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Simulation of Hydrology of Short Rotation Hardwood Plantations

John E. Parsons, Professor

Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695, john_parsons@ncsu.edu

Carl C. Trettin, Soil Scientist / Project Leader

Center for Forested Wetlands, USDA Forest Service, Charleston, SC 29414, trettinc@cofc.edu

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Abstract. *A 76 ha hardwood plantation at Trice Research Forest near Sumter, SC is being used to study forest hydrology on an operational scale. The overall objective of this project is to develop tools to enable forest managers to assess and manage sustainable short rotation woody crop production systems. This paper reports on the use of the water management model, WATRCOM, as a tool for assessing and managing hydrology and water use in these plantations. Four drainage catchments are being monitored for surface and subsurface movement of water and nutrients. The water management model, WATRCOM, is being tested and evaluated on these catchments. Two years of field data are compared to model simulations. Future model development and application to these sites are also discussed.*

Keywords. models, model validation, water management, watershed, woody plants .

Introduction

The study of sustainable systems for production of food and fiber has received much research interest in recent years. Many studies in the Southeastern US have been conducted to minimize off-site movement of sediment and chemicals while maintaining viable production levels. In the Coastal Plains this is challenging since many of the soils have shallow topsoil and tend to be droughty during the growing season. Chemical and physical barriers can also lead to shallow root zones in some of the soils.

At other times during the year, excess rainfall can lead to surface runoff/erosion and increased subsurface flows from the shallow water table. The excess water often necessitates a surface drainage system consisting of shallow channels and ditches to carry this water. However, these drainage systems tend to drain more than necessary during summer periods. These factors affect both agricultural and forest production systems with reduced yields and production capacity. Management and availability of reliable water resources often helps alleviate some of these problems. For short rotation woody crop production systems, poor water management can reduce production and extend harvest times. These systems are especially challenging in the Southeastern US.

This paper addresses a portion of a cooperative effort to research the sustainability of short rotation woody crop production systems in the Southeastern US Coastal Plain. The project is a cooperative effort involving the US Department of Energy, Oak Ridge National Laboratory, Tennessee Valley Authority, International Paper, USDA Forest Service, North Carolina State University and the University of Nevada. This portion of the overall project addresses the development of tools for evaluating water management approaches and assessing the soil water regimes on a watershed scale. This entails developing and evaluating the potential use of the water management model, WATRCOM, to describe soil water dynamics in a Coastal Plain hardwood plantation.

Site Description

The research site is located on a research/production farm owned and operated by International Paper Corporation in Sumter County, South Carolina. The study site consists of two watersheds with mixed agriculture/forestry approximately 5000 ac (Figure 1). Detailed hydrology measurements were concentrated in watershed 1. Catchments 1-4 in watershed 1 were selected for testing the water management model, WATRCOM (Figure 1). Each of the catchments is approximately 10 acres. Sweetgum or Sycamore was planted in each catchment in 1997. The predominant soils in the simulation area are Goldsboro, Norfolk, Rains and Coxville (Figure 1). In July 1999 flashboard riser structures were installed in the outlets of catchments 2 and 4 to reduce drainage.

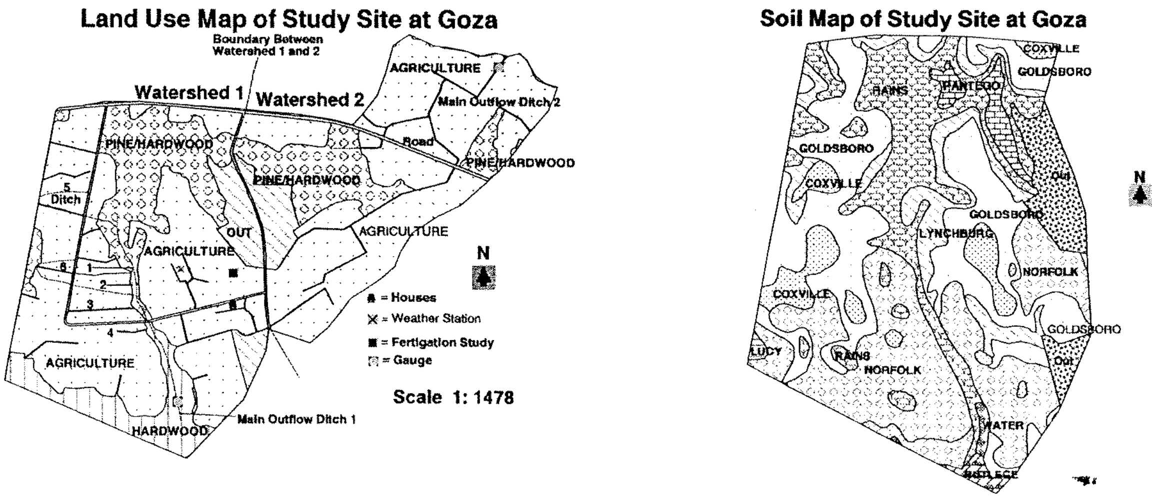

Figure 1. **The study area consists of the two watersheds (1 and 2) with flow monitoring at the outlets and in catchments 1-6 within watershed 1.**

Measurements

In each catchment, the outlet ditches are continuously monitored. In catchments 1 and 3, H-flumes are installed near the junction with the main outlet ditch (Figure 1). In catchments 2 and 4, flashboard riser structures were also monitored subsequent to installation in July 1999. Boards were installed in these structures to prevent outflow for ditch water levels up to 1 m. For levels above 1 m, a 90-degree V-notch weir was installed to measure outflow. Prior to installing the flashboard riser structures, flow was monitored with H-flumes. Flow from the main outlet ditch is also being monitored with H-flumes. In addition to the water flow measurements at each of these stations, water quality samples were collected on a weekly basis.

Catchments 5 and 6, which are outside the initial testing area for WATRCOM, also have H-flumes installed to monitor outflow. Water levels at the outlet culvert from watershed 2 are also being monitored. Water samples are also collected at these locations for water quality analysis.

Water levels at each outlet are monitored by a portable data acquisition system designed and developed at NC State University during this project. The system uses inexpensive components to keep equipment costs low, which enables more logging stations. The system consists of a pressure transducer and a single board battery-powered data acquisition system. The pressure transducers are Motorola[1] Model MPX-5010DP Silicon Pressure Sensor. These dual port sensors are mounted in a PVC pipe with one port at the bottom of the ditch and one port open to the atmosphere. The output ranges from 0.2 V to 4.7 V corresponding to water levels from 0 to 1 m. Errors in water levels from these sensors typically are less than 2 mm. A typical installation is shown in Figure 2.

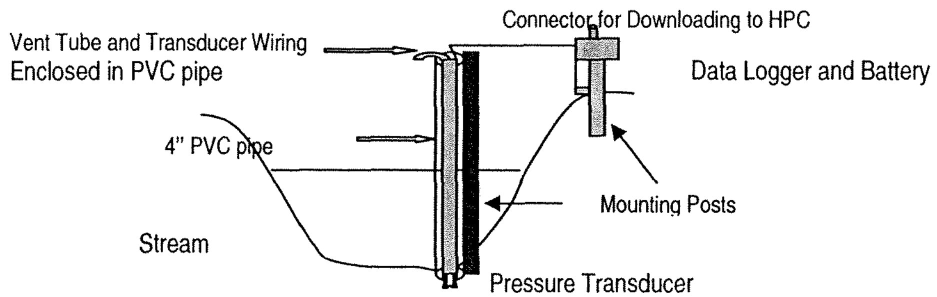

Figure 2. **Datalogger setup in each catchment.**

The battery-powered data acquisition system is based on a Domino 2A microcontroller from Micromint, Inc. This datalogger consists of an Intel 80252C microprocessor with a BASIC interpreter, 32K bytes of SRAM and 32K bytes of programmable EEPROM, 2 - 12 bit A/D channels, and 16 parallel bi-directional I/O lines. A circuit was designed around a Philips PCF8583P real time clock chip and a Microchip 24LC65 serial EEPROM to provide data storage and extend the battery life. The Philips real time clock chip provides an alarm function which powers on the data acquisition system for monitoring and storage of data. A combined BASIC and assembly language program was developed to monitor the pressure transducer at 1-minute intervals and store changes in water level at least once per hour. Tests indicate that the system will run unattended in excess of two-months using an inexpensive sealed lead acid battery (7-MAH). Data is downloaded to a handheld computer every two weeks and brought back to the lab for processing. Processing programs in the lab perform data integrity checks and apply the flow calibration data for each site to obtain flow rates versus time. A user manual and design specifications for the system is under development and available from NC State University.

Soil moisture readings were measured at 15 m, 30 m, and 60 m from outlet ditch in each catchment at depths of 15 cm, 30 cm, 45 cm and 70 cm using probes for time domain reflectometry on a biweekly basis. A deep and shallow water table well was installed in each catchment at 30 m from the outlet ditch. The deep and shallow well depths were 4.6 m and 1.8 m, respectively. The bottom 90 cm of the wells was screened. The wells and the soil moisture readings were measured on a biweekly basis.

Undisturbed soil cores were taken from catchments 1-6 to determine soil water characteristics and vertical saturated hydraulic conductivity. At least one core was taken in the top-soil (generally at a depth of 10 – 20 cm) and one core was taken in the subsoil (at depths ranging from 30 – 40 cm). Sample results from catchment 1 are shown in Figure 3.

[1] The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service or USDA Forest Service of the product named nor criticism of similar ones not mentioned.

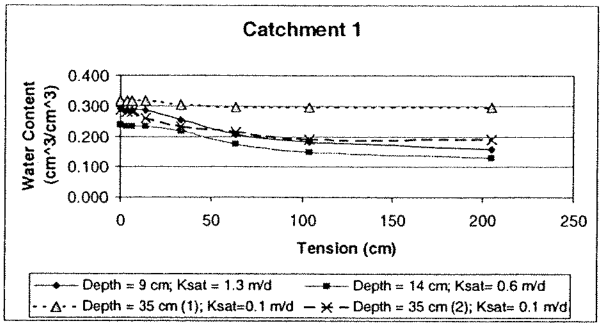

Figure 3. **An example of the soil hydraulic data measured in Catchment 1.**

Field Data

Examples of the flow data from the start of measurements through April 2000 are given in Figure 4 for catchments 1-4 in watershed 1. Each figure shows the flow rate along with the cumulative volume flowing from the outlet of each catchment and the main drainage ditch. The cumulative volume was found by summing the flow rate multiplied by the time of the given flow rate. Catchments 1 and 3 are not controlled and show flow throughout the period (Figure 4). The control structures were installed in catchments 2 and 4 in July 1999 and the outlet levels were raised to maintain water levels of 1-m. In both cases, there was little or no flow out of these areas after July 1999. In catchment 2, water levels reached the bottom of the weirs (ditch water depth of approximately 1.0 m) in late February 2000. Catchment 4 water levels reached a maximum of about 0.5 m ditch water depth during January 2000 but did not produce any outflow.

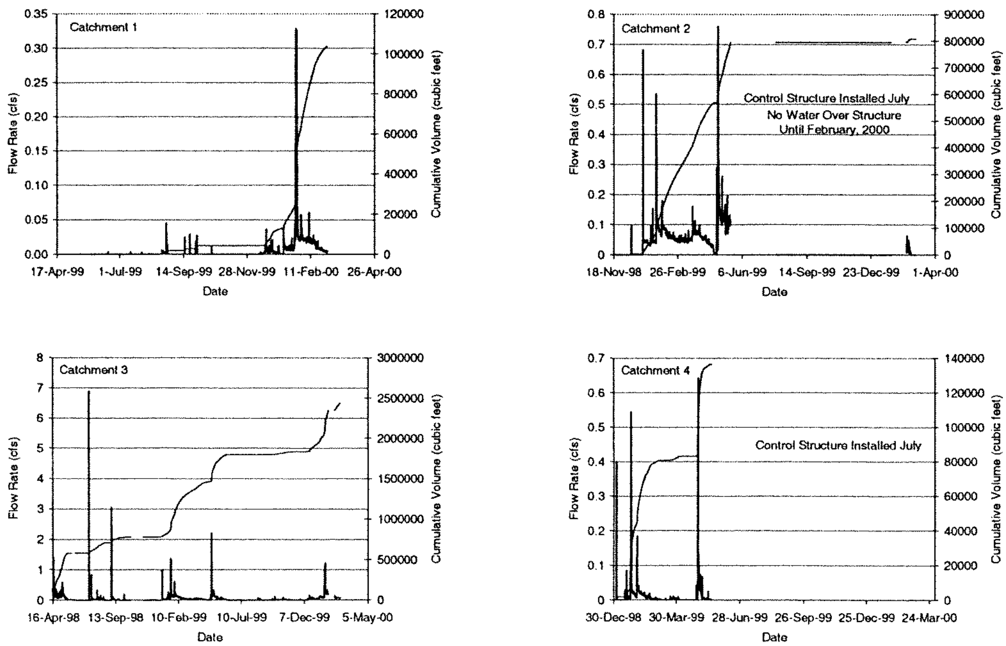

Figure 4. **Flow data during the project.**

Deep and shallow wells, located 30 m from the outlet ditch in each catchment, were monitored on a monthly basis. During periods that the shallow well was dry a water table depth of 200 cm was assigned. Figure 5 shows the water table depth versus time for each of the catchments. The outlet control was most effective for catchment 2. During the Fall of 1999 and Winter of 1999-2000, the water table levels in the shallow well in catchment 2 were near the surface until Spring 2000. In catchment 1, the water table depths in the shallow wells did go within 50 cm of the surface. However, drainage from catchment 1 lowered the water tables more quickly than the response recorded in catchment 2. In catchment 4, the water table response was not as evident. The water table in catchment 4 was closer to the surface than in the uncontrolled adjacent catchment 3 during the winter.

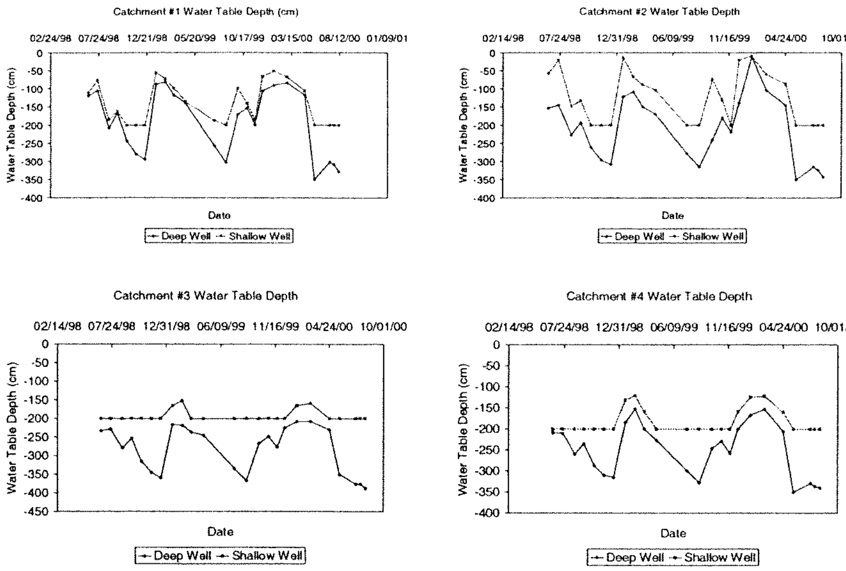

Figure 5. Observations wells in each catchment.

Figure 6 and Figure 7 show snapshots of the TDR readings in each catchment for February 2000 and July 2000, respectively. Readings at depths of 15 cm, 30 cm, 45 cm and 70 cm were recorded at 15 m (50 ft), 20 m (100 ft) and 60.5 m (200 ft). In most cases, the profile at 15 m would show the most influence from the outlet ditches. In the controlled catchment, 2, the moisture near the surface (15 cm depth) is higher than in the uncontrolled catchments on both dates. Below the 15 cm, the readings tended to be comparable in February. In July, the catchment 2 readings were above those in catchment 1 down to the 70 cm depth. Although there was little water in the outlet in catchment 2, this may be attributable to the reduced drainage earlier in the year. However, the effect was not as clear in catchment 4, which tended to follow from the lower water table depths shown in Figure 5. The July readings in catchment 4 were higher than those in catchment 3 at 15 m from the outlet ditches but was fairly dry at below 20% soil moisture. The time course comparisons of all soil moisture readings for 15 m from the outlet ditches in catchments 1 and 2 are given in Figure 8. After the start of control in catchment 2, these moisture readings tended to be higher than those recorded in catchment 1.There were no readings for catchment 2 in January, 2000 which was the wettest period in catchment 1.

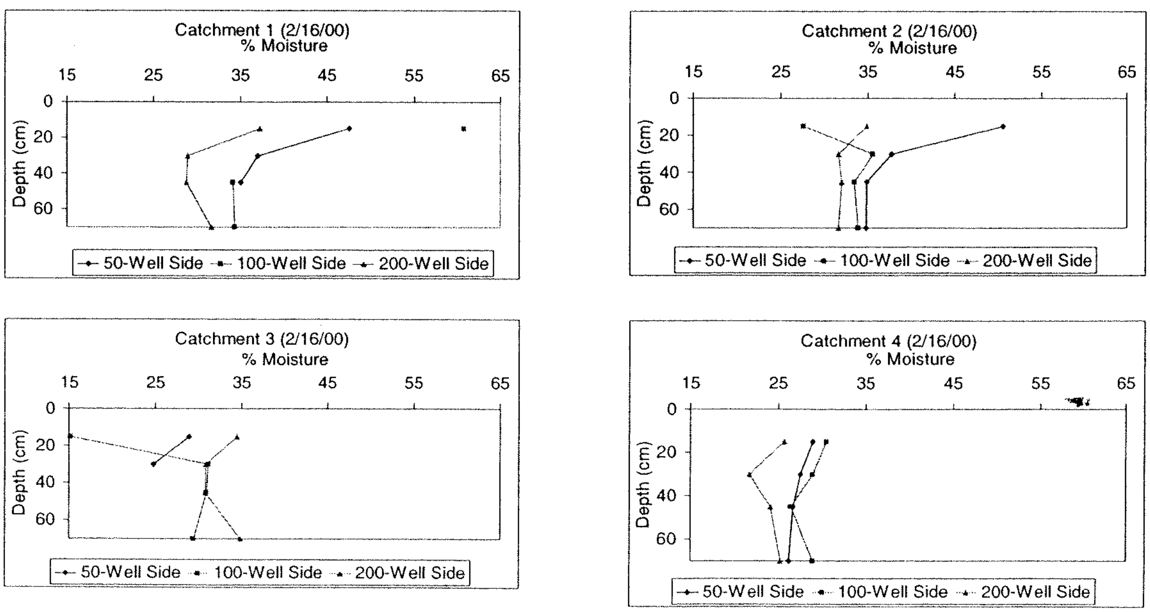

Figure 6. Snapshot of the soil water status on 2/16/200.

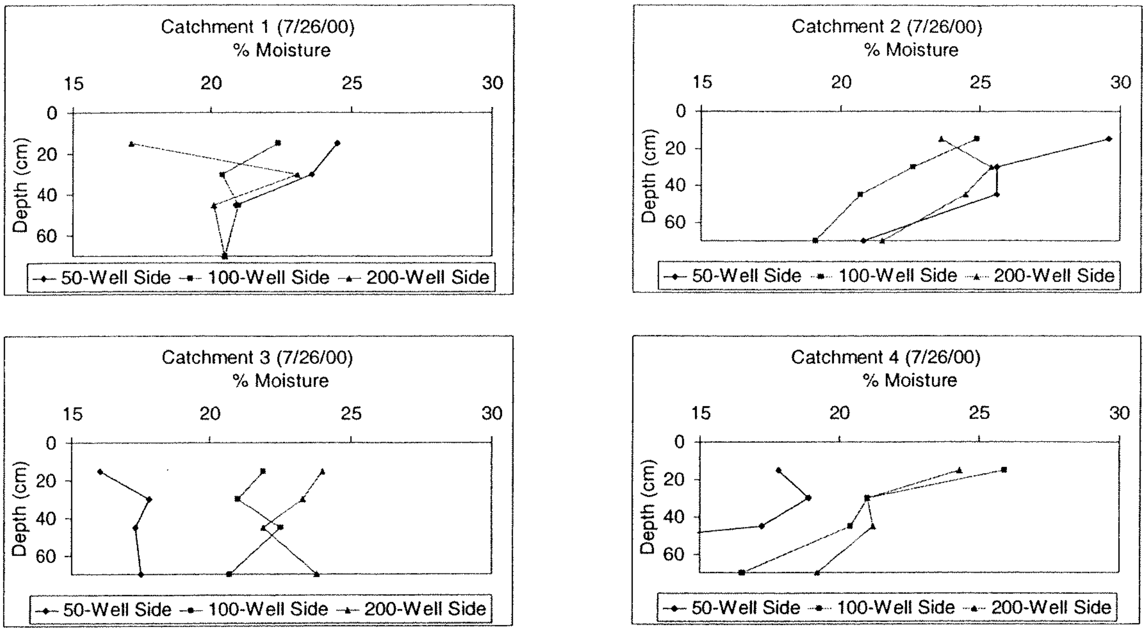

Figure 7. Soil Moisture versus depth on 7/26/2000.

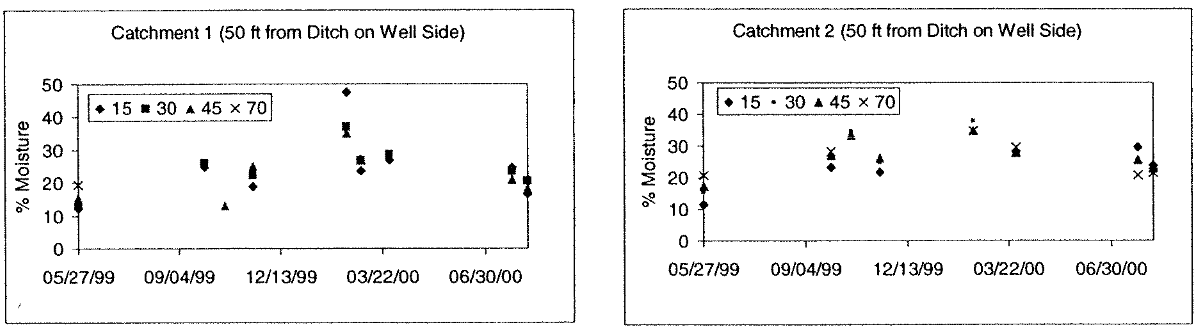

Figure 8. TDR readings in Catchments 1 and 2.

Model Description – WATRCOM

The computer simulation model (WATRCOM, 2-D, for 3-dimensional areas) was developed for analyzing water movement in small drainage districts. The three-dimensional water management model was developed for situations where multiple intersecting channels affect water movement and conservation (Parsons et al. 1991a and b).

The model is based on a mass balance of water in the simulated area. The area can vary in size and shape. A schematic representation of the water flows for the mass balance is shown in Figure 9.

The mass balance for any time period, DT, in equation form can be described as:

DELSAT + DELUNS = RAIN + AET + OUTFLOW – RO – RSTOR – PSTOR **(1)**

where DELSAT = the change in the volume of water stored in the saturated zone in cm^3 per unit surface area, DELUNS = the change in the volume of water stored in the unsaturated zone in cm^3 per unit surface area, RAIN = the amount of rainfall in cm^3 per unit surface area, AET = the actual evapotranspiration in cm^3 per unit surface area, OUTFLOW = the lateral flow across the boundaries in cm^3 per unit surface area, RO = the amount of surface runoff from the region in cm^3 per unit surface area, RSTOR = the change in potential runoff in retention storage at the end of the period in cm^3 per unit surface area, and PSTOR = the change in detention storage at the end of the period in cm^3 per unit surface area. Note that all quantities are given as volume of water per unit surface area and can be expressed as equivalent depth of water over the area.

At the start of each day during the simulation, weather data are read from input files, one for potential evapotranspiration and one for rainfall. The potential evapotranspiration data is stored as daily values. The input file for rainfall is organized as breakpoint data with a starting and ending time and an amount of rainfall. A water balance is conducted by solving equation 1 with a time step of 4 hours for days with no rainfall. On days with rainfall, a time step of 2 hours is used for the period with rainfall and 4 hours for the remainder of the day. The daily potential evapotranspiration is distributed evenly over time steps without rainfall. The breakpoint rainfall periods are split according to the 2 hour time steps such that the last time step period will be of length, less than or equal to 2 hours, to complete the breakpoint period.

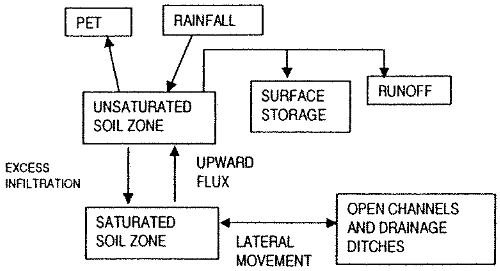

Figure 9. Schematic representation of the water flows simulated in the water management model, WATRCOM.

The change in the water in the saturated zone, DELSAT (Equation 1), is determined by solving the Boussinesq equation (van Schilfgaarde 1974) for saturated flow. The equation may be written as

$$f(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K(h)h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h)h\frac{\partial h}{\partial y}\right)+R \qquad \mathbf{(2)}$$

where f(h) = drainable porosity function of water table height, h = water table height above the impermeable layer in m, K = lateral saturated hydraulic conductivity function of water table height, h, in m/d, R = vertical recharge rate in m/d at the water table at each location in the region, x, y = location coordinates of the region in m, and t = time in days.

Equation 2 is based on the Dupuit-Forchhiemer assumptions that flow is primarily parallel to the impermeable layer. The equation is two-dimensional but enables the analysis of three-dimensional areas since the third dimension, h, is found. In the original form of the equation, boundary conditions are the specified water levels in the open channels throughout the area. These are assumed to be known, but may vary with time. In some cases a zero lateral flux is specified for certain boundaries. In addition to these boundary conditions, the model also handles controlled drainage outlets. A schematic representation of the saturated portion of the model is presented in Figure 10.

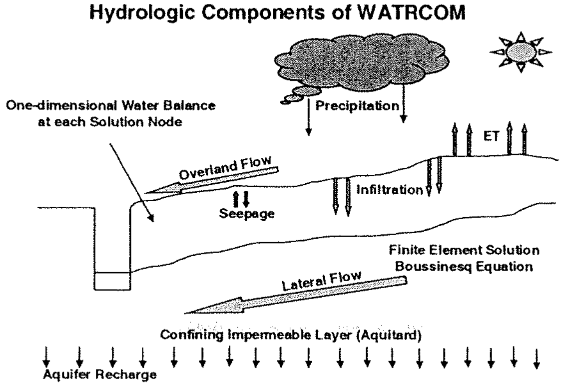

Figure 10. Schematic representation of the water flows simulated in the saturated zone along with linkages to the unsaturated zone.

The drainable porosity, f, and the lateral saturated hydraulic conductivity, K, are functions of space and water table height. The vertical recharge rate, R, at the water table boundary is determined at each time step based on the conditions in the unsaturated layers.

Equation 2 is solved using the Galerkin finite element procedure with linear interpolation functions. The region is divided into triangular elements (Norrie and de Vries 1978). These elements are used to discretize equation 2 into a system of nonlinear equations. This system of nonlinear equations is solved at each time step to determine the water table elevations each node in the area.

The changes in the unsaturated zone, DELUNS, are computed by finding the change in the available water during the day. The water in the unsaturated zone is assumed to move vertically. A one-dimensional water balance is performed at each node defined by the finite element grid (Skaggs 1978 and 1980). The water balance consists of routines for the extraction of water for evapotranspiration and the addition of infiltrated rainfall.

Extraction and addition of water in the unsaturated zone is done by layers. At the start of the simulation, the root zone layers are assumed to be at the water contents associated with a drained to equilibrium profile. The drained to equilibrium amount for each layer is found from the soil water characteristic curves using the water potential corresponding to the distance from the midpoint of the layer to the water table. The drained to equilibrium amount is assumed to be the maximum amount of water the layer will contain when the water table is at a given depth. Any water greater than this amount is assumed to drain to the next layer. Extraction of water from each layer is limited to a lower amount assumed to be the wilting point for the soil. Water requirements greater than the lower limit create a water deficit in the root zone, that is, available water is less than the demand.

As the root zone dries, the volume of water drained for a drop in water table depth will decrease since the root zone is no longer at drained to equilibrium. To be correct, an adjustment should be made to the drainable porosity function and hence the volume drained amount for each water table depth as the root zone dries. Analyses of the magnitude of the adjustment were conducted during the development of WATRCOM. The results indicated that for the worst case, a crop root depth of 45 cm, dried to the lower limit, the volume drained amounts are in error by less than 12% for the deeper water tables. The error in the drainable porosity for water table depths greater than 1.5 m is generally less than 6%. Due to the complexity of the model and the magnitude of the error, no correction is made and the computation of the volume drained is done based on the drained to equilibrium assumptions.

For time steps with evapotranspiration, any water ponded on the soil surface is used to meet the evapotranspiration first. Next, the amount of water, which will potentially move from the water table vertically into the root zone is found using tables of vertical upward flux versus water table depth from an evaporating surface. These tables are derived from the soil water characteristic and the unsaturated hydraulic conductivity curves for each soil type (Skaggs 1978 and 1980). The water table depth is used to find the vertical upward flux. This amount represents the potential amount of water, which will move into the root zone to supply evapotranspiration. If the potential evapotranspiration is less than this amount, then the actual evapotranspiration, AET, and the vertical upward flux, UPF, are set equal to the potential evapotranspiration amount and no water is extracted from the root zone.

If the potential evapotranspiration is greater than the vertical upward flux, UPF, then the difference between the vertical upward flux, UPF, and the potential evapotranspiration is extracted from the root zone water. The extraction takes place layer by layer from the soil surface downward to the last layer in the root zone. Water is extracted from each layer until the amount available in the layer reaches the lower limit (assumed to be the wilting point water content). The procedure stops when all the water in the root zone has been depleted or the remaining potential evapotranspiration demand is met. In the case where the water in the root zone is depleted, the actual evapotranspiration will be less than the potential creating a deficit. The model's water balance for extraction can be written as:

$$\mathbf{AET = WSP + RZW + UPF} \qquad (3)$$

where AET = the actual evapotranspiration in cm, WSP = the amount evaporated from the water ponded on the surface in cm, RWZ = the amount of water supplied from the root zone in cm, and UPF = water moving vertically from the water table to the root zone to meet the evapotranspiration demand in cm.

The coupling of the water extraction routines with the saturated portion of the model is accomplished using the UPF term in equation 1. As the water table becomes deeper, less water will move into the root zone to meet the evaporative demand. Additionally, the water available in the root zone will decrease since the hydraulic head associated with the drained to equilibrium water content will decrease as the distance from the root zone to the water table increases. The upward flux from the water table to meet evapotranspiration, UPF, is converted to a rate and used as the recharge term in equation 2. This balancing of water extraction is done for each node in the finite element grid.

For the purpose of this model, a rainfall event is assumed to extend from the time rainfall starts until rainfall has stopped and all water on the surface has either infiltrated or runs off the area. The amount of infiltration is determined using the Green-Ampt equation with the assumption that the parameters are a function of the water table depth and soil type (Green and Ampt 1911; Mein and Larson 1973; Brakensiek 1977; and Skaggs 1980). The equation is given by

$$INF = \frac{A}{F} + B \tag{4}$$

where INF = the infiltration rate in cm/d, A = a coefficient derived from the soil properties in cm^2/d, B = a coefficient derived from the soil properties in cm/d, and F = the cumulative infiltrated water in cm.

The coefficients A and B are derived as functions of the soil properties and the soil water content at the time rainfall starts. The equations for A and B are

$$\begin{aligned} A &= K_s S_{av}(\theta_s - \theta_i) \\ B &= K_s \end{aligned} \tag{5}$$

where K_s = the vertical saturated conductivity in m/d, S_{av} = the effective suction at the wetting front, θ_s = the volumetric saturated water content in cm^3/cm^3, and θ_i = the initial volumetric water content in cm^3/cm^3. An estimation of the effective suction at the wetting front, S_{av}, can be found in Brakensiek (1977).

At the start of a rainfall event, when F = 0, a routine is executed to infiltrate some water to obtain an initial nonzero value for F. The Green-Ampt parameters A and B for the water table depth, adjusted by the depth of the dry zone, at the start of the rainfall event are found and these parameters are used throughout the rainfall event.

From the Green-Ampt parameters, an estimate of the amount of water, which can be infiltrated before ponding will occur, is obtained. The rainfall intensity, RFI, is computed and compared to the parameter B. If the rainfall intensity is less than the parameter B, then the rainfall for this time step can be infiltrated. Otherwise, the amount of infiltrated water at ponding is given by

$$INF = \frac{A}{(RFI - B)} \tag{6}$$

This water, INF, is added to the root zone layer by layer starting from the soil surface. Water is added to each layer until the drained to equilibrium amount is reached. Any excess after all layers are filled is converted to a rate and added to the vertical recharge for the water table, R.

The rainfall balance equation is given by

$$RAIN = SUR + INF \tag{7}$$

where SUR = the amount of water added to the soil surface storage during this rainfall period in cm. The amount remaining on the surface is the difference in the rainfall over the time step and amount of infiltration. For the remainder of the first time step and subsequent time steps during the rainfall event the rainfall is balanced using equation 7. During the first time step, the rainfall in excess of infiltration after ponding begins is added to the term SUR.

For each time step after the first, the amount of infiltrated water is computed using the Green-Ampt equation, equations 4 and 5. A running total of infiltration, the cumulative infiltration, F, is kept after rainfall starts. The model attempts to infiltrate the rainfall for the time step in small amounts, DR. This small amount, DR, is added to the cumulative infiltration, F, and an infiltration rate, INF, is computed using equation 4. The amount of time required to infiltrate DR is found and summed to a time counter. If the time counter exceeds the time step size, then the amount of infiltration DR is adjusted for the remaining time in the time step and any remaining rainfall is added to the surface storage term, SUR. The infiltrated water is added to the root zone layer by layer until the drained to equilibrium amounts for each layer are reached. Any amount greater than the drained to equilibrium value is converted to a rate and added to the vertical recharge term, R, for the water table. The water balance for infiltration can be written as

$$INF = WRZ + WWT \tag{8}$$

where WRZ = the amount of infiltration added to the root zone in cm and WWT = the amount of infiltration in excess of that added to the root zone which goes to vertical recharge of the water table in cm.

During time steps where there is water on the surface, SUR > 0, the model executes routines to distribute this water by overland flow. The water on the surface is present in retention storage and detention storage. The retention storage is the surface depression storage, which will be infiltrated or evaporated, and never leave the node. The detention storage is the film of water in excess of the retention storage, which will eventually move to surrounding nodes.

The first step in the overland flow routines is an ordering of the nodes from largest total elevation to smallest. The total elevation is defined as the sum of the surface elevation, retention, and detention storage. At any node with detention storage, runoff can occur to any surrounding node within the time step. Each node is assumed to have an associated area. This area consists of the sum of one-third of the area in each triangular element the node is a part of. The movement of water on the surface between any two nodes is described as open channel flow in which the width of the channel is much greater than the depth. The routine uses Manning's equation to compute the potential depth of water at the end of the time step at each surrounding node. Manning's equation for a wide rectangular open channel, (Chow 1959), is given by

$$Q = S^{\frac{1}{2}} W d^{\frac{5}{3}} \frac{1}{n} \tag{9}$$

where Q = the discharge in m^3/d, S = the slope of the free water surface between the node of interest and the surrounding node, W = the width of the flow corridor between the two nodes of interest in m, d = the average depth of water in the flow corridor between the node and the surrounding node in m, and n = the Manning's roughness value.

The discharge, Q from equation 9, is converted to the depth of water at the surrounding node using the area associated with the node. This assumes the potential runoff is distributed over the area of the node. The discharge value is also converted to the depth leaving the node and summed to find the total potential depth of water to leave the node. After all the potential depths for all surrounding nodes are computed, the total potential depth to leave the node is compared to the actual depth of water in detention storage at the node. If the actual depth in detention storage is less than the potential depth to leave the node, the potential depths to the surrounding nodes are adjusted to reflect the actual detention storage. The total depth of water leaving the node reduces the depth of water in detention storage at the node and the depths of water arriving at the surrounding nodes are adjusted. Runoff can leave the area via the boundary of the flow domain. Water on the surface arriving at the boundary nodes is runoff and leaves the area. This water is the RO term in equation 1. The water left in retention storage for each node at the end of the time step is in the PSTOR term in equation 1 and the water left in detention storage at the end of the time step is represented by the term RSTOR in equation 1.

The subsurface lateral outflow from the region is computed along each boundary element using the water table elevations and the hydraulic conductivities, h and K, at the element's nodes. **Figure 11** shows a section of a possible finite element grid along a boundary. The estimate of the flow perpendicular to boundary side of element e with nodes i and j can be found as follows. Find the point, p, on side ij where the perpendicular from node k intersects. Let L be the length of the perpendicular and b be the length of the boundary side between nodes i and j. Values of h and K are computed for this point using weighted averages of h and K at nodes i and j. Let K_p and h_p represent these averages. Along the perpendicular from node k to the boundary, the water table shape is assumed to be an ellipse with a major axis of L and a minor axis of $(h_k - h_a)$. Let K_a and h_a be the K and h values at a point halfway along the perpendicular to the boundary assuming the elliptical water table shape, then the discharge is given by

$$Q = -\left(K_a h_a \frac{(h_p - h_k)}{L} \right) b \tag{10}$$

These discharges are summed along each boundary for lateral outflow from the region.

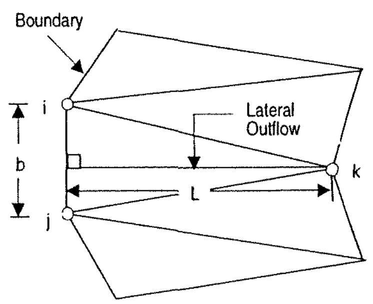

Figure 11. A diagram of the parameters used to compute the subsurface lateral flow at the boundary.

Graphical User Interface

A graphical user interface is being developed for WATRCOM to enable easier application of the model to projects such as this. A prototype of the interface has been completed. The interface organizes model applications into project files (Figure 12). From the project files, the user can select and edit parameter inputs along with specifying the level of output and the output files. Figure 12 shows a typical screen for editing the input parameters. One of the most difficult tasks to apply the model is the development of finite element grids for the area of interest. This version of the user interface provides some tools to help the user with this task (Figure 13). Current development is proceeding to interface the graphical front end with ArcView mapping files from a project area.

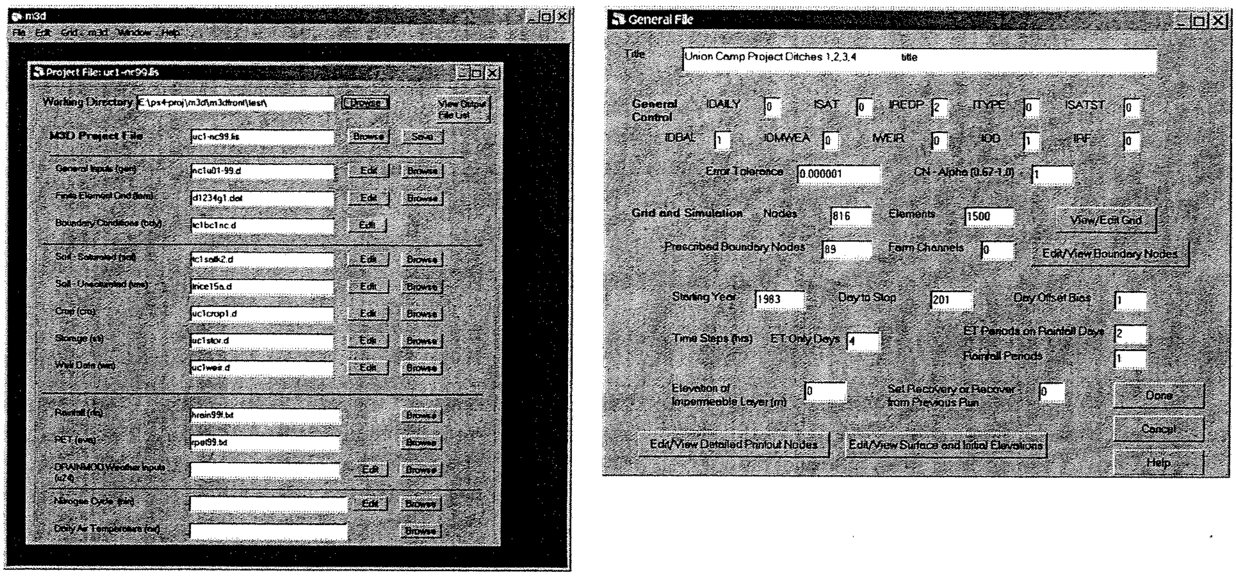

Figure 12. Simulations are organized by project files and all parameters inputs can be edited.

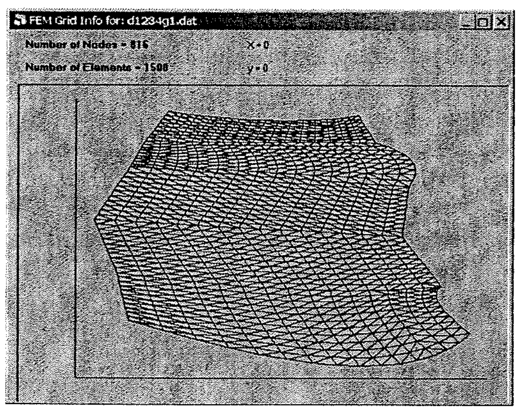

Figure 13. Editing the finite element grid.

Simulations

The simulation site for catchments 1 - 4 is shown in Figure 14. Water control structures were installed in ditches 2 and 4 in July 1999. The control structures in these ditches were raised to within 0.6 m of the surface to control the outflow from these areas. This area represents about 20% of the drainage basin for the main outlet channel (Figure 1). A triangular grid was created for the area consisting of 816 nodes. Input parameters were assigned for each node based on the topography and soil type using measured data where possible. The main drainage channel and each catchment were treated as boundary conditions. The first set of simulations was conducted to examine the feasibility of using water level control structures in ditches 2 and 4. The next group of simulations was done to evaluate the applicability of WATRCOM to this site by comparing observed flows from each catchment with simulated values.

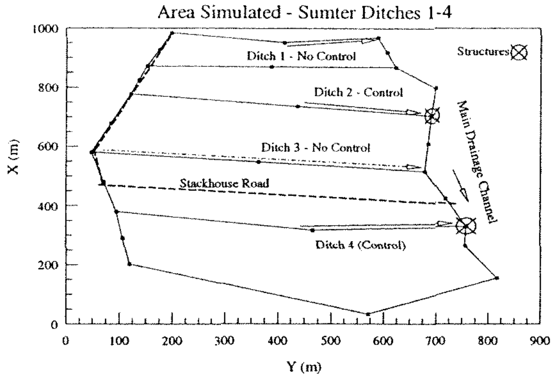

Figure 14. Simulation Area for WATRCOM.

Feasibility of Controlling the Outlets in Catchment 2 and 4

Two simulations were conducted to demonstrate the feasibility of installing the control structures for water conservation on ditches 2 and 4. The first simulation (Control) assumes that the outlets from Ditches 2 and 4 are raised to within 0.5 m of the surface from day 60 - day 300. For the second simulation (No-Control) all ditches 1-4 and the main are assumed to be near empty - at a level of 1.2 m below the surface and allowed to drain freely. Both simulations were done for 1996 weather data from the Sumter, SC. Figure 15 shows the contrast in water tables on day 150 of the simulations. The bottom plane shows a projection of the water table surface as a contour map. In the both figures, light gray areas represent the drier zones (directly below the uncontrolled ditches). In the controlled setting, the area below ditches 2 and 4 are wetter than in the uncontrolled scenario. The channel does not influence the dark gray areas in the figure. One of the potential benefits of the control includes the ability to supply water to the trees via capillary movement into the root zone from the shallower water table. An additional benefit that we will attempt to quantify with the model is the change in nitrogen dynamics. The controlled ditches should also help reduce off-site flow of nutrients. There may also be the opportunity to utilize some of the water stored in ditches 2 and 4 for a source of irrigation water - however, we still need to do some investigation of the viability of this. Some of the linkages of the modeling effort to other aspects of the project include: 1) the need information related to root depths and water extraction by the trees, 2) leaf area index information for relating tree growth to the nutrient dynamics, 3) nutrient uptake and concentrations in the trees to aid in the N-modeling effort, and 4) the collection of leaf litter information will help with the organic nutrient dynamics along with developing relationships between rainfall, stem flow and infiltration.

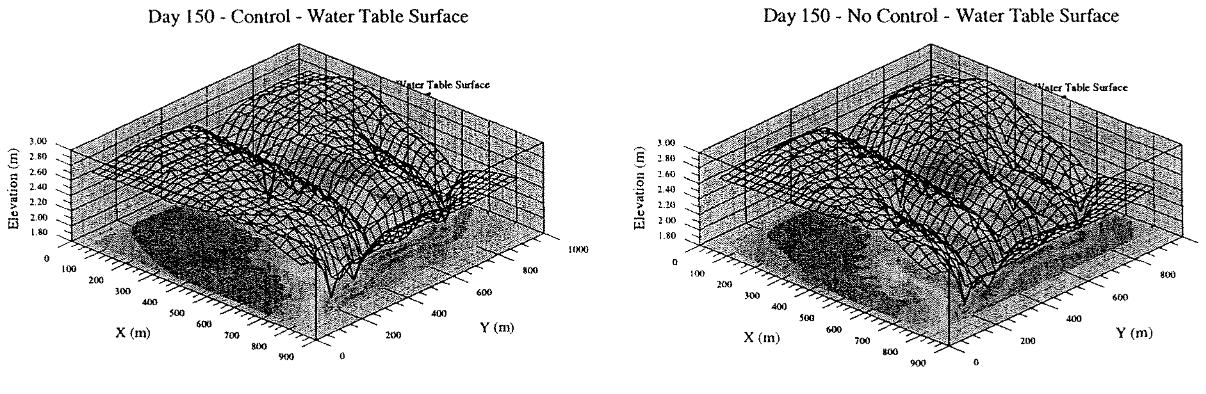

Figure 15. **Snapshot of the Water Table Elevation on Day 150 with and without Control Structures on the Outlets of Catchments 2 and 4.**

Figure 16 compares the discharge from ditches 2 and 4 with and without control. From day 60 - day 300, period with controlled drainage, very little discharge occurred from ditches 2 and 4 for the controlled scenario. In the controlled drainage situation, only the rainfall event around day 150 yielded discharge from ditches 2 and 4. The remainder of the time, the flow of water was from the ditches to the adjacent soil profile. This situation could be exploited by pumping irrigation water from ditch 2 and 4. However, the frequency and amount would need to be determined based on the ability of the adjacent land to recharge the ditches. Although this can be done with WATRCOM, it was not done with these simulations.

For the no control simulations, the discharge from the ditches was always greater than 10 m^3 per day. The net flow from the soil profile resulted from higher adjacent water tables than the assumed ditch water levels (bottom assumed for the No Control Simulations). The peak subsurface drainage events to ditches 2 and 4 are also shown in Figure 16. Comparing the discharge during the control periods between the with- and without control situations reveals that drainage to the ditches is slowed considerably with control. Again, the ability to recharge ditches 2 and 4 in the controlled drainage scenario will depend on many factors including the evapotranspiration of the trees, the lateral saturated conductivity, and the amount and frequency of water withdrawal from the ditches.

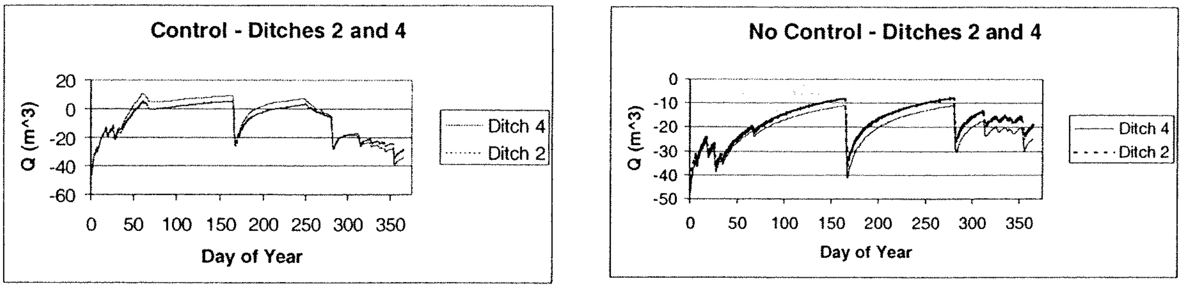

Figure 16. **Discharge, Q, from ditches 2 and 4 with and without control.**

Testing and Evaluation of WATRCOM

The next set of simulations compare observed flow data from each catchment with simulated values. Input data sets for WATRCOM were developed from field measurements. In cases where measurements were not available, estimates were made based on the site characteristics and tables and other information sources such as NRCS soils databases. For these simulations, the topography of the site was assumed to be flat although the elevation change within catchments 1-4 is approximately 1.5-2.0 m with land slopes generally less than 2%. For the application of WATRCOM, an impermeable layer was assumed to be present at 1 m below the ditch bottoms yield a soil surface elevation of 4 m above this layer. The ditch bottoms were assumed to be at 1.5 m above the impermeable layer. Surface depression storage was estimated at 0.1 m. The unsaturated inputs for the area were determined from the soil water characteristic data measured on each catchment. The saturated hydraulic conductivity data were measured from the soil cores for the shallow layers and estimated for the deeper layer. The soil water characteristic data was used to estimate the drainable porosity for each catchment. Table 1 shows the saturated hydraulic conductivities for each catchment.

Table 1. Saturated hydraulic conductivity (m/d) input data by catchment and soil layer.

Catchment	**Bottom Depth of Layer**		
	0.2 m	**0.6 m**	**4.0 m**
1	1.0	0.1	1.2
2	0.2	0.2	2.0
3	0.4	0.2	3.5
4	3.5	0.7	0.4

Model testing was done for the 1999 and 2000 flow data from each catchment. The monthly rainfall and potential evapotranspiration for the simulation period along with long-term data is shown in Figure 17. Simulated discharge into each catchment ditch was compared with measured data (Figure 18 and Figure 19). Due to the lack of rainfall during the summer of 1999, reference measurements for the ditches draining catchments 1 and 2 have not yet been computed. The measured flow data procedure requires an ending stage measurement to verify the previous stage measurements for each data set. During the summer of 1999, the timing of data collection in catchments 1 and 2 has corresponded to no flow conditions resulting in no ending stage measurement to verify the previous data sets. Flow during these periods will be calculated once a valid stage measurement is obtained at a future download time.

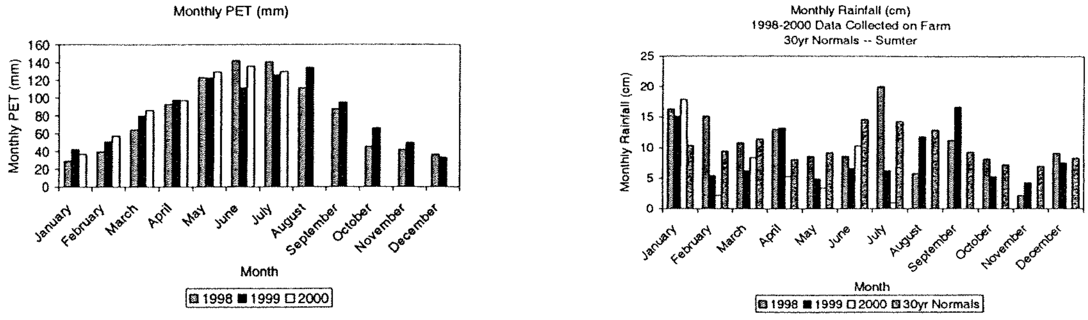

Figure 17. Monthly rainfall and potential evapotranspiration for 1998-2000.

In catchments 1-4, WATRCOM did a good job simulating the trend in discharge from each of these areas. However, the peak discharge events tended to be underestimated. In this first iteration of model testing, the surface depression storage was estimated at 0.1 m, which resulted in no surface runoff. This underestimation may be due in part to surface runoff from the catchments. Our flow measurements do not account for this separately from the subsurface discharge measurements. This possibility of underestimating surface runoff can be seen the results from catchments 1 and 4 for the events that occurred on days 24 and 121, 1999 (Figure 18). For example, in catchment 2 the measured discharge for day 24 was 513 m^3 and the simulated discharge was 152 m^3. In catchment 2 the measured discharge for days 23 and 25 were 224 m^3 and 282 m^3, respectively, for daily rainfall amounts of 4.4 cm and 2.3 cm on days 22 and 23, respectively. For days 23 and 25, WATRCOM underestimated discharges of 162 and 140 m^3, respectively. Although, these underestimations are not good, we are encouraged that the trends were predicted correctly. The current version of WATRCOM uses a fairly simplistic overland flow routing scheme, which can be improved to better reflect surface runoff contributions. These changes are currently being implemented. This should enable much better comparisons.

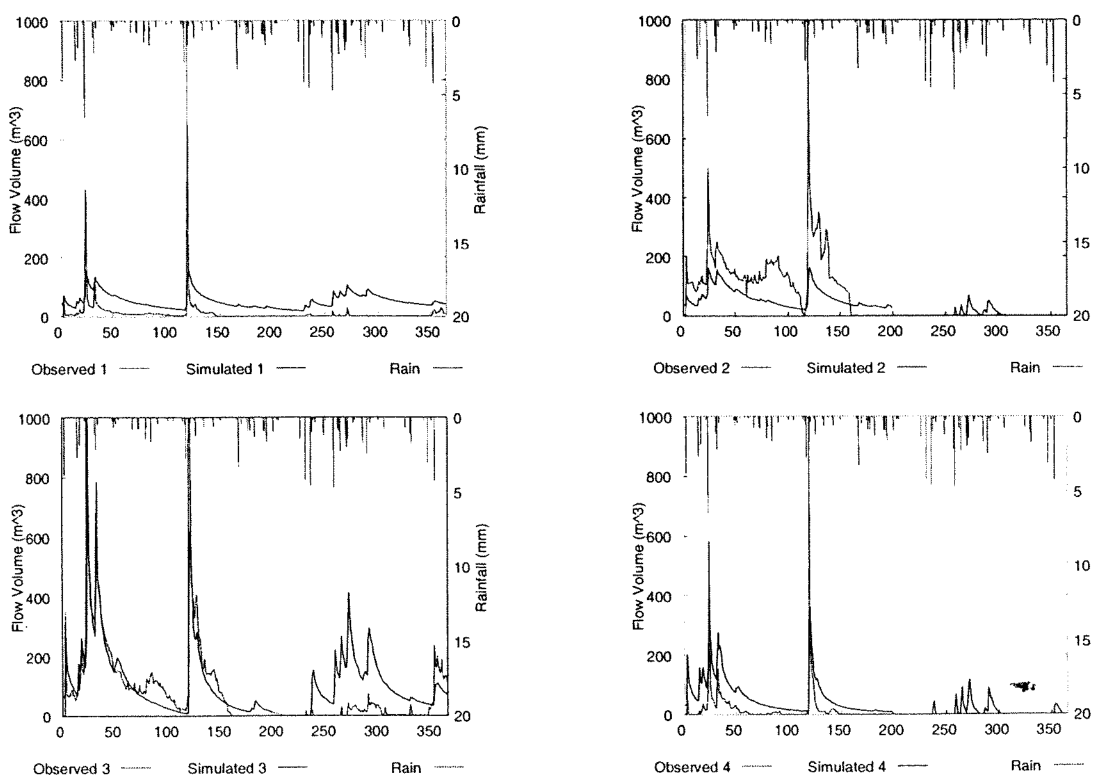

Figure 18. Comparison of Outflows for each Catchment for 1999.

In 2000, little flow was measured from the controlled catchments (2 and 4). The model predicted some flow from catchment 4 for the rainfall events in late January (Figure 19). In 2000, the model did not show the rapid decline in discharge measured in catchment 3. This is probably due to more of the measured discharge being due to surface runoff than subsurface drainage. Again, this is an area of the model we will be improving in our future efforts.

It should also be noted that these results were without any prior calibration using input parameters derived from on-site measurements. Calibration of WATRCOM would probably result in better fits to the measured data.

Comparison of measured discharge from the main outlet was not done. In this case, WATRCOM simulates only the direct seepage and runoff to the main outlet in the simulation area. The total simulated discharge to the outlet from the simulation area was assumed to be the sum of the discharge amounts from catchment 1-4 along with the direct seepage to the main outlet. From examining the watershed maps of the area (Figure 1), we assumed that this represented 20% of the area drained by the main outlet.

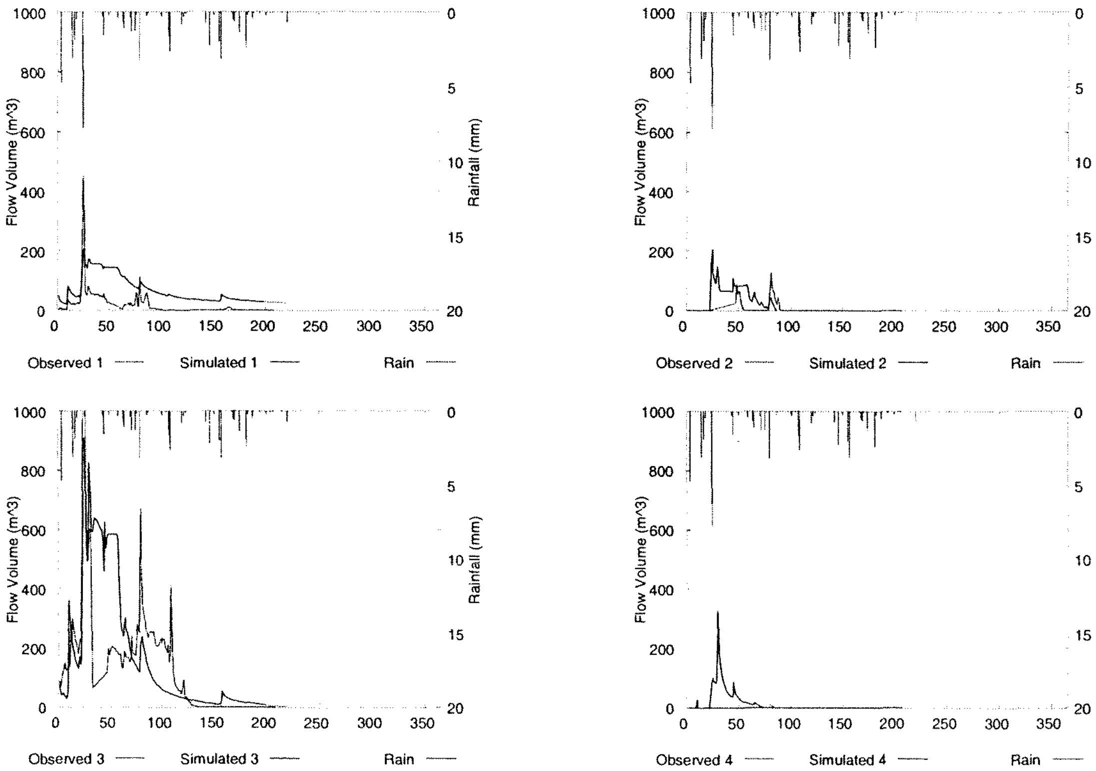

Figure 19. Comparison of Outflows for each Catchment for 2000.

Summary and Conclusions

A watershed-scale project was developed near Maysville, SC to study water and nutrient relationships on short rotation hardwood plantations in the Coastal Plain region of the Southeastern US. Six catchments (approximately 4.05 ha) were instrumented to monitor water tables, unsaturated soil water and drainage outflows. In 1999, flashboard riser structures were installed in the outlet ditches of two of the catchments.

Input datasets for the water management model, WATRCOM-2D were developed for the area with catchments 1 – 4. These were used to evaluate the potential benefit of the flashboard riser structures in catchments 2 and 4. These evaluations indicated that WATRCOM-2D was potentially applicable to the area along with showing that there was potential water management benefits from the structures.

Subsequent simulations were conducted with WATRCOM-2D to test the model's performance against field observations. Measured discharge data from catchments 1 – 4 was compared with simulated data for 1999 and 2000. Overall, WATRCOM-2D did a good job simulating observed discharge trends from each of the catchments. For major discharge events, the model underpredicted the discharge, which was probably attributable to weakness in WATRCOM-2D's surface runoff prediction algorithms.

Work is proceeding on a graphical user interface for WATRCOM-2D to link the model with mapping data from ArcView geographic information system. Additional evaluation and work is also being done on the surface runoff algorithms to better predict discharge events in which runoff dominates the flow.

Acknowledgements

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