which water tables

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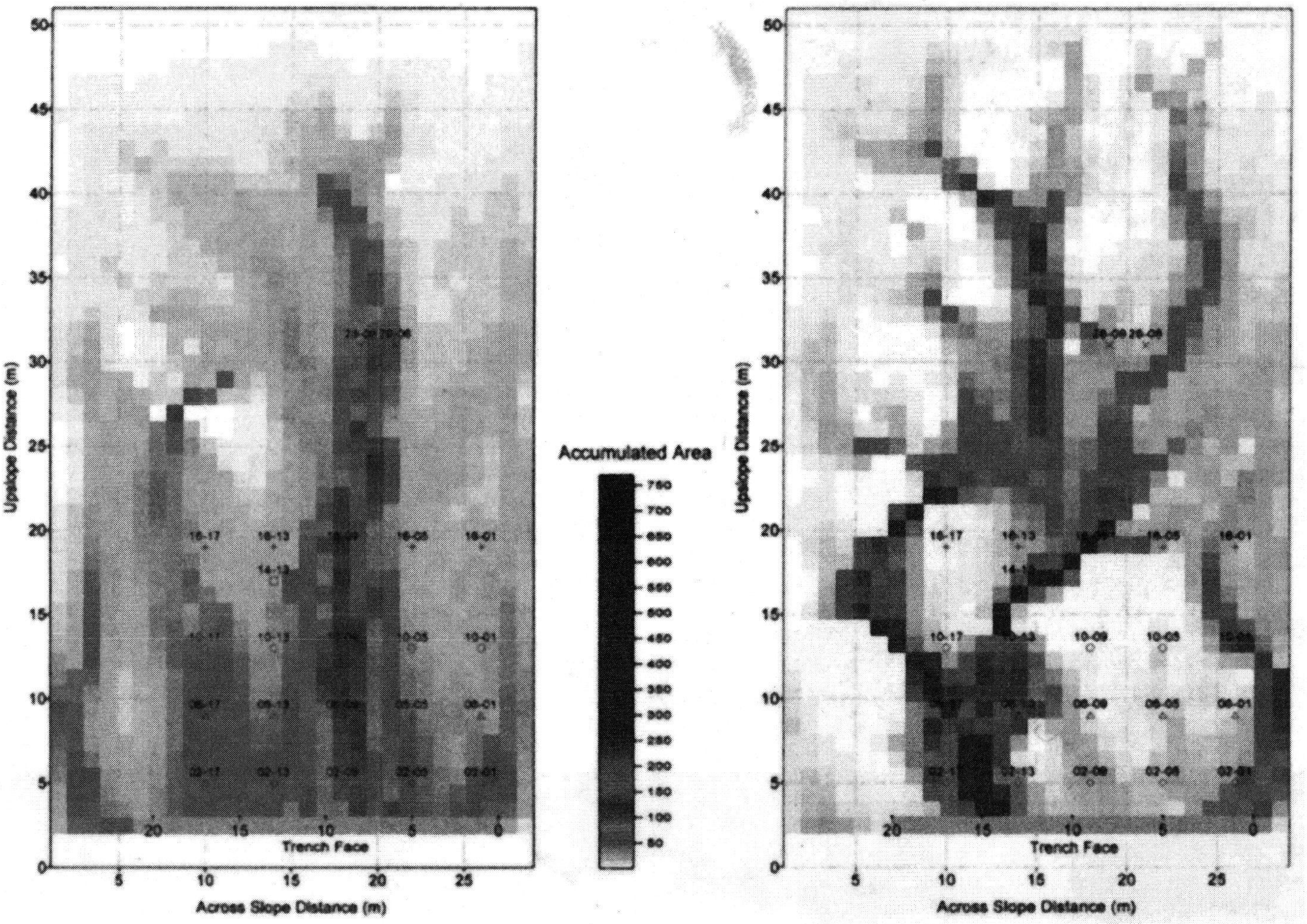

Fig. 1. Plan-view maps of the 20 × 48 m hillslope being studied at the research watershed in Panola Mountain, Ga. Plots show two different "hydrologic surfaces" using an accumulated area multiple flow direction algorithm to calculate the ln (a/tan b) index: the left-hand plot shows the surface based on topography; the right-hand plot shows the bedrock surface. The trench is shown in gray at the downslope portion of the hillslope. The color scale denotes increasing accumulated area from light (low accumulated area) to dark (high accumulated area). The symbols on the slope identify tensiometer positions. Original color image appears at the back of this volume.

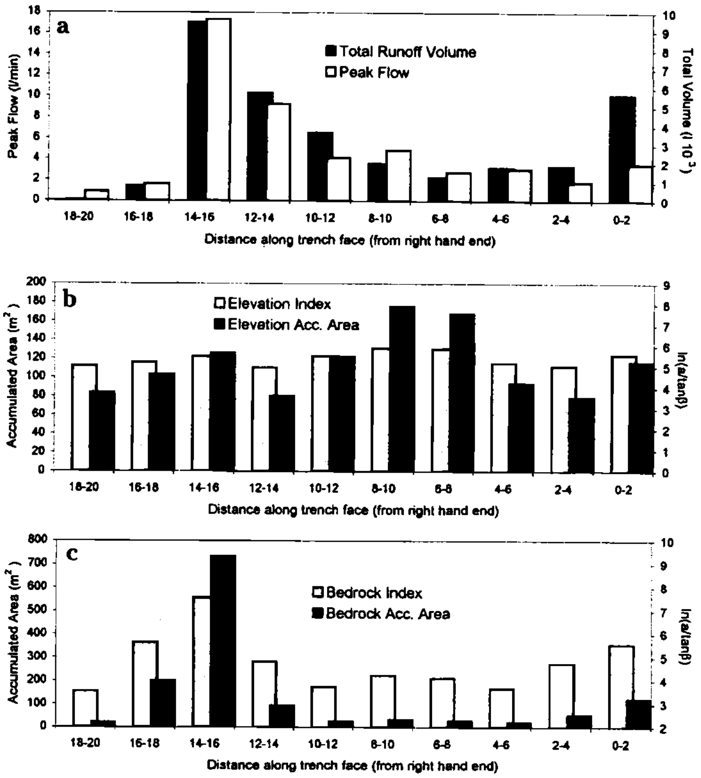

Fig. 2. Histogram plots from the hillslope at the Panola Mountain research watershed trench face. a) Runoff information from each 2-m trench section is plotted in and clearly shows the dominance of flow from the bedrock flow path at troughs 14–16. Accumulated areas are shown for b) the topography-based index and c) the bedrock index. The bedrock index is closely related to flow distribution at the trench.

develop during rain and snowmelt events. Consequently, this is where large amounts of subsurface flow are produced. Despite the fact that the bedrock surface may be different than the surface topography, it has not previously been used in hillslope modeling approaches.

An intensive field and modeling campaign was begun in January 1996 at the Panola Mountain research watershed in Georgia. Panola is one of five Water, Energy and Biogeochemical Budgets (WEBB) sites operated by the U.S. Geological Survey [*Lins*, 1994] where researchers are identifying subsurface hydrological flow paths and the resulting chemical and isotopic compositions of associated soil water, groundwater, and streamflow. The project is a unique collaboration between the National Science Foundation, U.S. Geological Survey, and universities in the United States (the State University of New York's College of Environmental Science and Forestry) and abroad (University of Lancaster, England).

The role of surface topography in controlling hillslope runoff processes has received much attention over the past 2 decades. Early work focused on the effects of convergent hollows in generating enhanced subsurface flow and saturation overland flow [*Anderson and Burt*, 1978], the nature of saturated wedge development [*Weyman*, 1973], macropore flow [*Mosley*, 1982], and hillslope runoff production [*Dunne and Black*, 1970]. Today, concerns about the biogeochemical controls of nonpoint source pollutants such as acid deposition and agricultural chemicals are driving hillslope hydrologic studies.

The hydrological flow paths through the hillslope must be understood before we can determine what soil/rock units may be leached by infiltrating waters and the residence time of the water in the hillslope. Interpretations of hydrological processes on hillslopes have often been refuted or questioned after analysis of soil solutions has contradicted perceptions of flow path, age, and mixing [e.g., *Brammer and McDonnell*, 1996]. The need for a more precise description of water movement has hydrologists reexamining their ideas about hillslope flow; the study at Panola Mountain seeks to understand its spatial and temporal nature.

Experiment at Panola Mountain

A 20-m-long trench was excavated down to saprolite bedrock (0.4–1.8 m) at the base of a 20 × 48 m hillslope in the Panola catchment, based on the design of *Woods and Rowe* [1996] at Maimai, New Zealand. A grid of instrumentation on the slope recorded soil water potentials and enabled chemical sampling in time and space. The trench was divided into ten 2-m sections so that water arriving at each section could be routed through a tipping bucket and sampled for major anions, cations, and oxygen-18. The hillslope and the instrumentation were surveyed, and the depth to the bedrock surface was obtained. Both surface and bedrock topographies were used to compute the hillslope ln(a/tan b) index, where a is the upslope contributing area to a point and tan b is the local slope angle. This index has been used as a measure of hydrological similarity [*Beven and Kirkby*, 1979], and the pattern of the index can be used to indicate the propensity of a point to become saturated. The related flow path information was used to test whether or not the downhill flow of water was controlled by surface topography or bedrock surface topography.

Figure 1 shows the two computed surfaces (topographic and bedrock) for the 20 × 48 m hillslope; a multiple flow direction algorithm was used to calculate the ln(a/tan b) index. The downslope distribution of the accumulated area of each cell is controlled (weighted) by the local topographic gradients. The color scale denotes increasing accumulated area from light (low accumulated area) to dark (high accumulated area). The surface topography of the accumulated area shows a clear and dominant "flow path" straight down the hillslope to buckets 6–10.

In contrast, the bedrock-computed surface shows two distinct "snaking" flow paths converging approximately 10 m above the trench face and flowing to buckets 14–16. These different flow paths present alternative routes for hillslope hydrologic flux. Water flow volume captured at the trench face and its age and chemistry are used to "test" which pathway controls flow. Furthermore, spatial and temporal changes in soil water potential on the hillslope should be related to patterns in flow at the trench face.

Flow was collected and analyzed from the trench sections after several rainfall-runoff events in February and March 1996. Flow from the hillslope base and upslope water table was controlled by the bedrock surface. Figure 2a shows the flow distribution for individual troughs during an event on March 6, 1996. At troughs 14–16 (the predicted bedrock controlled flow path), flow was 85% greater than that at any other slope sections in terms of total runoff volume and peak flow. The surface topography-inferred flow path (troughs 6–10) carried much less flow and did not appear to differ much from neighboring trough sections. Accumulated areas at the trench face were derived for surface topography and bedrock topography; these values are shown in Figures 2b and 2c, respectively. Upon examination, these data along with the flow data are striking; they show that the bedrock index and the bedrock accumulated areas closely resemble the distribution of saturation on the hillslope and flow at the trench face. The index histograms represent the downslope accumulation of the values plotted spatially in Figure 1. These data provide compelling evidence that the bedrock surface controls downslope movement of water at the hillslope scale.

The complete results of this work including chemistry, hillslope tensiometry, and work with TOPMODEL will be presented in sessions at the Fall Meeting, **Hydrological Processes in Headwater Catchments (H71E, H72B**, and **H11C)** and **Spatial Processes and Scaling: Merging Field Data Collection Methods and Distributed Modeling (H21D** and **H22A)**.

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References

Anderson, M. G., and T. P. Burt, The role of topography in controlling throughflow generation, *Earth Surf. Proc., 3*, 331, 1978.

Beven, K., and M. J. Kirkby, A physically-based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull., 24*, 43, 1979.

Brammer, D. D., and J. J. McDonnell, An evolving perceptual model of hillslope flow at the Maimai catchment, in *Advances in Hillslope Processes*, vol. 1, edited by M. G. Anderson and S. M. Brooks, pp. 35-60, John Wiley, New York, 1996.

Dunne, T., and R. D. Black, Partial area contributions to storm runoff in a small New England watershed, *Water Resour. Res., 6*, 1296, 1970.

Lins, H., Recent directions taken in water, energy and biogeochemical budgets research, *Eos Trans., AGU, 75*, 433, 1994.

Mosley, M. P., Subsurface flow velocities through selected forest soils, South Island, New Zealand, *J. Hydrol., 55*, 65, 1982.

Weyman, D. R., Measurements of the downslope movement of water in soil, *J. Hydrol., 20*, 267, 1973.

Woods, R., and L. Rowe, Consistent temporal changes in spatial variability of subsurface flow across a hillside, *J. Hydrol.*, in press, 1996.

Space Shuttle Views Changing Carbon Monoxide in Lower Atmosphere

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During April and October 1994, the Space Shuttle Endeavor flew missions expressly to study Earth's surface and atmosphere. Among the instruments aboard the shuttle was the Measurement of Air Pollution from Satellites (MAPS) Experiment, which measured carbon monoxide in the middle troposphere. While the spacecraft was in orbit, the flight crews photographed the planet with a variety of cameras and films. Concurrent aircraft and ground-based measurements of CO were made at a number of locations between northern Alaska and the edge of the Antarctic continent.

The combination of the middle tropospheric CO from MAPS and measurements made from the ground and from aircraft provide a unique picture of carbon monoxide in the lower atmosphere. Never before has such extensive knowledge of the CO distribution been obtained.

The Measurement System

Many atmospheric trace gases, including CO, exhibit absorption spectra in the infrared portion of the electromagnetic spectrum. Each gas absorbs and emits radiation in very narrow lines whose center wavelengths and strengths are unique to a particular gas. The pattern of these lines is, in effect, a "fingerprint" that reveals the presence of the gas in the atmosphere. The MAPS instrument measured the outgoing, planetary thermal radiation at 4.67 μm, the fundamental wavelength of CO. To determine the amount of CO in the atmosphere, we used gas filter correlation, a technique that is based upon the signal difference between optical cells containing different gases or gas concentrations. The data reduction procedure used in 1994 to determine the atmospheric CO mixing ratios was a refined version of that described by *Reichle et al.* [1986, 1990].

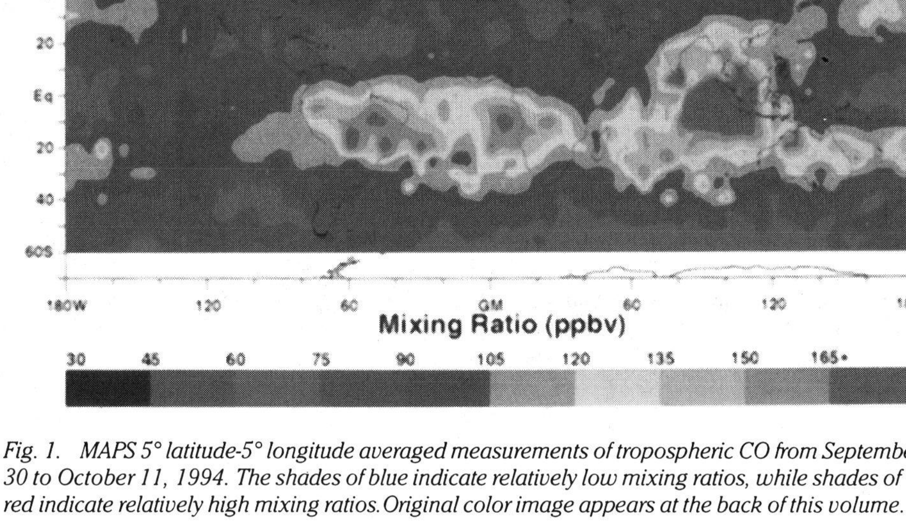


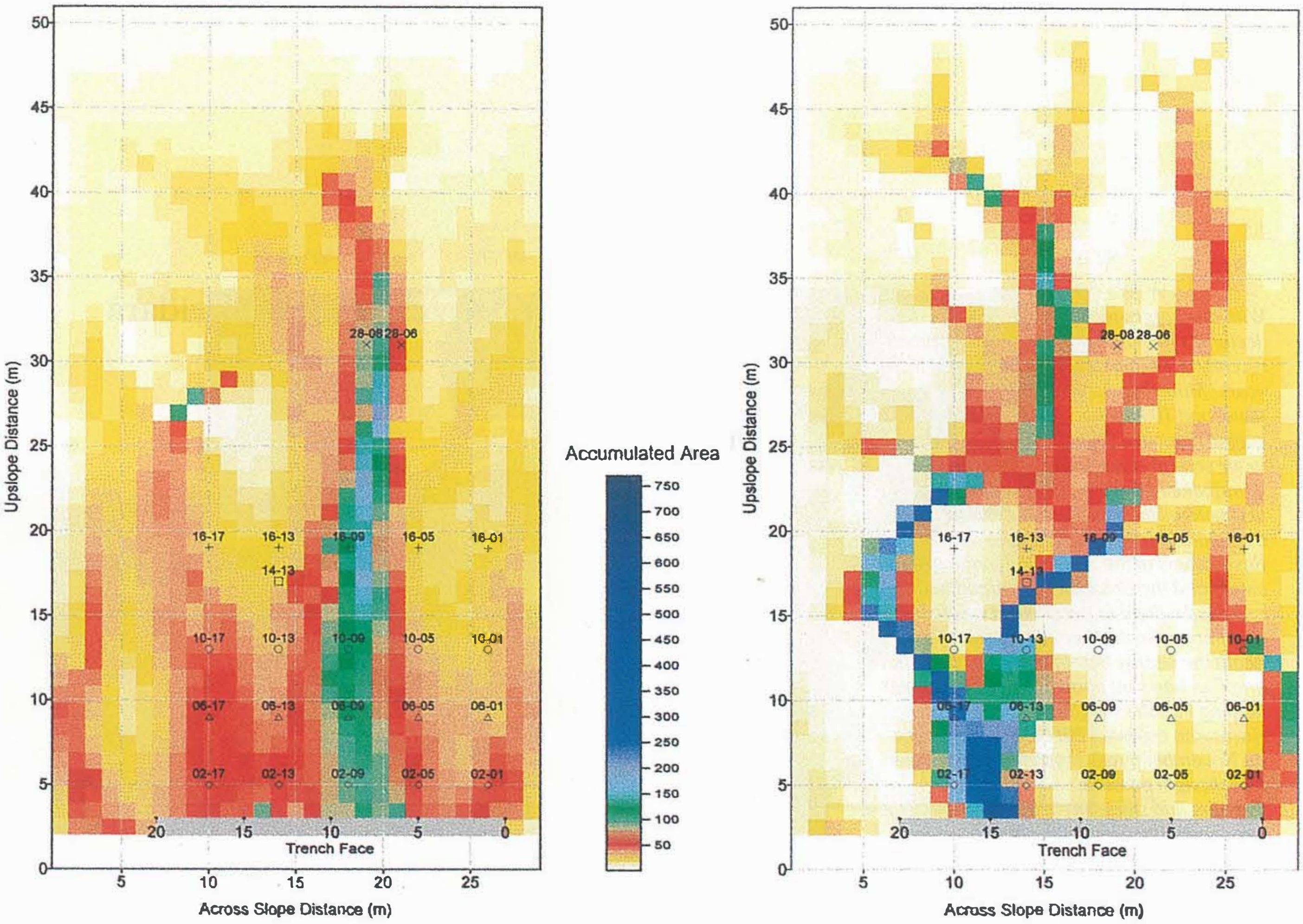
Fig. 1. MAPS 5° latitude-5° longitude averaged measurements of tropospheric CO from September 30 to October 11, 1994. The shades of blue indicate relatively low mixing ratios, while shades of red indicate relatively high mixing ratios. Original color image appears at the back of this volume.

The Data Sets

The MAPS instrument acquired data each day during 10-day Space Shuttle missions between April and October 1994. The instrument viewed the nadir, and data were acquired between 57°N and 57°S latitudes during both day and night. All longitudes were sampled. The system is most sensitive to CO in the altitude range of 2–12 km with the signal maximum centered at about 8 km. It is least sensitive to CO in the lowest few hundred meters. Data were acquired once each second over an area on the surface that is about 20 km^2. Improvements in the retrieval algorithms used for the 1994 flights removed much of the bias observed in the previous experiments. Preliminary comparison of the 1994 MAPS data to correlative data acquired over North America and Australia indicates that the MAPS values were within 10% of those measured by aircraft flying at an altitude of 8–10 km.

During April, there was relatively little change in the amount of CO with longitude, but there was a significant gradient with latitude. Except for a few "hot spots," the highest values appeared at high northern latitudes with values of about 120 ppbv. One ppbv equals one part of CO by volume in 10^9 parts of air. Mixing ratios decreased more or less smoothly to the high southern latitudes where CO was nearly constant at about 45–60 ppbv. This distribution is consistent with a reduced winter time destruction rate in the Northern Hemisphere and strong sink plus evenly distributed sources in the tropics and the Southern Hemisphere.

A strikingly different pattern is revealed in October, shown in Figure 1. In general, the amount of CO in the middle troposphere



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