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Modeling Storm Water Runoff and Soil Interflow in a Managed Forest, Upper Coastal Plain of the Southeast US.

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Abstract. *The Forest Service-Savannah River is conducting a hectare-scale monitoring and modeling study on forest productivity in a Short Rotation Woody Crop plantation at the Savannah River Site, which is on Upper Coastal Plain of South Carolina. Detailed surveys, i.e., topography, soils, vegetation, and drainage network, of small (2-5 ha) plots have been completed in a 2 square-km watershed draining to Fourmile Creek, a tributary of the Savannah River. We wish to experimentally determine the relative importance of interflow on water yield and water quality at this site. Interflow (shallow subsurface lateral flow) can short-circuit rainfall infiltration, preventing deep seepage and resulting in water and chemical residence times in the watershed much shorter than that if deep seepage were the sole component of infiltration. The soil series at the site (Wagram, Dothan, Fuquay, Ogeechee, and Vaucluse) each have a clay-rich B horizon of decimeter-scale thickness at depths of 1-2 m below surface. As interflow is affected by rainfall intensity and duration and soil properties such as porosity, permeability, and antecedent soil moisture, our calculations made using the Green and Ampt equation show that the intensity and duration of a storm event must be greater than about 3 cm per hour and 2 hours, respectively, in order to initiate interflow for the least permeable soils series (Vaucluse). Tabulated values of soil properties were used in these preliminary calculations. Simulations of the largest rainfall events from 1972-2002 data using the Green and Ampt equation provide an interflow: rainfall ratio of 0 for the permeable Wagram soil series (no interflow) compared to 0.46 for the less permeable Vaucluse soil series. These initial predictions will be compared to storm water hydrographs of interflow collected at the outflow point of each plot and refined using more detailed soil property measurements.*

Keywords. hillslope hydrology, interflow, infiltration, Green and Ampt equation, silviculture.

Introduction

In the Southeast U.S., short rotation silviculture usually has a minimal impact on the quantity of water runoff because many areas are not moisture limited for most of the year (Sun et al., 2002). However, a major concern is potential water quality effects as the hydrologic dynamics are altered due to the changing land use patterns in the Southeast. Most studies have been conducted using small plot factorial experiments, which do not give an accurate assessment of impacts at the watershed scale. The United States Department of Agriculture - Forest Service (USDA-FS) is conducting a long-term study at the Savannah River Site, near Aiken, South Carolina, using catchment-scale plots to determine the effects of short rotation silviculture (tree farming) practices on biodiversity, hydrologic budget, and nutrient fate and transport.

Ten catchments varying in size between 1.4-5.2 hectares have been delineated in the upper Fourmile Branch watershed on the Savannah River Site, a National Environmental Research Park (Figure 1). A catchment is defined as an area where the topography indicates that all surface water and shallow subsurface soil water (interflow) moves across or just beneath the land surface to a common low point. Currently each catchment supports managed pine saw timber. It has been proposed that this field site will be monitored for climate, flow, soil water content, and water table dynamics for two to three years. Monitoring will also include evaluating quality and quantity of water entering and leaving individual catchments. After the calibration phase, eight of the catchments will be converted to short rotation pine or hardwood stands receiving water and nutrients through drip irrigation, and compared to both untreated and undisturbed plots.

The study site lies within the Fourmile Branch watershed, a subwatershed of the Savannah River (figure 1). Due to its proximity to the Savannah River Site's nuclear waste treatment facilities, the hydrology and hydrogeology of the area are well documented (Dosskey and Bertsch, 1994; Dosskey and Bertsch, 1997; Fletcher et al., 2000; Giese et al., 2000; Halverson, 2001; Williams and Pinder, 1990). Watershed data including digital elevation models, soil surveys, land use surveys, forest stands, and streamflow data are available for public access. Most of these data are available for use within a Geographic Information System and are useful in assessing the study site with respect to various parameters.

Within the Fourmile Branch watershed, and perhaps throughout parts of the upper coastal plain, it has been hypothesized that interflow plays a large role in catchment runoff. Sandy surface soils overlie clay horizons with a sloping topography. Precipitation quickly infiltrates into the top sandy soil horizon resulting in minimal surface runoff except during extreme precipitation events. Within this area, interflow is commonly observed as seeps along road cuts where the clay horizon is exposed, however it has not been directly measured (Williams and Pinder, 1990). Using the indirect approach of hydrograph separation and streamflow partitioning, Williams and Pinder (1990) determined that over 90 percent of streamflow is due to groundwater discharge, with the rest due to surface runoff and interflow. While that study gave indirect estimates of runoff and interflow, direct quantification of interflow seems to be lacking.

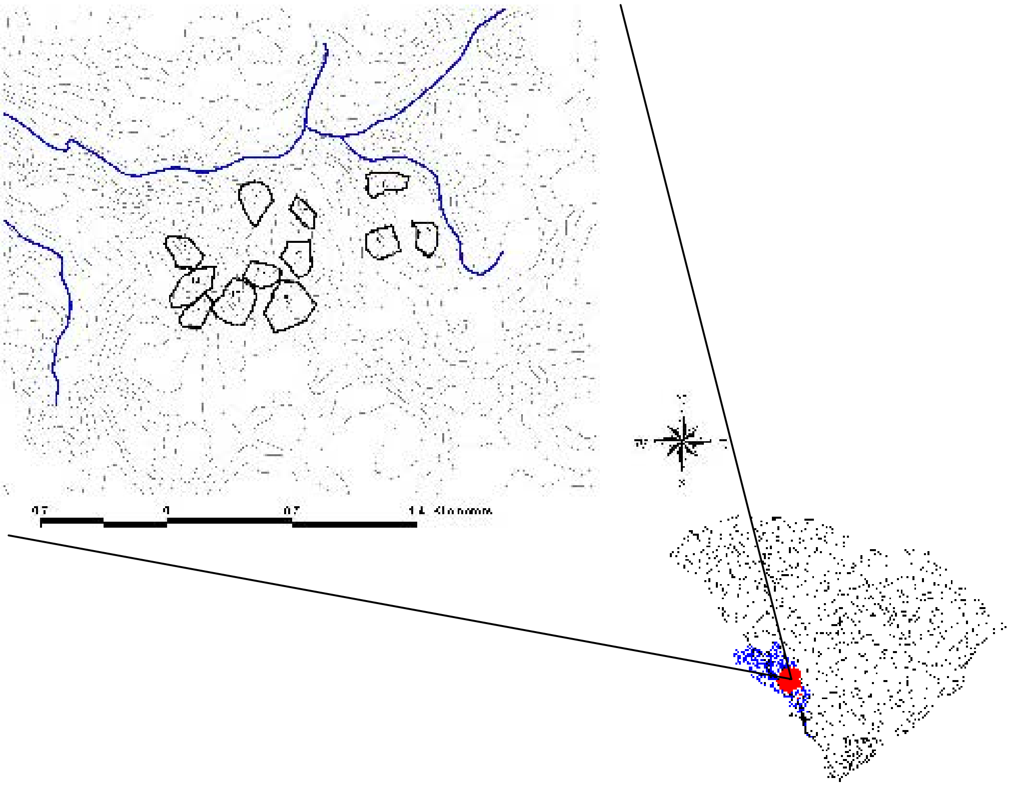

Figure 1. Location of study catchments within the Savannah River Site in Barnwell County, South Carolina. The Middle Savannah River watershed is denoted in blue (light grey) and the Savannah River Site is denoted in red (darker grey).

Using a variety of available spatial data of the study site, GIS was used in the delineation, instrumentation, and characterization of the experimental plots. The primary purpose of this experiment is to measure hydrologic and chemical inputs and outputs across individual plots. Plots were designed to contain a natural drainage outlet with hydrologic and chemical monitoring within each plot. Fundamental hydrologic measurements include discharge, precipitation, throughfall, relative humidity, soil moisture, water solute concentrations, and water table depth. In this experiment a special emphasis has been placed on biogeochemical processes along the hill-slope gradient, which is reflected in the placement of some of the instrumentation.

Although not enough groundwater data have been collected to determine annual or seasonal trends of groundwater flux, there are enough data to qualitatively determine the flux of groundwater at the site. Infiltration rates and cumulative infiltration through the upper soil layers can be estimated using approximate theory based methods. Together these can provide preliminary approximations as to how much precipitation recharges the aquifer and how much becomes surface runoff/interflow.

Methods

Plot delineation

Two-foot contour maps in a digital shapefile were used in Arcview 3.2 to identify twelve individual catchments. A polygon theme was created with Arcview in which the perimeters of the individual catchments were drawn. The sides of the plots were drawn following ridge divides assuming that runoff and interflow would follow surface topography. Due to the complex nature of the top ridge divide, the top perimeter was drawn to conform to a contour line instead of conforming to the actual catchment divide following the ridge line. Thus each catchment is not a closed system at the top boundary, however the objective of the long term study is to measure changes in flux between pretreatment and post treatment conditions. The bottom perimeter of the plot was designed as a line straight across the bottom of the catchment connecting the two ridge divides with the intention of placing a water collection device for monitoring flow across the entire bottom of the drainage (figure 2).

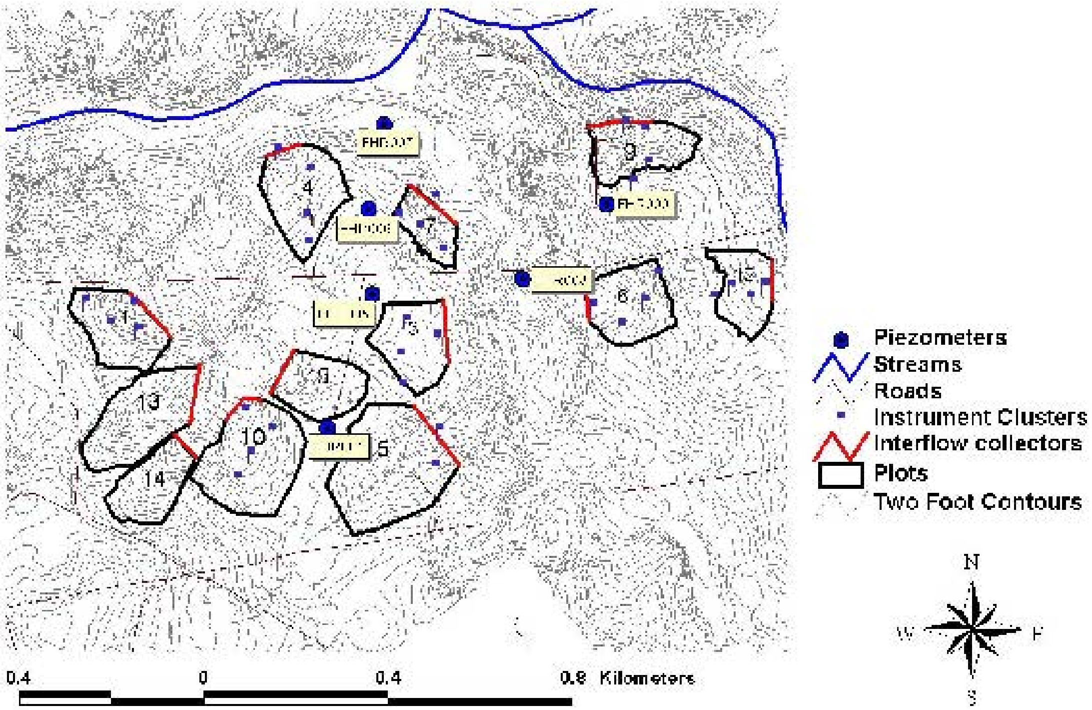

Figure 2. Plots and instrumentation within study site.

Currently there are plans to determine if plots 10, 13, and 14 are isolated systems (figure 2) through field surveying and soil coring. In addition, the GIS maps do not show a depressional wetland that exists to the east of plot 12. Plot 5 lies within an ephemeral stream; therefore it will not be used. One of the other plots will not be used, which will likely be determined through further field surveys.

Instrumentation

Previous soil surveys (Rogers, 1990) and earlier research (Williams and Pinder, 1990; Dosskey and Bertsch, 1994) show that the soils in the study area are highly permeable sands (0.10-2.74 meters thick) overlying a clay-rich (argillic) horizon (figure 3). Due to these soil conditions along with the slope of the catchments, it is hypothesized that the main source of discharge within the catchments will be interflow; therefore instrumentation was designed to measure this laterally flowing water.

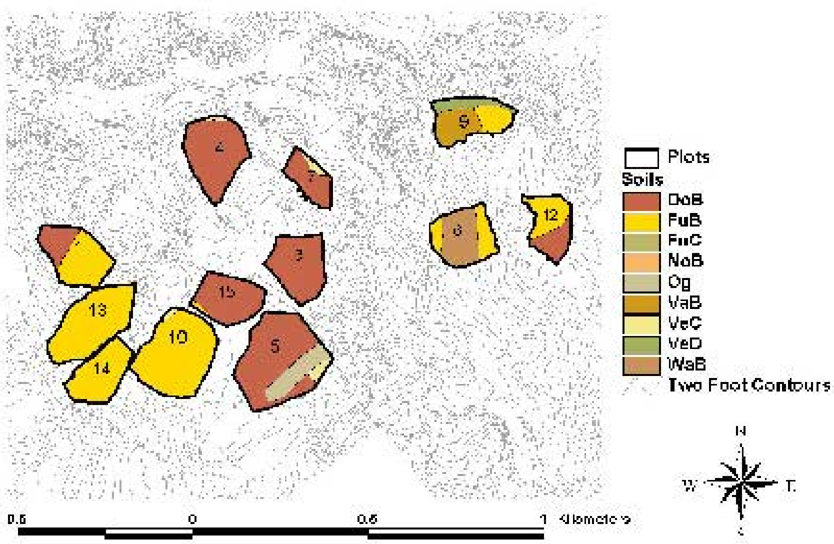

Figure 3. Soil types at the site. DoB=Dothan, FuB=Fuquay B, NoB= Norfolk, Og=Ogeechee, WaB=Wagram B, VeC=Vacluse C, Pk=Pickney, VeD=Vacluse D, VaB=Vacluse B.

Two paired sets of instruments were placed in each plot, one pair toward the top of the plot and one pair toward the bottom of the plot. Instrument clusters include a precipitation gauge, an air temperature thermometer, and a soil temperature thermometer. Each instrument cluster pair includes one set of instruments placed at a higher elevation near the ridge divide and one set of instruments placed within the central drain.

Six piezometers were installed at the study site (figure 2). The local water table varies from 2 m to 15 m below ground surface (bgs). Locations for the new piezometers were determined using a two-foot contour map. Four piezometers were located in a north-south orientation across the main drainage of the area. The other two piezometers were located perpendicular to this line to the east. The third existing piezometer was located west of the study site. All instrument locations were mapped using Arcview 3.2 with a two-foot contour layer of the study site. A point shapefile was created, placing a point for each instrument cluster (figure 2). The points were determined using the above criteria based on the contour lines. The points were then located and marked using a Trimble Global Positioning System. The elevation of each point was then measured using a Spectra-Physics Laserplane 650 laser level and the instruments were installed.

Estimation of infiltration rates

The Green-Ampt method integrates Darcy's law with the law of conservation of mass. In this approach, a soil profile is considered to be homogeneous and infinitely deep. It also assumes that there is no water table, capillary fringe, impermeable layers, or evapotranspiration (Dingman, 2002). An initial water content (Φ_o) of 0.3 was used. Water is assumed to infiltrate as a straight horizontal wetting front. If the water input (W) is less than or equal to the saturated hydraulic conductivity (K_h), then the infiltration rate (f) is equal to the water input (W). If the W is greater than K_h, then the infiltration rate f(t) is equal to the saturated hydraulic conductivity until the infiltration capacity, or cumulative infiltration (F) is reached. Once the infiltration capacity is reached, water overcomes the capacity of the porous medium to transmit it downward, therefore water ponds at the surface. The infiltration rate is determined using the following equation:

$$f(t) = K_h \left[1 - \left(\frac{\Psi_f + H(t)}{z(t)} \right) \right] \tag{1}$$

where ψ_f is the wetting front suction (tension), H(t) is the depth of ponding at time t, and $z_f(t)$ is the depth of the wetting front at time t (Dingman, 2002).

While the Green-Ampt method assumes that a soil profile has an infinite thickness, it can be applied to layered soils if K_h of the layers decreases with depth. Infiltration rates will equal the top soil layer until the wetting front enters the next soil layer. At this point K_h will be set equal to the harmonic mean

$$K_h = \left(K_{h1} K_{h2} K_{h3} ... K_{hn} \right)^{\frac{1}{n}} \tag{2}$$

where n is the number of layers. Nielsen and Perrochet (2000) have used this technique to investigate water table dynamics under capillary fringes.

Infiltration rates, cumulative infiltration, and depths of the wetting front were calculated for the five major soil series within the study site. These parameters were calculated using the Green-Ampt model used within a Microsoft Excel spreadsheet developed by Dingman (2002). The five major soil series within the study site include Dothan, Fuquay, Ogeechee, Vaucluse, and Wagram. The soil textures and depths of each texture for the five soil series were taken from Rogers (1990). The soil parameters of porosity (Φ), K_h, air-entry tension (ψ_{ae}), and pore-size distribution index were taken from Clapp and Hornberger (1978).

In the case where W is less than K_h, f will equal W. Due to the relatively high permeability ($K_h \geq 12.5$ cm hr^{-1}) of the upper soil layers at the study site, this is the expected case for typical storm events. From 1972-2002 at the Savannah River Site H-area no storm events greater than 12.5 cm hr^{-1} were recorded, therefore the infiltration rates in the top soil layers were assumed to always equal W. The infiltration rates were then calculated for the remaining soil layers. In order to force a ponding effect, a simulated storm event where $W > K_h$ for a duration of 2 hr was input into the Green-Ampt model. This value was chosen because it is approximately equal to the average field capacity of these soil series.

In the Green-Ampt model, once it is established that $W > K_h$, then the wetting front suction is calculated as

$$\left|\varphi_f\right| = \left(\frac{2b+3}{2b+6}\right)\left|\varphi_{ae}\right| \tag{3}$$

The time of ponding (t_p) is calculated as

$$t_p = K_h\left|\varphi_f\right|\frac{(\phi-\theta_o)}{W(W-K_h)} \tag{4}$$

If the time of ponding is less than the time of the storm event (t_w), then the model can continue. The infiltration rate will be equal to the water input rate until $t = t_p$. At this point F can be computed as:

$$F(t_p) = W\,t_p \tag{5}$$

Following this calculation, values for F(t) are selected where $F(t_p) \le F(t) \le$ total rainfall. Values for time (t), infiltration rate [f(t)], and wetting front depth [$z_f(t)$] are then calculated for the corresponding values of F(t) using the following equations:

$$t = \{[F_t - F(t_p)]/K_h\} + [|\psi_f|(\phi-\theta_0)/K_h] * \ln\left\{\frac{[F(t_p)+|\psi_f|(\phi-\theta_0)]}{[F(t)+|\psi_f|(\phi-\theta_0)]}/\right\} + t_p \tag{6}$$

$$f(t) = K_h\left[1-\left(\psi_f + \frac{H(t)}{z_f(t)}\right)\right] \tag{7}$$

$$z_f(t_p) = \frac{K_h|\psi_f|}{W-K_h} \tag{8}$$

The final value selected for F(t) gives the amount of water that infiltrated the soil during this particular storm event. This value can be subtracted from the total water input to give an estimate of runoff. Because these soils are overlain by sand, runoff would be in the form of interflow.

As previously stated, the upper sandy soil layers were assumed to have infiltration rates equal to the water input (W) due to their high saturated hydraulic conductivities (Kh*). However the Vaucluse soil series has additional layers beneath the sandy top layer. Due to the layered nature of this soil, the infiltration rate, cumulative infiltration, depths of wetting front for the upper soil layers were calculated until the depth of wetting front reached the next soil layer. At this point the wetting front suction ($|\psi_f|$) was changed to that of the next layer. The value of K_h was changed to the harmonic mean of the two soil layers as proposed by Maidment (1993). The infiltration rates, cumulative infiltration, and depths of wetting front were then graphed for each major soil series and estimates were made for the amount of interflow that could occur after the simulated storm event.

Results and Discussion

The soil textures with corresponding depths and physical properties for the five major soil series are presented in table 3. In order to simulate conditions where $W > K_h$, a simulated storm with an intensity of 4 cm hr^{-1} for a duration of 2 hr was input into the Green-Ampt model. This created conditions where $W > K_h$ for the lower soil layers except in the Wagram soil series. The value of K_h of the lower layer is 12.5 cm hr^{-1}. Simulating a storm event with an intensity greater than this is unrealistic, therefore the infiltration rate is assumed to equal to K_h for the Wagram soil series. The infiltration rates and saturated hydraulic conductivity values for the Ogeechee soil series is shown in figure 4. The values and patterns were similar for the Dothan and Fuquay soils series. The Vaucluse soil series has a heterogeneous hydraulic conductivity and infiltration rate due to the variation in soil textures (figure 5).

The simulated storm event produced 8 cm of available water (W). The final cumulative infiltration was 4.85 cm for the Vaucluse soil series and 7.40 cm for the Dothan, Fuquay, and Ogeechee soil series. This would result in 3.15 cm of interflow for the Vaucluse soil series, and 0.6 cm of interflow for the Dothan, Fuquay, and Ogeechee soil series.

The largest daily rainfall value measured near the study site was 15 cm on August 21, 1990, recorded about 2 km NW of the study site. In order to simulate this event, a storm with a rainfall intensity of 3.75 cm hr^{-1} lasting 4 hours was input into the model. The final cumulative infiltration was 6.90 cm for the Vaucluse soil series and 13.10 cm for the Dothan, Fuquay, and Ogeechee soil series. This would result in 8.1 cm of interflow for the Vaucluse soil series, and 1.9 cm of interflow for the Dothan, Fuquay, and Ogeechee soil series.

The estimated infiltration, cumulative infiltration, and interflow for the five soil types follow what would be expected based on the soil textures. Because the Wagram soil series consist of highly permeable sand and sandy loam, the infiltration is equal to the water input rate, therefore no ponding occurs. The Dothan, Fuquay, and Ogeechee soil series all have a layer of sandy clay loam. This layer has a saturated hydraulic conductivity low enough to result in ponding, therefore allowing interflow during the simulated storm events. Because the Vaucluse soil series has a low permeable clay layer underneath a sandy clay loam layer, further ponding occurs, allowing more interflow.

Table 3. Textures with corresponding depths and physical properties for major soil types within the study site (Rogers, 1990).

Soil Series	Texture	Depth (cm)	Φ	K_h (cm hr^{-1})	Ψ_{ae} (cm)	b
Dothan	Sand	0-18	0.395	63.4	12.1	4.05
	Sandy loam	18-30	0.435	12.5	21.8	4.90
	Sandy clay loam	30-165	0.420	2.3	29.9	7.12
Fuquay	Sand	0-56	0.395	63.4	12.1	4.05
	Sandy clay loam	56-152	0.420	2.3	29.9	7.12
Ogeechee	Sandy loam	0-59	0.435	12.5	21.8	4.90
	Sandy clay loam	59-150	0.420	2.3	29.9	7.12
Vaucluse	Sandy loam	0-13	0.435	12.5	21.8	4.90
	Sandy clay loam	13-43	0.420	2.3	29.9	7.12
	Clay	43-51	0.482	0.46	40.5	11.4
Wagram	Sand	0-56	0.395	63.4	12.1	4.05
	Sandy loam	56-155	0.435	12.5	21.8	4.90

Φ = porosity, K_h = saturated hydraulic conductivity, Ψ_{ae} = air-entry tension, b = moisture characteristic exponent

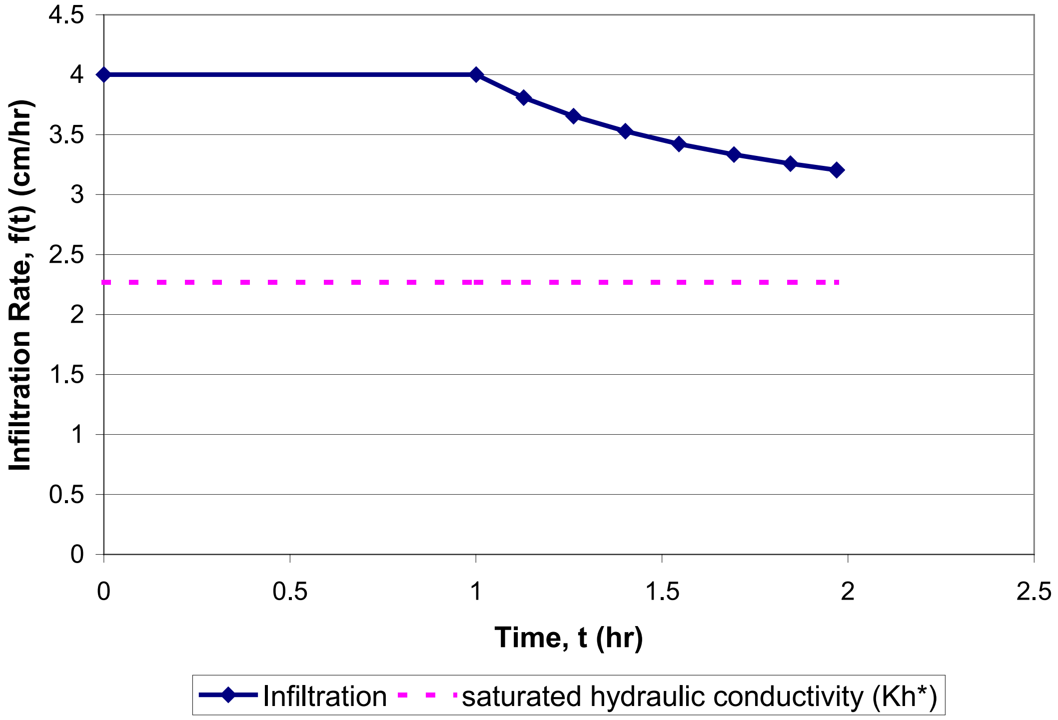

Figure 4. Infiltration rate of Ogeechee soil series.

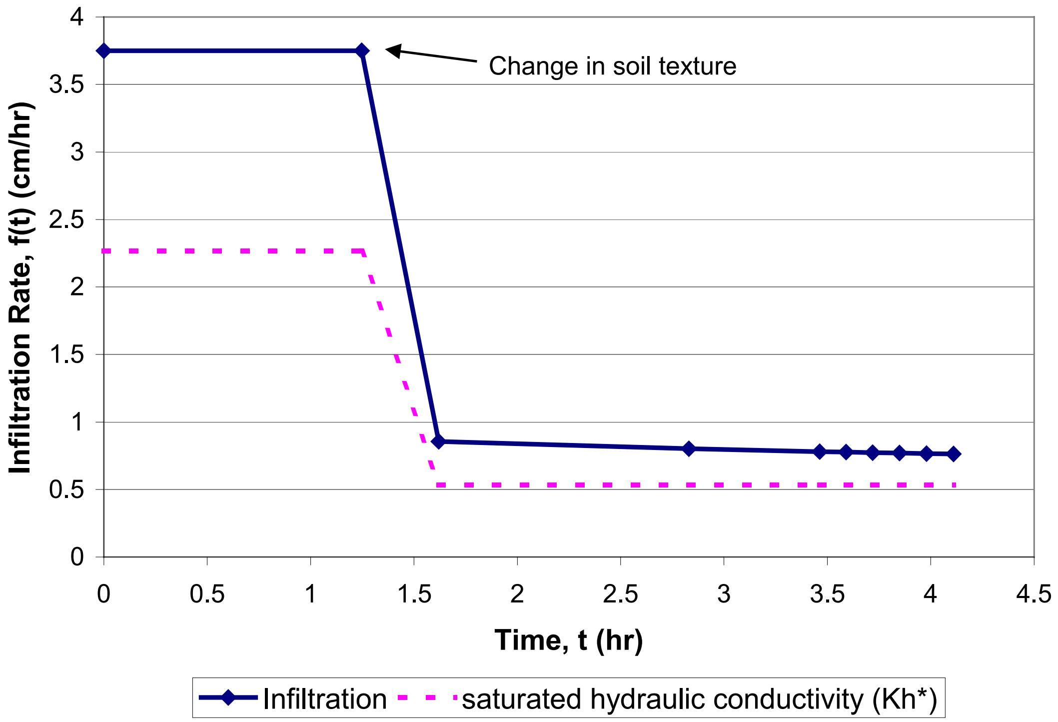

Figure 5. Infiltration rate of Vaucluse soil series.

Continued study of interflow and infiltration of precipitation at this site will be coordinated with the site management schedule. Hydrographs of the water table, obtained from the piezometers on site, will be analyzed to estimate infiltration and groundwater recharge rates. Preliminary data from the piezometer near Fourmile Creek (FHR-007) show an apparent diurnal fluctuation, possibly due to daily variations in evapotranspiration flux (the water table is about 2 m below ground surface at this location). Future management at the site may involve clearing the mixed pine stands and planting short-rotation woody crops in a factorial design to determine the relationship of tree productivity to (1) irrigation and (2) fertilization over a several years. This monitoring project will focus on determining the importance of storm event interflow on water quality in the Fourmile Creek area, a sub-watershed of the Savannah River basin.

Conclusion

Infiltration rates, cumulative infiltration, and depths to wetting front were estimated for the five predominant soil series within the study site using the Green and Ampt method. Various storm events were simulated to estimate cumulative infiltration and interflow. Storm events with an intensity less than 2.3 cm hr^{-1} resulted in no interflow. A simulation of a rainfall event of 4 cm hr^{-1} lasting two hours resulted in interflow/rainfall ratios of 0% for the Wagram soil series; 7.5% for the Dothan, Fuquay, and Ogeechee soil series; and 39% for the Vaucluse soil series. A simulation of the largest daily rainfall event from 1972-2002 resulted in interflow/rainfall ratios of 0% for the Wagram soil series; 13% for the Dothan, Fuquay, and Ogeechee soil series; and 46% for the Vaucluse soil series. The remaining water is available for groundwater recharge. However, these values are most likely inflated because the Green-Ampt model ignores evapotranspiration and hysteresis; and the true antecedent moisture conditions were unknown.

Infiltration calculations and preliminary field data from piezometers and an interflow collector suggests that groundwater recharge and interflow through and across the argillic horizon will occur simultaneously following storm events where water input is greater than infiltration capacity ($W > F$). Infiltration rates will vary due to different soil types, antecedent moisture conditions, and rainfall intensity and duration. Interflow may be an important component of the hydrologic budget within the Fourmile Branch watershed.

Through the presented experimental design, the hydrologic budget of ten small catchments will be monitored. Changes in vegetation type and moisture levels will then be observed when silvicultural and irrigation treatments are administered. Detailed monitoring of infiltration and interflow at the site will allow us to estimate the water and nutrient runoff in the Fourmile Creek area, a subwatershed of the Savannah River basin. As development pressures continue to stress coastal areas, understanding the impact of nutrient loading from inland areas to the coasts is becoming invaluable for land managers and policymakers.

Acknowledgements

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