# MODELING THE EFFECT OF SLOPE AND PRECIPITATION ON LATERAL FLOW IN A PIEDMONT SOIL

Elizabeth Crisfield[1], David E. Radcliffe[2]

*AUTHORS:* [1]Graduate Student and [2]Professor, Crop and Soil Science, Miller Plant Sciences, Room 3111, University of Georgia, Athens, Georgia 30602.
*REFERENCE: Proceedings of the 1999 Georgia Water Resources Conference,* held March 30-31, 1999, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, University of Georgia, Athens, Georgia.

**Abstract.** Nutrient contamination of surface water has received more attention in recent years prompting scientists to look for ways to protect water quality. Success in this effort will depend on a complete understanding of both surface and subsurface flow, especially in the dynamic period during and just after a storm. This study provides a theoretical estimate of lateral flow using the computer model VS2DT (Variably Saturated Two-Dimensional Transport). Model storms with two-year return periods were used to estimate the percent of the total infiltration that flowed laterally under four slope conditions. The volume of lateral flow was directly related to the slope, with the 2, 5, 10, and 20-degree slopes contributing 0.8, 2.05, 5.96, and 12.00% after seven days of drainage following a 2-hour storm of 2.54 cm/hr precipitation rate. A shorter, more intense storm resulted in higher percentages of lateral flow (10.71% for the 10-degree slope.) Timing and total volume of lateral flow were also effected by storm distributions.

## INTRODUCTION

The growing interest in nutrient and water resource management in Georgia has necessitated a more complete understanding of subsurface flow. The state's diverse topography and soils require more focused hydrologic studies, especially in the Piedmont where older soils with strong horizonation combine with steeper slopes to produce a complicated hydrologic regime. Scientists have looked at riparian buffer strips as filters to protect stream and lake water quality, but their effectiveness will depend not only on the volume of surface runoff, but on the depth of water flow beneath the riparian root zone. This modeling study seeks to determine the effect of slope and precipitation on the quantity of lateral flow at different depths as a percentage of the infiltrating precipitation.

Field studies have shown that significant volumes of water may flow laterally in the shallow soil layers of watersheds with steeper slopes or soils that have a less permeable horizon. A 1983 study by Hubbard and Sheridan in the Coastal Plain of Georgia found that 24.9% of the precipitation flowed laterally over an impermeable subsurface horizon. Another study in Eastern Tennessee found that 1.3% of the total volume of precipitation flowed laterally to the stream, (Wilson et al., 1990). However, this same study found that the lateral flow of an individual storm could account for as much as 12.5% of the precipitation. These studies demonstrate the potential significance of lateral flow in contaminant transport. However, while field research is limited by the physical characteristics of the particular hillslope on which it is located and by the weather conditions during the study, modeling studies can investigate more diverse conditions.

The current study employs a two-dimensional finite difference solution of Richard's equation to predict lateral flow in Cecil soils, which are common in the Piedmont provinces of Georgia, Alabama, North Carolina, and South Carolina.

## MATERIALS AND METHODS

### *Model Space*

A two-dimensional finite difference model, VS2DT, was used to predict the effect of slope on shallow lateral flow (Lappala et al., 1987; Healy et al., 1990). The model solves Richards' Equation for saturated and unsaturated conditions and was run on a Sun SPARCstation 20 requiring about 1.5 days per simulation.

The model space was a rectangular hillslope (20 m long and 10 m deep) with varying slope (2 - 20 degrees.) The hillslope was divided into 8500 cells (100 lateral x 85 vertical) that were each 20 cm long and varied in depth while maintaining an aspect ratio (length to depth) between one and four. (Fig. 1)

Complete soil profile descriptions and soil physical parameters were taken from Bruce et al. (1983). The selected description was for a soil pedon located two miles west of Watkinsville, GA, in a field with less than

2% slope. The soil profile is a typical Cecil with a shallow, slightly eroded Ap (to 21 cm) underlain by a thick illuvial clay horizon (from 26 cm to 131 cm.) The data required for the model including bulk density, $\rho_b$, mineral density, $\rho_m$, saturated hydraulic conductivity, $K_s$, and moisture release data were included in the publication. Porosity, $\phi$, was calculated from the reported data. Van Genuchten's equation (below) was used to fit the moisture release data to determine the parameters $\alpha$ and $\beta$, and the residual water content, $\theta_r$, for each horizon, (saturated water content, $\theta_s$, was defined as $\phi$) (van Genuchten, 1980).

$$\theta(h) = ([1+(-\alpha h)^{\beta}]^{(\frac{1}{\beta}-1)})(\theta_s - \theta_r) + \theta_r$$

In addition to the above parameters, VS2DT requires a measure of anisotropy in $K_s$ and specific storage. Overbaugh, 1996 showed that $K_s$ anisotropy in similar soils was negligible, although Bathke and Cassel (1991) found faster horizontal than vertical conductivity in the Cecil Series in North Carolina. Because of the large error recognized to be inherent in laboratory hydraulic conductivity measurements, lateral and vertical conductivities were assumed to be equal, an assumption that results in a conservative estimate of field lateral flow. Shrink-swell clays are generally a small contribution to the total amount of clay in these soils so the specific storage was considered to be zero for all horizons. Eleven depths were completely described and similar horizons were grouped to produce six horizons with representative soil parameters. (Table 1.)

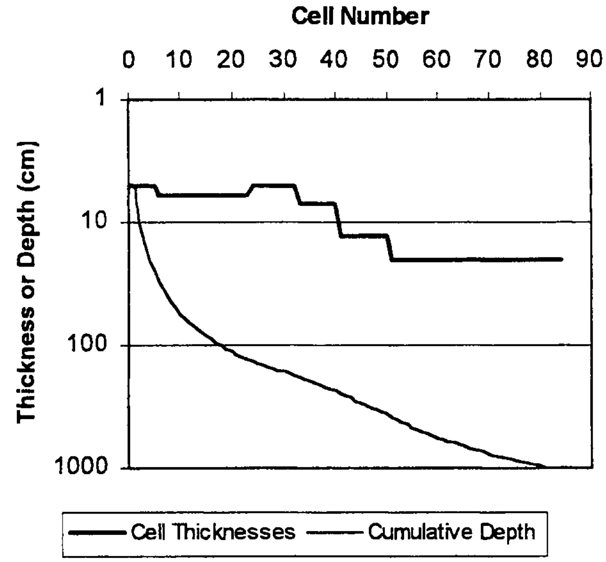


**Figure 1. Cell dimensions and cumulative depth.**

***Boundary and Initial Conditions***

The upslope boundary was treated as a watershed divide and was therefore defined as a no-flow boundary. The downslope boundary consisted of a seepage face from the surface to a depth of 1.8 m with a no-flow boundary below the seepage face to a depth of 10 m. The bottom boundary at 10 m was treated as a bedrock interface and was therefore defined as a no-flow boundary. The soil surface (top boundary) was a specified flux boundary with the flux defined as the precipitation rate – zero after the event. The profile was allowed to drain for seven days after the model storm.

Three model storms were studied. Storms 1 and 2 consisted of steady precipitation rates (2.54 cm/hr and 10.16 cm/hr) for a duration which corresponded to a two-year recurrence interval (two hr and ten min, respectively.) The third storm used a Type II 24-hour storm distribution. Two-year 24-hour precipitation curves predicted a total of 9.27 cm of rain in the vicinity of the selected pedon. (Georgia Soil and Water Conservation Commission, 1992.)

Initial conditions were developed by allowing the profile to drain for 14 days from a profile in equilibrium with a water table at a depth of 1.5 m at the seepage face, (simulating a perennial stream,) and a pressure head lower limit of -1 m. This drainage was simulated with the same physical characteristics and boundary conditions as the lateral flow simulations except for a no-flow soil surface boundary.

**Table 1. Profile Description and Soil Physical Parameters.**

| Horizon | Lower Boundary (cm) | Bulk Density ($g/cm^3$) | Mineral Density ($g/cm^3$) | Porosity ($\phi=\theta_s$) | $K_{sat}$ (cm/hr) | $\theta_r$ | $\alpha$ (cm) | $\beta$ |
|---|---|---|---|---|---|---|---|---|
| Ap/BA | 25 | 1.56 | 2.66 | 0.414 | 14.4 | 0.026 | 8.2 | 1.4 |
| Bt1 | 100 | 1.43 | 2.72 | 0.473 | 10.2 | 0.135 | 14.1 | 1.1 |
| Bt2 | 140 | 1.56 | 2.73 | 0.430 | 0.206 | 0.145 | 212.8 | 1.2 |
| BC | 163 | 1.53 | 2.75 | 0.444 | 0.0351 | 0.011 | 91.5 | 1.1 |
| C1 | 195 | 1.48 | 2.73 | 0.458 | 0.71 | 0.015 | 136.1 | 1.2 |
| C2 | 1000 | 1.39 | 2.73 | 0.491 | 0.223 | 0.010 | 29.0 | 1.2 |

### *Calculations*

The model output consisted of total head, pressure head, water content, saturation, and parallel and normal water velocities (relative to the soil surface) for selected nodes at selected time steps.

The lateral flux parallel to the soil surface was calculated for each node by multiplying the parallel velocity component by the water content. This was converted to volume of lateral flow by multiplying by the depth of soil each node represents and by the thickness of the two-dimensional model space (one cm). A vertical transect of nodes to a depth of two m was selected near the middle of the hillslope to avoid being influenced by the boundary conditions. Boundary conditions appeared only to effect the column of nodes closest to the edges.

Lateral flow as a percentage of the total infiltration was calculated by summing the cumulative lateral flow contributions of each node in the vertical transect, dividing by the total depth of the profile (two m), and then dividing by the depth of infiltrating precipitation. Because of a period of ponding during the simulation, the infiltration is less than the precipitation, the balance being surface runoff. Lateral flow for each horizon was calculated as a weighted average of the flows for each of the nodes in that horizon.

## RESULTS

### *Slope Study*

Storm 1 was simulated with four slopes: 2, 5, 10, and 20 degrees. The results of the four simulations were identical in timing with peak lateral flow occurring at about 0.75 hr when the shallowest node came closest to saturation. Lateral flow dropped quickly to a sustained rate for the rest of the 2-hour storm event and approached a constant rate after the event. After the two-hour storm, the lateral flow from the 2, 5, 10, and 20- degree slopes accounted for 0.23, 0.58, 1.17, and 2.38 % of the total infiltration of this storm event, respectively. The constant lateral flow after about 55 hours resulted in a steady increase in lateral flow as a percent of infiltration of about 0.003, 0.007, 0.024, and 0.048 % $hr^{-1}$ resulting in a total of 0.80, 2.05, 5.96, 12.00 % after seven days. (Fig. 2)

While flow rates differed in magnitude between the slope simulations, the Ap/BA horizon contributed far more lateral flow than any other horizon in all four simulations. Figure 3 shows the relative contributions of the six horizons for the 10 degree slope simulation. The other slope simulations resulted in similar relationships and identical timing. With the exception of the Bt1 horizon, lateral flow percentages were related to the hydraulic conductivities for each horizon, (the Bt1 contributed far less lateral flow than the Ap/BA horizon despite having a relatively high hydraulic conductivity.)

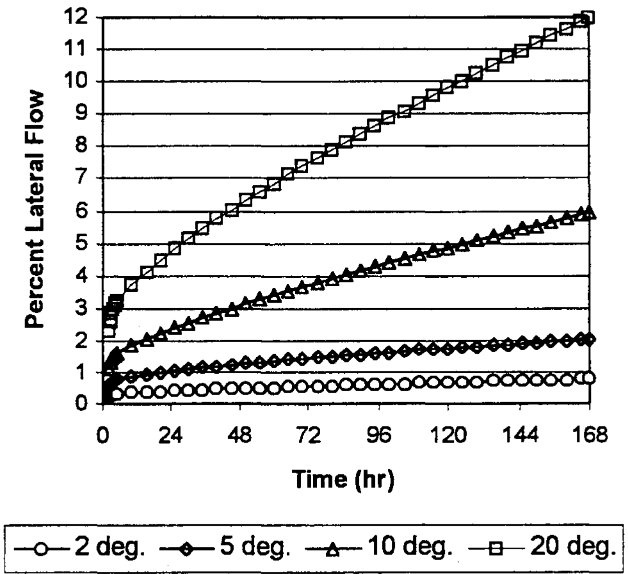


**Figure 2. Percent of infiltration flowing laterally under four different slope conditions.**

Examination of the relationship between lateral flow and slope also showed that zero slope would result in roughly zero lateral flow. This prediction was confirmed by a simulation with zero slope which resulted in 0.005% lateral flow after seven days of drainage.

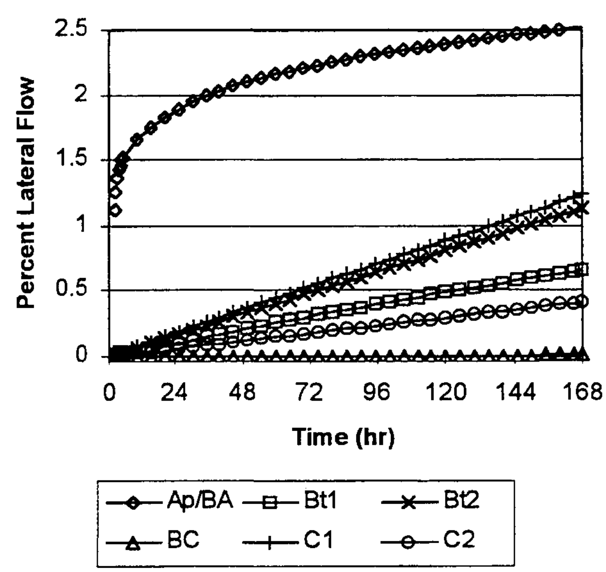


**Figure 3. Percent of infiltration flowing laterally for each horizon in the 10-degree slope simulation.**

***Storm Study***

The results of the three model storms demonstrated that the intensity, duration, and distribution of precipitation events had a significant effect on lateral flow. Results of the 10-degree simulations for the three model storms are summarized in Table 2. As expected, the short intense storms (Storm 2 and part of Storm 3) produced significantly more surface runoff than Storm 1. It is also evident that while the total volume of lateral flow from the short intense storm was much less than that of the longer storms, as a percentage of the infiltration it was much greater. The volume of lateral flow was related to the total amount of infiltration, though it was not the only factor.

Dramatic differences between the model storms were most evident in the timing of the percentage lateral flow and the changes in water tension within the profile. Near saturated conditions were strongly correlated with peaks in lateral flow volume. In addition, because of the low intensity rain for the first 11.75 hours in Storm 3, the lateral flow appeared delayed compared to the other storms and deeper soil depths approached saturation almost simultaneously with the shallower depths. Deeper soil depths in the short, intense Storm 2 never approached saturation.

## CONCLUSIONS

Simulations on four different slopes with a precipitation event of 2.54 cm/hr for 2 hours showed that slope was an important factor in the volume of lateral flow produced. Hillslopes with 2, 5, 10, and 20-degree slope produced 0.23, 0.58, 1.17, and 2.38 % of the total infiltration as lateral flow immediately after the 2-hour storm event. Most of the lateral flow occurred when the shallow horizons with high hydraulic conductivities were close to saturation. Under all slope conditions, the majority of the lateral flow occurred in the Ap/BA horizon. Watersheds with zero slope produced no significant lateral flow.

Storms with different precipitation distribution produced widely varying results. The short intense storm (Storm 2) produced the least volume of lateral flow though it was the greatest as a percentage of the infiltrating precipitation (10.71%). Storms 1 and 3, though different in total precipitation and distribution, produced similar percentages of lateral flow (5.96% and 6.40%, respectively). The timing of the drainage curves of the three storms was strongly affected by their distributions.

Future research will focus on the contribution of horizonation to lateral flow.

**Table 2. Comparison of Storm Events for a 10-degree Hillslope.**

| Total Precipitation Each Storm | Duration (hours) | Runoff (%) | Lateral Flow at Storm End (%) | Lateral Flow at 24 hours (%) | Lateral Flow at 168 hours (%) |
|---|---|---|---|---|---|
| Storm 1 (5.08 cm) | 2 | 2.1 | 1.15 | 2.41 | 5.96 |
| Storm 2 (1.69 cm) | 0.166 | 8.9 | 0.13 | 2.16 | 10.71 |
| Storm 3 (9.27 cm) | 24 | 12.9 | 2.73 | 2.73 | 6.40 |

## LITERATURE CITED


Bruce, R.R., J.H. Dane, V.L. Quisenberry, N.L. Powell, and A.W. Thomas, 1983. *Physical Characteristics of Soils in the Southern Region: Cecil.* Southern Cooperative Series Bulletin 267. Georgia Agricultural Experiment Station and University of Georgia, Athens, Georgia. pp. 39-159.

Georgia Soil and Water Conservation Commission. Manual for Erosion and Sediment Control in Georgia. 3rd ed. 1992. pg A-3-5

Healy, R.W, 1990. Simulation of Solute Transport in Variably Saturated Porous Media with Supplemental Information on Modifications to the U.S. Geological Survey's Computer Program VS2D. Water-Resources Investigations Report 90-4025, U.S. Geological Survey, Denver, CO.

Hubbard, R.K., and J.M. Sheridan. 1983. Water and Nitrate-Nitrogen Losses From a Small, Upland, Coastal Plain Watershed. J. Environ. Qual. 12(2):291-295.

Lappala, E.G., R.W. Healy, E.P. Weeks, 1987. *Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media.* Water-Resources Investigations Report 83-4099, U.S. Geological Survey, Denver, CO.

Overbaugh, M.J, 1996. *Assessment of the hydraulic properties of a soil-saprolite sequence near Watkinsville, GA.* Unpublished thesis, Athens, GA.

Van Genuchten, M.Th, 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *SSSAJ*, 44:(5) 892-898.

Wilson, G.V., P.M. Jardine, R.J. Luxmoore, and J.R. Jones, 1990. Hydrology of a forested hillslope during storm events. *Geoderma*, 46:119-13.