A HYDRUS 2D EVALUATION OF ALTERED DEPTHS TO THE ARGILLIC HORIZON DUE TO EROSION: WHAT IMPACTS ON HILLSLOPE INTERFLOW?

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Abstract. Numerical models of hillslope hydrology often use characteristics from soil classification maps to parameterize subsurface hydrologic flow paths. These soil maps, however, may lack sufficient spatial detail and may not accurately represent landscapes that have been eroded from historical farming. Therefore, a spatially explicit model of eroded landscapes, particularly in the Piedmont region of GA, could be valuable. Hillslope hydrology of the Piedmont typically involves an argillic horizon with low permeability causing high lateral flow in periods of high precipitation. In hillslope models this layer of low permeability is generally parallel to the soil surface creating different zones of interflow along the hillslope. Highly eroded landscapes, such as those within South Carolina's Calhoun Critical Zone Observatory, have a redistribution of soil from higher to lower landscape positions altering the depth to the low permeable layer and possibly altering patterns of interflow. This study used extensive soil sampling within highly eroded and undisturbed hillslopes to map spatial variation in depth to the argillic horizon. In undisturbed hillslopes, the argillic horizon was relatively parallel to the surface while in eroded hillslopes depth to the argillic was shallower upslope and deeper in lower slope positions. These spatially explicit hillslope data were used to parameterize a HYDRUS 2-D model and outflows at the lower slope were compared to the conventional parallel depth model.

INTRODUCTION

Historic agricultural practices led to accelerated erosion throughout the Piedmont region of the southeastern USA (Trimble 1974). These practices degraded soil quality, altering hydrologic processes across the landscapes by limiting infiltration and leading to overland flow and erosion (Huang et al. 2002). Accelerated erosion has substantially redistributed soil from upper to lower landscape positions (Gabbard et al., 1998). Hillslopes with soil redistribution have a non-uniform thickness of the topsoil that is shallower along ridges and increasing in depth further down slope. Highly weathered subsoils, such as Ultisols within Piedmont, are susceptible to gully formation (Hansen & Law, 2008), creating erosion that not only removes topsoil but also down cuts and erodes the clay rich argillic horizon beneath. As such, compared to hillslopes that were not farmed, both the depth to and the thickness of the argillic horizon has been impacted by soil erosion due to past farming practices.

Numerical models of hillslope and watershed hydrology have used estimates of topsoil thickness either from soil classification maps (Dialynas et al., 2016), digital elevation models (Paniconi & Wood, 1993; Quinn et al., 1991), or an approximate thickness that is parallel to the soil surface (Jackson et al., 2014; O'loughlin, 1981). For quantifying hillslope interflow these estimates may lack sufficient spatial detail and may not accurately represent landscapes that have been eroded (i.e. topsoil with a non-uniform thickness). This redistribution can lead to a depth to the low permeable layer that is not consistently parallel to the soil surface. Therefore, a spatially explicit model containing a non-uniform topsoil thickness and a variable argillic horizon thickness could create zones of interflow that are different than current estimates using uniform topsoil thickness and thicker clay horizons.

In this research, we use field based measurements within the Calhoun Critical Zone Observatory in the Piedmont of South Carolina along hillslopes that had evidence of historic farming and erosion compared to others that did not. Measurements along these hillslopes of depth to the argillic horizon were used as a basis for parameterizing 2D models in HYDRUS to compare outflow at the base of the hillslope. We hypothesized that erosion has increased interflow along the hillslope and thus outflow at the base of the slope.

METHODS

Research Site

The Calhoun Critical Zone Observatory is based in the USDA Forest Service Sumter National Forest in the Piedmont of South Carolina and incorporates the historic Calhoun Experimental Forest (34.6177°N, 81.6914°W). Cultivation of cotton, corn, wheat, and other crops led to significant soil erosion starting about 1800 and continuing to the early twentieth century (Trimble, 1974; Richter and

Markewitz, 2001). The mean annual precipitation is around 1260 mm, and the mean annual temperature is about 17°C. Elevation ranges from 113 to 196 m above sea level. The area is covered for the most part by highly weathered acidic Ultisol and Inceptisol soils (Richter and Markewitz, 2001; Richter et al., 2014).

Model Parameterization

HYDRUS-2D/3D is a computational computer program that can simulate water transport (Šimůnek et al., 2016). The program numerically solves the Richards equation (1931) for saturated and unsaturated water flow and can model time varying pressure head boundary conditions. Parameters for the model can be estimated within the model, from literature, or from direct field measurements.

A hillslope model with uniform soil properties and with thick soil layers were developed. Both hillslope models simulate daily precipitation and evapotranspiration for a period of two years and 270 days from March 1958 to December 1960. Rainfall data original collected from 1949 - 1962 (range gage #9) by scientists of the USDA-FS Southern Experiment Station were recently digitized and provided by Dr. Jingfeng Wang (personal communication, 2015). Daily evapotranspiration data from 1949 – 1962 was obtained from the NOAA National Center of Environmental Information (climate data online services) for Station: Union 8S, SC US GHCND: USC00388786 (Elevation 480 ft. Latitude 34.605 degree. Longitude 81.663 degree).

The water retention parameters for both hillslope models are shown in Table 1. Saturated hydraulic conductivity (K_s) and saturated volumetric water content (θs) were measured on site and reported in Dialynas et al. (2016). The residual volumetric water content (θr), and the water retention functions α and n were estimated using the Neural Network Prediction option (Schaap and Leij, 1998) within the soil hydraulic parameters of HYDRUS 2D. This option uses the Rosetta Model (Schaap et al., 2001) to predict van Genuchten's water retention parameters (van Genuchten, 1987) from textural information.

Conditions for pressure head during the initialization period were set at an equilibrium gradient between the soil surface and the bedrock (-1400 to 2000 cm) creating varied pressure head with depth and a water table at about 14 m below the ridge. This condition was used at the start of the initialization period which ran for approximately 270 days and served as a warm-up period for the actual model simulation, an additional 730 days (Figure 1).

Table 1. Soil water retention parameters and saturated hydraulic conductivity for soil materials.

Soil Texture	r (cm^3/cm^3)	s (cm^3/cm^3)	α (1/cm)	n (-)	K_s (cm/day)
Sandy Loam	0.14	0.35	0.02	1.44	19.2
Clay	0.15	0.43	0.01	1.25	2.4
Clay Loam	0.04	0.54	0.01	1.41	14.4

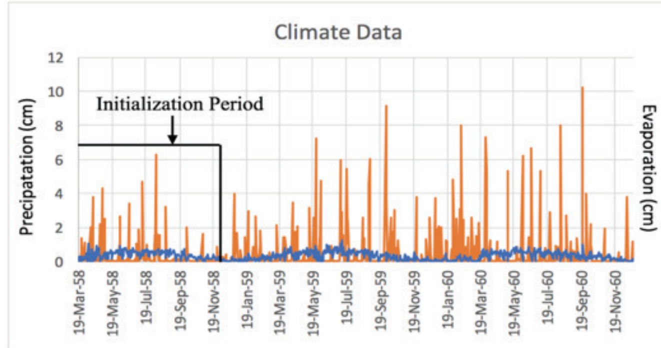

Figure 1. Climate data for HYDRUS 2D model. Precipitation (orange) and evapotranspiration (blue) from March 1958 to December 1960. Initialization of ~270 days was used before simulation with additional two years thereafter. Years 1959 and 1960 were chosen due to the high precipitation events to allow for increased interflow.

Precipitation and evapotranspiration interact with the hillslope model via the atmospheric boundary condition along the soil surface. The ground water outlet at the bottom of the hillslope along the bank was set as a seepage face boundary. The pressure head along the seepage face is equal to zero for the saturated part of the seepage face and the outflow is equal to zero for the unsaturated portion of the seepage boundary. A no flux boundary condition (Figure 2) was used for both the bottom of the modeled space (i.e., bedrock) and below the ridgeline at the upper hillslope (i.e., the watershed divide).

The root uptake parameters were estimated using the Feddes et al. (1978) option in HYDRUS. Values used for root water uptake parameters were T_1 = -10 cm, T_2 = -25 cm, T_3 = -300 cm, T_4 = -15000 cm and T_{TTT} = 0.5 cm d^{-1}. The root distribution was set as an exponential decay gradient from the soil surface, with an 8% slope, to the bottom of the modeled space using a root biomass distribution for pine trees located within the southeastern piedmont (Qi, 2016).

Soil texture distribution along the hillslope within the modeled spaces for 1) non-uniform thickness of topsoil and thinner clay horizon and 2) uniform thickness of topsoil and thicker clay horizon are reported in Table 2.

Table 2. Upper and lower depths of the soil profile layers for both non-uniform and uniform thickness of topsoil. The thickness of the clay layer averages 40 cm for the non-uniform hillslope and 100 for the uniform. Depths of each soil layer were determined from 82 soil cores for non-uniform hillslope and 9 for uniform.

Soil Texture	Ridge (cm)	Shoulder (cm)	Mid-slope (cm)	Foot-slope (cm)	Toe-slope (cm)
Non-uniform					
Sandy Loam	0-28	0-33	0-42	0-71	0-87
Clay	28-60	33-82	42-91	71-120	87-105
Clay Loam	60+	82+	91+	120+	105+
Uniform					
Sandy Loam	0-45	-	0-40	-	0-48
Clay	45-125	-	40-140	-	48-175
Clay Loam	125+	-	140+	-	175+

These hillslope catenas consist of a sandy topsoil over laying a clay subsoil similar, in profile, to the Ultisols found at the study site.

A finite element mesh generator was used to create a triangular mesh within the 2D modeling space. This mesh was refined at the soil surface (including the boundary) to have a smaller sized element to accommodate infiltration during large rain events so that the percolation into the lower permeable clay horizon could be calculated at a higher resolution. The mesh for the soil surface was set to 13 cm and gradually increased in size with depth to the global mesh size of 50 cm.

Interflow patterns were visualized using flow pathways created by particle tracking. The location and trajectory of seven particles located within the top soil along the hillslope were tacked over the simulation run.

RESULTS

A preliminary model run for a homogeneous hillslope without soil layering was analyzed for model validation and comparison to the models with soil layering (Figure 2). In this model, all parameters beside soil material are identical to those within the non-uniform and uniform depth to argillic horizon models. The pathways shown by the particle tracker illustrate the soil water flow over the simulation period (1000 days). In this model, given the high rainfall years simulated, even in the absence of a low permeable soil layer, horizontal interflow is initiated and water flows pass the seepage face. All water exits at the very base of the seepage face in this case.

The first layered soil model is that of the historically farmed hillslope with a non-uniform depth of topsoil

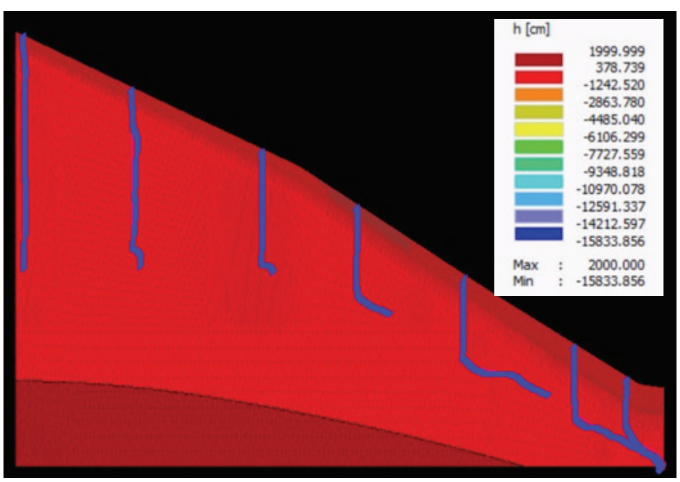

Figure 2. Resulting pressure head at the end of the simulation for a homogenous soil profile, all other parameters beside soil material are identical for the uniform and non-uniform depth to argillic horizon model. The pathways shown by the particle tracker (blue lines) illustrates the soil water movement when unaffected by soil layering. This figure has been stretched with a ratio of 1 unit vertical to 4 units horizontal to visualize the particle tracking.

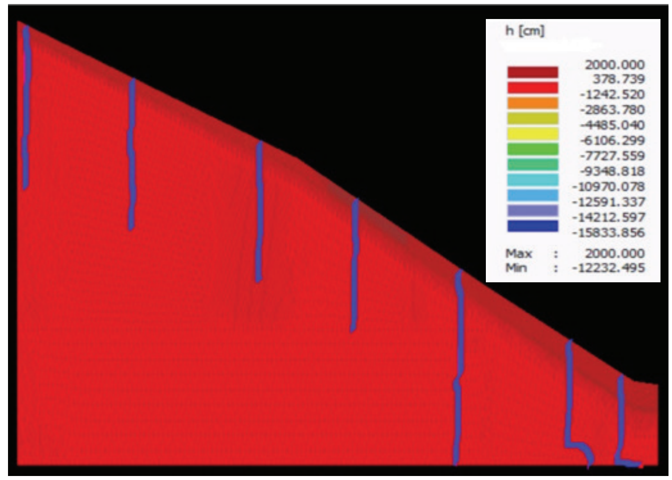

Figure 3: Resulting pressure head for non-uniform depth to argillic horizon hillslope for a simulation of 870 days. The pathways shown by the particle tracker (blue lines) illustrates the soil water movement affected by a thin argillic horizon. This figure has been stretched with a ratio of 1 unit vertical to 4 units horizontal to visualize the particle tracking.

and a thin argillic horizon (Figure 3). The simulation period for this model ran for 870 days, due to a large precipitation event the model was unable to continue to the full 1000-day period. Soil water flow patterns in the non-uniform model differ from the homogenous profile with increased vertical flow to bedrock. Horizontal flow occurs after soil water hits bedrock before exiting the seepage face. Pressure head positive and consistent throughout the non-uniform hillslope profile but compared to the homogenous hillslope did not generate similar deep soil saturation.

The second layered soil model is a hillslope with no agricultural history consisting of uniform topsoil depth and a thick argillic horizon (Figure 4). The simulation period for this model ran for 600 days; like the non-uniform model

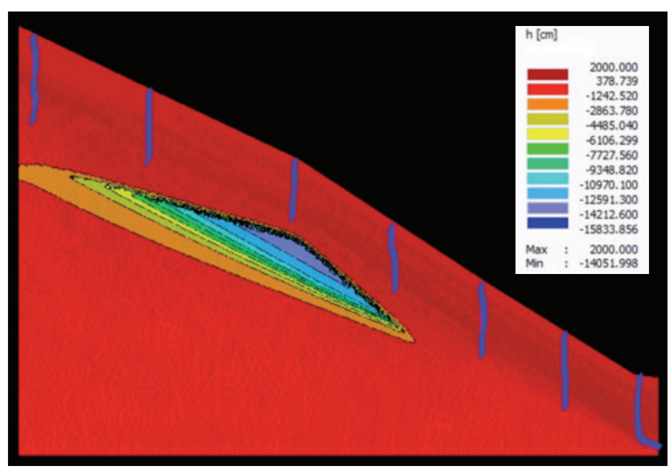

Figure 4: Resulting pressure head for uniform depth to argillic horizon hillslope for a simulation of 600 days. The pathways shown by the particle tracker (blue lines) illustrates the soil water movement affected by a thick argillic horizon. This figure has been stretched with a ratio of 1 unit vertical to 4 units horizontal to visualized the particle tracking.

this model was unable to continue through the 1000-day period. The soil water flow patterns for the uniform model differ from the non-uniform hillslope with decreased vertical movement. This may partly result from the thicker (100 cm) low permeability layer. Like the homogenous hillslope model soil water also exits near the bottom of the seepage face. The pressure head also varies more with depth in this uniform model suggesting a drying out zone below the 100-cm argillic layer.

CONCLUSION

Historic agricultural practices have led to erosion and soil redistribution from higher to lower landscape positions on many landscape of the southeastern Piedmont. Soil erosion also down cut into the argillic horizon creating a hillslope with a non-uniform argillic horizon thickness. Due to the thinner argillic horizon of the historically farmed hillslope the soil water flow patterns within these simulations suggest that soil water moves quickly through the argillic horizon with less horizontal interflow occurring over the simulation period. A result counter to expectations of greater interflow after topsoil loss. Hillslopes with no agricultural history (i.e. uniform topsoil depth with a thicker argillic horizon) show some interflow movement at the bottom of the argillic layer towards the base of the hillslope. A hillslope with a thicker argillic horizon also suggests subsoil portions of the profile that may become drier, at least over this 600-day simulation, as a result of limited hydraulic conductivity.

Further work will include additional hillslope models. Models will consist of a non-uniform depth of topsoil with a thicker argillic horizon as well as a uniform topsoil depth and thinner argillic model. These additional models will be used to isolate soil water interflow processes.

LITERATURE CITED

Dialynas, Y. G., Bastola, S., Bras, R. L., Billings, S. A., Markewitz, D., & Richter, D. d. (2016). Topographic variability and the influence of soil erosion on the carbon cycle. *Global Biogeochemical Cycles, 30*(5), 644-660. doi:10.1002/2015GB005302

Feddes, R. A., Kowalik, P. J., & Zaradny, H. (1978). Simulation of field water use and crop yield: Centre for agricultural publishing and documentation.

Gabbard, D., Huang, C., Norton, L., & Steinhardt, G. (1998). Landscape position, surface hydraulic gradients and erosion processes. *Earth Surface Processes and Landforms, 23*(1), 83-93.

Hansen, W. F., & Law, D. L. (2008). Gully control on the Sumter National Forest in SC.

Huang, C., Gascuel-Odoux, C., & Cros-Cayot, S. (2002). Hillslope topographic and hydrologic effects on overland flow and erosion. *CATENA, 46*(2), 177-188.

Jackson, C. R., Bitew, M., & Du, E. (2014). When interflow also percolates: downslope travel distances and hillslope process zones. *Hydrological Processes, 28*(7), 3195-3200.

O'loughlin, E. (1981). Saturation regions in catchments and their relations to soil and topographic properties. *Journal of Hydrology, 53*(3-4), 229-246.

Paniconi, C., & Wood, E. F. (1993). A detailed model for simulation of catchment scale subsurface hydrologic processes. *Water Resources Research, 29*(6), 1601-1620.

Qi, Ji. (2016). Potential climate change effects on deep soil carbon and hydrology in loblolly pine plantations of the southeast US (Doctoral dissertation). University of Georgia. Athens, GA.

Quinn, P., Beven, K., Chevallier, P., & Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes, 5*(1), 59-79.

Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. *Physics, 1*(5), 318-333.

Richter Jr, D. D., & Markewitz, D. (2001). Understanding soil change: soil sustainability over millennia, centuries, and decades: Cambridge University Press.

Richter Jr, D. D., Bacon, A. R., Billings, S. A., Binkley, D., Buford, M., Callaham, M. A., Curry, A. E., Hofmockel, M. Fimmen, R.L., Grandy, A.S., Heine, P.R., Hofmockel, M. and Jackson, J.A., (2014). Evolution of soil, ecosystem, and critical zone research at the USDA NFS Calhoun Experimental Forest. *In USDA Forest Service Experimental Forests and Ranges (Pp. 405-433):* Springer New York.

Schaap, M. G., & Leij, F. J. (1998). Using neural networks to predict soil water retention and soil hydraulic conductivity. *Soil And Tillage Research, 47*(1), 37-42.

Schaap, M. G., Leij, F. J., & Van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal Of Hydrology, 251*(3), 163-176.

Šimůnek, J., Van Genuchten, M. T., & Šejna, M. (2016). Recent developments and applications of the hydrus computer software packages. *Vadose Zone Journal, 15*(7).

Trimble, S. W. (1974). Man-induced soil erosion on the southern piedmont. *Soil Conserv. Soc. Am., Ankeny, Iowa*, 1700-1970.

Van Genuchten, M. T. (1987). A numerical model for water and solute movement in and below the root zone: United States Department Of Agriculture *Agricultural Research Service US Salinity Laboratory.*