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An Overview of Hydrologic Studies at Center for Forested Wetlands Research, USDA Forest Service

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Abstract. *Managing forested wetland landscapes for water quality improvement and productivity requires a detailed understanding of functional linkages between ecohydrological processes and management practices. Studies are being conducted at Center for Forested Wetlands Research (CFWR), USDA Forest Service to understand the fundamental hydrologic and biogeochemical processes linking aquatic and terrestrial eco-systems. The first study is based on the long-term experimental watersheds established in 1960s on the USDA Forest Service Santee Experimental Forest, with the purpose of quantifying the soil moisture dynamics, flow regimes, and water chemistry of low gradient forested wetlands in South Carolina. In a cooperative research with North Carolina State University, a long-term study is being conducted at Weyerhaeuser Company's managed pine forest in Carteret County, North Carolina to quantify the effects of various water and silvicultural management impacts on the hydrology and water quality. A third long-term ecosystem study on*

MeadWestvaco's Coosawhatchie River bottomland hardwood site in South Carolina addresses recent public concerns on the need of protection, restoration, and sustainable management of forested wetlands. A fourth study conducted between 1997 and 2000 evaluated the plantations hydrology and water quality of intensively managed Short Rotation Woody Crops on International Paper's Trice Experimental Forest in the upper coastal plain of SC. A fifth study was recently conducted at MeadWestvaco's Carolina Bay site also in the SC upper coastal plain to assess the surface water and groundwater interactions between Carolina bays and their surrounding uplands.

Keywords. Ecosystem, Watershed, Vegetation, Hydroperiod, Drainage, Nutrients, Models.

Introduction

Managing forested wetland landscapes for water quality improvement, quantity control, and productivity requires a detailed understanding of functional linkages between ecohydrological processes and management practices. This requires an accurate understanding of hydrologic and nutrient cycling processes that occur across landscapes. Multiple land use components such as forests, wetlands, uplands and water bodies in a landscape complicate our understanding of watershed-level hydrologic processes. Even greater complexity is added when agricultural and urban lands are considered.

Scientists have for a longtime recognized the need for long-term ecohydrologic monitoring of watersheds to understand the basic physical processes that occur as a result of both natural events and anthropogenic disturbances and their interactions with management practices. Long-term monitoring provides us with a base line data as a basis for impact assessment and conservation of regional ecosystems, evaluating responses and generating new scientific hypotheses, and a wide range of observational data for testing of hydrologic and water quality models. The Southern Forest Resource Assessment (SOFRA, 2002) emphasized a need of research to assess the long-term cumulative non-point source impacts of silvicultural activities on water quality and overall watershed health. In order to evaluate the effects of these activities and develop database for reference wetlands on these various forest ecosystems, it is essential to understand the hydrologic processes and quantify the long-term hydroperiod dynamics and water and nutrient budgets.

Long-term hydrologic data from small, paired, experimental forested watersheds at Coweeta Hydrologic Laboratory in North Carolina (NC) integrated with an ecosystem approach have provided basic understanding of eco-hydrological processes for regional upland watersheds (Swank et al. 2001). Tajchman et al. (1997) reported the water and energy balance of a 39 ha central Appalachian watershed covered with 80-yr old upland oaks and cove hardwoods using 40 years of hydrologic data. However, there are only a few such observational studies done for the forested landscapes that occur along the lowlands of southeastern coastal plain. These landscapes are comprised of natural and managed forests, depressional wetlands, pine flatwoods, riparian buffers, bottomland hardwoods (BLH) on brackish waters. They are characterized by poorly drained high water table soils due to both wet sites and low topographic relief. Some of these wetlands have been artificially drained to lower water tables for providing both trafficability and reducing excessive moisture for crop growth. Unlike the upland watersheds dominated by hillslope processes, hydrologic processes on relatively low gradient poorly drained coastal plains are usually dominated by shallow water table positions. Most of the outflows (surface runoff and subsurface drainage) from these watersheds, in fact, drain from saturated areas where the water is either at the surface or a shallow water table is present. This means the total outflow is dependent upon the position of the water table (hydroperiod), which is driven by rainfall and evapotranspiration (ET). ET, on its part, although is primarily controlled by solar energy (potential ET), it is also dependent upon soil type and vegetation type and its seasonal dynamics. Thus through interactions with vegetation and soils, hydrology plays a key role in various wetland functions that have great societal and economic values. An important function of these wetlands in the southeastern coastal plains is timber production. Many wetland areas, if properly managed, are productive silvicultural and agricultural lands with both economic and environmental benefits. However, only a few studies have been done on understanding the processes of the depressional wetlands, BLH, pine flatwoods and their interactions with surrounding uplands (Pyzoha, 2003; Burke and Eisenbies, 2003).

In the last two decades, there has been a growing concern over the impact of both human activities (forest management, land use conversion, agriculture and urbanization) and natural disturbances (droughts, fire, floods, and hurricanes) on the hydrologic and nutrient cycling, as well as export processes of forested wetlands. Particularly, hydrologic and water quality impacts of sustainable forest management practices (e.g. harvesting, site preparation, bedding, regeneration, and thinning of pine forests) on receiving water bodies are becoming an important issue. Timber harvests in the South are expected to increase over the next 20 years, and it is likely that impacts to forested wetlands as a result of increasing and intensified forestry will continue (SOFRA, 2002). Studies show that removing the forest canopy reduces ET, elevates the ground water level (Grace et al., 2003; Xu et al., 2002; Sun et al.,2000a), and increases the water yield from a forested site until the canopy is regenerated. Potential negative impacts may include increased total maximum daily load (TMDL) into water bodies, contaminated drinking water source areas, increased peak flows, decreased low flows, and compromised ground water and stream water levels. Without proper management, effects may be far reaching, such as impacts on brackish habitats essential for juvenile development of marine fish and shellfish species. Studies in North Carolina have shown that water management using controlled drainage can be used to reduce nutrient and sediment loadings, primarily due to reduction in peak outflows, from intensively managed pine plantation on poorly drained soils. Similarly, other studies have shown the benefits of using riparian buffers for reducing the impacts (NCASI, 1994; Dissmeyer, 1994; Wynn et al., 2000). However, there is a lack of information on harvesting and regeneration impacts on water quantity and quality of the forested wetlands. SOFRA (2002) indicated that additional studies are needed of the water-quality effects (e.g. nutrient loading, of increased spraying of fertilizers and pesticides) of the intensive forest management treatments in streams and watersheds.

A few studies have recently documented some of the impacts on soil properties, hydrology and water quality as a result of harvesting and subsequent regeneration of pine forests in the poorly drained lowlands of Atlantic Coastal Plain (Grace et al., 2003; Xu et al., 2002; Sun et al., 2001; Blanton et al., 1998; Lebo and Herrmann, 1998; Amatya et al., 1997; Crawford et al., 1992; Ursic, 1991; Riekerk, 1989; Swindel et al., 1982). Shepard (1994) reviewed results of effects of silvicultural practices on water quality from nine wetland forest sites and found that harvesting timber raised nutrient concentrations, with concentrations decreasing to “natural” levels after one to four years. Sun et al. (2001) in their synthesis study on effects of timber management on wetland forests reported that the hydrologic impacts of various forest management practices across the southern US are variable, but generally minor, especially when forest best management practices (BMPs) are adopted. Using a conceptual model, the authors suggested that in addition to soils, wetland types, and management options, climate is an important factor in controlling hydrology and magnitude of disturbance. Chescheir et al. (2003) reported the baseline outflow and nutrient characteristics of pine forested watersheds using more than 100 site years of hydrology and water quality data from the coastal North Carolina sites. In recent years, short rotation woody crop is being investigated as an alternative to growing timber demand in the southeast. But there is only a limited study on the processes that occur on and hydrologic and water quality impacts of managing SRWC. So base line data from various forested ecosystems are essential for evaluating the impacts of management practices and climate and also for developing and testing models (Amatya et al., 2003a; Amatya and Skaggs, 2001; McCarthy et al., 1992; McCarthy and Skaggs, 1992; Sun et al., 1998a; 1998b). Hydrologic and water quality models are often used to address the questions on various processes for spatial and temporal time scales that are otherwise impossible using monitoring alone and also for various alternative management decisions. But the models that are applicable to address the complex processes of the low gradient coastal streams both in a field and watershed scales are limited in literature.

The main objective of this paper is to provide an overview of five main experimental studies that have been or are being conducted by USDA Forest Service, Center for Forested Wetlands Research in Charleston, SC in collaboration with various area institutions, forest industries and other agencies to address issues discussed above using scientific monitoring and modeling approaches. These studies are: (1) Long-term studies at first order headwater streams at Santee Experimental Forest, SC, (2) Long-term studies at managed (drained) pine forest at Carteret County, NC, (3) Long-term bottomland eco-system study at Coosawhatchie River site, SC, (4) Experimental Study on High Intensity Short Rotation Woody Crop site at Trice Farm, SC, and (5) Experimental Study of Depressional Wetlands and their Interactions with Uplands at Burch Farm, SC.

Methods

1. Long-term studies at first order headwater streams at Santee Experimental Forest, SC:

SITE DESCRIPTION:

This naturally drained experimental watershed study site is located at 33^{o}N latitude and 80^{o}W longitude in the Santee experimental forest, which is part of Francis-Marion National Forest (USDA Forest Service) near Charleston, South Carolina (Figure 1, left). A first experimental forested watershed (WS 77) of 160 ha size was established by US Forest Service on a headwater stream (Figure 1, right) in 1963 to conduct studies on hydrologic processes, flooding pattern, and water balance components (especially ET and drainage) for the low gradient, forested wetlands of the humid coastal plain. This is one of the paired watersheds (with WS 80 of 200 ha size) on headwater stream draining to Turkey Creek on the lower Atlantic Coastal Plain (Figure 1, right). Later during 1964 to 1968 Forest Service expanded the experimental study at this site by installing two additional watersheds of larger sizes adjacent to these watersheds. One is WS 79 with 500 ha drainage area on a second order stream containing both WS 77 and WS 80 watersheds and another is WS 78 with about 5000 ha in area drained by Turkey Creek (outlet in Fig. 1, right, but full boundary not shown).

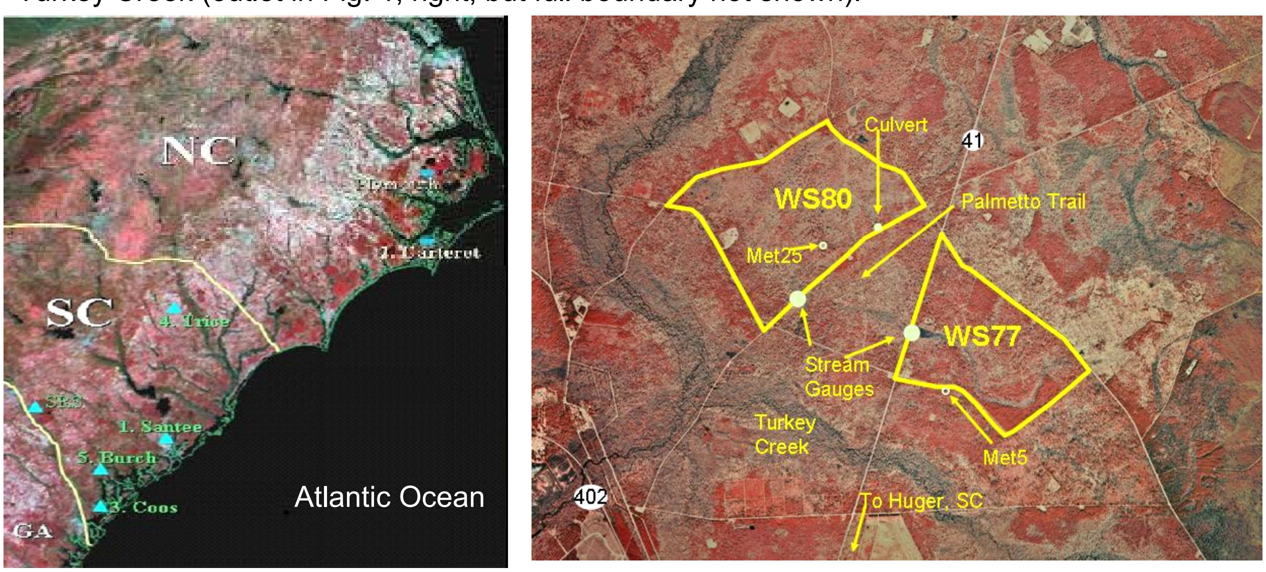

Figure 1. On the left side is the location map of five study sites. Picture on the right side shows two experimental watersheds at Santee Experimental Forest in Coastal South Carolina.

The study site (WS 77 and WS 80) is on a marine terrace of the Pleistocene epoch (Gartner and Burke, 2001). The area has low relief with surface elevations ranging from 4.0 to 10.0 m above mean sea level. Loblolly pine, longleaf pine, cypress, and sweet gum are dominant forest species in the watershed (Sun et al., 2000b). WS 77 (treatment) was salvage harvested soon after Hurricane Hugo in September 1989 as opposed to WS 80 (non-salvaged). WS 77 with naturally grown pine trees has recently had understory burning. Soils are primarily (loams) strongly acid, infertile Aquults, characterized by seasonally high water tables and argillic horizons at 1.5 meters depth with low base saturation (Gartner and Burke, 2001). The climate of the research area is classified as humid subtropical with long hot summers and short mild winters (Sun et al. 2000b). Mean annual precipitation is about 1350 mm with the highest rainfall in July-August and the lowest rainfall in the November-April period as the driest months.

OBJECTIVES

- To quantify the hydrologic processes, flow dynamics and baseline water and nutrient budgets for forested watersheds on headwater streams in the coastal plain.
- To develop and test hydrologic models for these naturally drained coastal forests for evaluating the management impacts and understanding the interactions between soils, vegetation and hydroperiods.
- To conduct long-term ecohydrological studies for coastal headwater forests.

MONITORING:

Measurements of precipitation, weir stage height for flow rates, water quality parameters, water table elevations, and weather data are being collected on WS 77, WS 79, and WS 80 (Figure 1, right and Table 1) for quantifying water nutrient budgets, flow and water table dynamics of these low-gradient forested watersheds. Watershed WS 77 is gauged with a flow recording station upstream of a compound V-notch weir spanning across the stream. Watershed WS 80 has a stream gauging station consisting of a compound V-notch and a flat concrete weir with a recording gage inside a stilling well installed at the watershed outlet in 1968. The flow measurement structure on WS 79 is also a recording gauge upstream of a V-notch weir at the center with two concrete box culverts on either side of it with their bases at the level of the top of V-notch. However, flow measurements on all three watersheds were interrupted in 1981 and did not start again until after Hurricane Hugo in September 1989. Flow data on the largest watershed WS 78 were discontinued in 1984. Automatic ISCO-4210 flow data loggers were installed on WS 77 and WS 80 only in 1996. Flow data were missing for intermittent periods on all watersheds. Water table measurements were measured using manual wells at several locations in the watersheds (WS 77 and WS 80) until 1995 and one automatic recording well (WL-40) on WS 80 and two on WS 77 were installed in late 1995 (Table 1).

Meteorological data (daily maximum and minimum air temperatures and precipitation) have been collected since 1964 at Met-5 station inside the watershed on WS 77 and since 1976 at Met-25 station inside the watershed on WS 80. A complete weather station measuring maximum and minimum air temperatures, solar radiation, wind speed and wind direction was installed in 1946 at Santee Headquarters, which is about 10 km from the watersheds.

Long-term data for daily precipitation, air temperature, and stream flow from this study site is recently being made available through HYDRO-DB, a WEB based data sharing and harvesting site hosted by Oregon State University and sponsored by USDA Forest Service and National Science Foundation's Long term Ecological Research (LTER) study. The site is located at *www.fsl.orst.edu/climhy/hydrodb/* and data from various participating sites are posted here for inter-site comparisons and other useful hydro-ecological assessments including forest fire.

Table 1. Type of infrastructures and their description for each of the four watersheds.

Watershed No.	Drainage area	Estab.	Outlet Design	Associated Data	Condition	Needs
77 (Treatment) (First order, Fox Gully)	160 ha	1963	Compound V-weir	Stage, Soil moisture, Water quality, GW levels, Met station	Good and monitoring continuing (No data 1981- 1989)	Analysis of old data and publications
78 (Turkey Creek)	5000 ha	1964	Outlet in a Dam	Stage, velocity, Flow rates	Discon-tinued in 1984	Digital Processing of old data, Analysis and publications; Restart monitoring water quantity and quality
79 (Second order Fox Gully)	500 ha	1965	V-Weir and 3-Box culvert	Stage, Water quality	Good and monitoring continuing	Processing data analysis, Publications
80 (Control)	206 ha	1969	Compound weir	Stage, Water quality, GW levels, Met station, Throughfall	Good and monitoring continuing (No data 1981-1989)	Analysis of old data and publications

RESULTS TO DATE:

- Young (1967; 1968): Excess water in the form of surface runoff and subsurface drainage did not appear to be a problem on WS 77. Base flow from the watershed was undependable. Reliability of water balance ET varied depending upon the temporal scale. 20% of the annual rainfall, on average, resulted as the storm flow, depending upon the seasonal soil moisture storage.
- Richter et al. (1983): Hydrologic fluxes of N, P, S, and basic cations, from burned pine litter to ground and stream waters, are not likely to have appreciable impacts on water quality in the Atlantic and Gulf Coastal Plain.
- Sun et al. (2000b): Annual stream flow was 25 to 30% of annual precipitation. However, simulations using MRSWARM model showed as much as 50% depending upon annual rainfall pattern. Salvage logging after Hurricane Hugo greatly increased annual stream flow on WS 77.
- Miwa et al. (2003): Headwater stream flow on these watersheds was highly responsive to rain events and is also influenced by vegetation and topography. Quantitative base flow separation is difficult on these flat coastal watersheds.

- Amatya et al. (2003b): Using minimal calibration and available data **DRAINMOD**'s (Skaggs, 1978) predictions of daily stream flows of watershed WS 80 was encouraging.
- A six-year hydrologic comparison study (Amatya et al., 2003a) between naturally drained watershed WS 80 in SC and an artificially drained watershed in NC showed a wide variation in annual outflows affected by water table position, which is dependent upon both rainfall and ET. Naturally drained watershed in SC had much shallower water table depths with higher frequent outflows compared to drained NC site although average annual rainfall was lower at the former site. The differences in soil and vegetation types at these two locations might have also contributed to this.

NEXT STEPS:

- A study is being conducted on the control watershed WS 80 to quantify the water budget using both monitoring (rainfall, throughfall, outflow, PET, water table) and modeling. DRAINMOD will be tested further with measured field data on soil hydraulic properties and weather parameters.
- Similarly, a distributed hydrologic model MIKE-SHE is also being used to test its ability to predict hydrology of the watershed WS 80 (Sun, 2004, personal communication).
- Long-term flow data from the first order watersheds are being used for preliminary analyses of base line loading calculations for Charlestom Bay water quality model being developed by Tetra-Tech, Inc. (Miller, 2004, Personal communication).
- Event water quality sampling in this year will soon be conducted at second-order watershed (WS 79) by Tetra-Tech, Inc. for the Charleston Bay water quality model.
- Water quality data on nutrients from the watersheds treatment are being analyzed to compare the effects of natural regeneration and prescribed understory burning on treatment watershed WS 77 compared to the control (WS 80).
- Long-term flow data from 5,000 ha watershed (WS 78) may be analyzed to evaluate the water budget, flow dynamics including flow-frequency-duration compared to the first order watershed WS 77, and second order watershed WS 79.
- Monitoring on large watershed WS 78 is planned to be restarted back again with a flow meter and a staff gauge at Turkey Creek and an automatic rain gauge.
- A DRAINMOD-based watershed scale model (Amatya et al., 1997) may be tested on this large naturally drained coastal watershed dominated by forest vegetation so that it can be applied to evaluate the impacts of various management practices.

2. Long-term Studies on Managed Pine Forest at Carteret County, NC

SITE DESCRIPTION:

A long-term forest hydrology and water management study was initiated on an experimental site in Carteret County, North Carolina in early 1988 to quantify the potential impacts of both silvicultural and water management practices on downstream hydrology and water quality. The study site (Figs. 1 and 2) is located at approximately 34° 48' N latitude and 76° 42' W longitude and is owned and managed by Weyerhaeuser Company. The research site consists of three artificially drained experimental watersheds, each about 25 ha in size planted to loblolly pine in 1974. Topography of the site is flat at an elevation of about 3 m a.m.s.l. and soils have shallow water tables. The soil is a hydric series, Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Each watershed is drained by four 1.4 to 1.8 m deep parallel lateral ditches spaced 100 m apart that drain to a roadside collector ditch, which ultimately drains to an estuary about 3 km downstream (Fig. 2).

OBJECTIVES:

- To conduct the long-term field studies to examine the impacts of different water management and silvicultural treatments on the hydrology and water quality of drained pine plantations in the coastal plain.
- To develop and test DRAINMOD based models for their application in predicting and evaluating hydrology and water quality for the forested watersheds under these treatments.
- To apply the results of field scale research (both data and models) to assess cumulative impacts of alternative land uses and management practices on hydrology and water quality of large coastal watersheds.

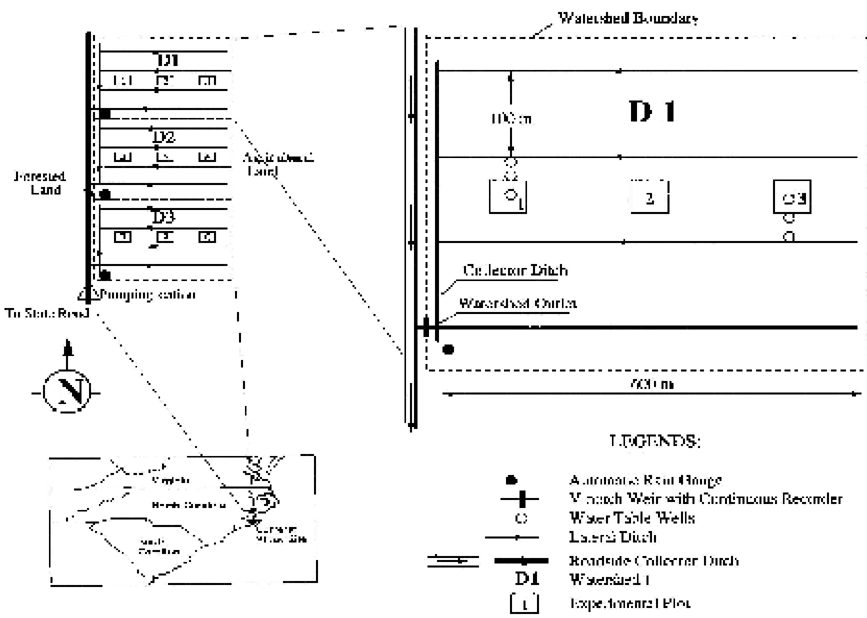

Figure 2. Location map and layout of experimental watersheds (D1 – control and D2 and D3– treatment watersheds) at Carteret County, North Carolina.

MONITORING:

Data on hydrology, soil and vegetation parameters were collected from three experimental plots (each about 0.13 ha) in each watershed (Fig. 2). Rainfall was measured with an automatic tipping bucket rain gauge with a datalogger in an open area on the western side of each watershed. Air temperature, relative humidity, wind speed and net radiation were continuously measured by an automatic weather station located at the center of the treatment watershed (D2). An adjustable height 120^o V-notched weir, located in a water level control structure at a depth nearly equal to the bottom of outlet ditch, was used to measure drainage outflow in each watershed. Upstream of each weir, water levels were measured at six-minute intervals by a water level recorder and an automatic datalogger. An additional recorder was placed downstream from the weirs (not shown) to determine if weir submergence occurred and to correct flows in that event. In 1990, a pump was installed downstream from all three watersheds in the roadside collector ditch to prevent weir submergence during larger events. Water table elevations were measured by a continuous water level recorder at two locations midway between the field ditches for each watershed (Fig. 2). The reader is referred to McCarthy et al. (1991) and Amatya et al. (2000; 1996) for a detailed description of the site and measurements, including the history of the loblolly pine stand planted in 1974. Details of procedures of sample analysis in the laboratory have been documented by Amatya et al. (1998; 2003c). Chronology of various treatments that were undertaken on the site is shown in Table 2 below.

RESULTS TO DATE:

- ET was the dominant component (~70% of annual rainfall) followed by drainage outflows (McCarthy et al., 1991; Amatya et al., 1996). Interception was estimated to be 15% of the average annual rainfall. Seasonal loss through ET was as much as 96% of the rainfall depending upon the season.
- Controlled drainage (CD) with a weir (D2, D3) and an orifice-weir (D3) significantly reduced outflows compared to free drainage from the control watershed (D1) (Amatya et al., 1996; 2003c).
- CD with a weir on D2, D3 reduced the export of N, P, and sediment, primarily as a result of reduced drainage outflows (Amatya et al., 1998). But CD with an orifice-weir reduced P and sediment, but not the N export, despite the reduced outflows (Amatya et al., 2003c);
- Using data from this study, a forestry version of **DRAINMOD** (Skaggs, 1978), the hydrologic model **(DRAINLOB)** was developed, tested (McCarthy et al., 1992), modified for watershed scale (Amatya et al., 1997), and successfully applied on large coastal watersheds on pine forest (Amatya et al., 2003d).
- The data were used to test the model DRAINLOB for various water and silvicultural management practices on the managed pine forest. (McCarthy and Skaggs, 1992; Richardson and McCarthy, 1994). The model was further tested with a long-term data from the study site (Amatya and Skaggs, 2001).
- This study, together with a large watershed scale experimental study near Plymouth, NC resulted in a long-term data base and hydrologic and water quality models for evaluating the cumulative impacts of various agricultural and silvicultural management practices on a lower coastal plain watershed (Amatya et al., 1997; 2002; 2004; Chescheir et al., 1998; Fernandez et al., 2002; Skaggs et al., 2003).

Table 2. Chronology of Water and Silvicultural Treatments on Three Experimental Forested Watersheds at Carteret 7, North Carolina

Year Since Study Began	Watersheds			Management Scenarios
	D1 (24.72 ha)	D2 (23.62 ha)	D3 (26.75 ha)	
1974				
1987	Experiment/Monitoring equipment installation			All watersheds 13 year old pines
1988	Testing of various weir levels on all three watersheds for free drainage (Calibration period)			Monitoring began, all watersheds commercially thinned in October
1989	Testing of various weir levels on all three watersheds for free			Fertilizer application and

	drainage (Calibration period)			Hurricane Hugo's impact on weir submergence
1990	Free Drainage (control)	Controlled drainage (June-November)	Controlled drainage (March-June)	Water management treatment for tree growth (D2) and minimum offsite impact (D3)
1991	Free Drainage (control)	Controlled drainage (June-November)	Controlled drainage (March-June)	Water management treatment for tree growth (D2) and minimum offsite impact (D3)
1992	Free Drainage (control)	Controlled drainage (June-November)	Controlled drainage (March-June)	Water management treatment for tree growth (D2) and minimum offsite impact (D3)
1993	Free Drainage (control)	Controlled drainage (June-November)	Controlled drainage (March-June)	Water management treatment for tree growth (D2) and minimum offsite impact (D3)
1994	Free Drainage (control)	Controlled drainage (June-November)	Controlled drainage (March-June)	Water management treatment for tree growth (D2) and minimum offsite impact (D3)
1995	Free Drainage (control)	Harvested (June-July)	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1996	Free Drainage (control)	Site Prep/Bedding in October	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1997	Free Drainage (control)	Planted for regeneration (Feb)	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1998	Free Drainage (control)	Planted for regeneration (Feb)	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1999	Free Drainage (control)	Planted for regeneration (Feb)	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
2000	Free Drainage (control)	3-year old pine trees	Back to free drainage (orifice removed February)	Silvicultural treatment (D2) and water management (D3)
2001	Free Drainage (control)	4-year old pine trees	Back to free drainage (orifice removed February)	Silvicultural treatment (D2) and water management (D3)
2002	Free Drainage (control)	5-year old pine trees	Thinned in June	Silvicultural treatment on D2 and D3
2003	Free Drainage (control)	6-year old pine trees	After thinning	Silvicultural treatment on D2 and D3

Notes: Pine trees on all three watersheds (D1, D2 and D3) were planted in 1974 with a pre-commercial thinning in 1980 and fertilizer application in 1981 (After Amatya et al., 1996). Most of these studies are being supported by NCASI, Inc.

NEXT STEPS:

- A study is continuing to evaluate the hydrologic and water quality impacts of harvesting and subsequent planting for regeneration on watershed D2 and second commercial thinning on mid-rotation pine trees on watershed D3.
- A long-term trend in water quality parameters (nutrients and sediment) on the control watershed (D1) may be evaluated during the growth cycle of the pine stand.
- A study to evaluate the impacts of forest fertilization on the 6-7 year old young pine stand on watershed D2 and 30-yr old mature thinned stand on watershed D3 on the downstream water quality compared to the control (D1) is being planned.
- A monitoring and modeling synthesis study is planned to evaluate the long-term hydrology of a drained pine forest throughout its life cycle (from planting to harvest). The modeling outputs using DRAINLOB with 40 years of weather data along with 16 years (1988-2003) of observed data may be used to synthesize the results in water and nutrient balance and processes of the pine forests during its life cycle.

3. Long-term Bottomland Eco-system Study at Coosawhatchie River site, SC

SITE DESCRIPTION

A multi-agency collaborative bottomland ecosystem study that addresses recent public concerns on the need of protection, restoration, and sustainable management of forested wetlands was started in 1994 at the Coosawhatchie river basin, SC (Fig. 1 left and Fig. 3). As described by Burke et al. (2003), the study site is a 350-ha tract owned by MeadWestvaco Corporation in Jasper County, South Carolina, USA (32^o 40'N latitude and 80^o 55'W longitude), just above tidal influence on the Coosawhatchie River (Figure 3). The river is a fourth order, anastamosing, blackwater stream that drains a 1,012- km^2 watershed. Dominant trees on the site are 80+ years old, and evidence of most recent logging on the site dates to before 1950. The naturally regenerated bottomland hardwood forest grades into upland mixed hardwood-pine forest and loblolly pine plantations. The study site is dominated by loamy and clayey soils on the lower terrace and a fine-loamy soil on the higher terrace of the floodplain. Relief is approximately two meters. The hydroperiod is relatively unaltered. The dominant land uses in the watershed are agriculture (42%), forestry (30%), and wetlands (24%). The details of the site description can be found elsewhere (Burke et al., 2003; Burke and Eisenbies, 2000).

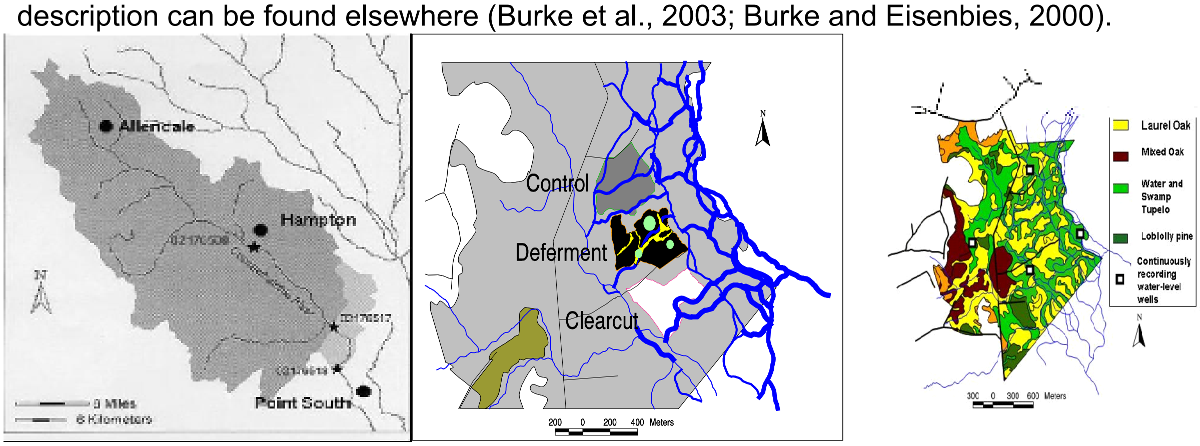

Figure 3. Coosawhatchie river basin with stream gauging stations (left), treatments (center) and plant communities at the study site.

OBJECTIVES

- Quantify hydroperiods across the site for use in describing community structure and dynamics and ecological processes as they relate to hydrology.
- Develop hydrologic models for predicting water level changes on the site.
- Produce long-term hydrologic and meteorological databases on the site for use in ecosystem and hydrologic models.
- Collaborate in an assessment of surface water quantity and quality in the Coosawhatchie River watershed as a component of the USGS's National Water Quality Assessment (NAWQA) program.

MONITORING

Long-term river stage data from 24 km upstream (Hampton Station), 8 km upstream (Early Branch) and at the lowest part of the study site (Grays) (Fig. 3, left) were used in conjunction with other continuously recording water table wells on the site (Fig. 3 right) and 18 manual PVC wells at permanent productivity plots (Burke and Eisenbies, 2000) to measure water level and develop relationships for modeling long-term flooding pattern. Descriptions of the stream gauging stations are presented in Table 3 below. Piezometers were used to measure ground water movement and interactions with surface water. From October 1994 to October 1998, river stage was measured on the site and from July 1996 to October 1998, water table elevations were measured manually every two weeks in the 18 PVC wells. Also, during the later interval, water levels of the surficial aquifer were recorded continuously in four wells installed in the river channel (Grays) and across the site (Figure 3, right). Piezometers were used to determine the recharge-discharge relation between the ground water and surface water.

Table 3. Three stations on the Coosawhatchie River used in CBES studies, the information collected, period of operation, and responsibility for operation.

USGS Station Number	Station Name	Function of station	Data collected	Period of USGS operation	Period of Forest Service operation
02176500	Hampton	River Stage monitoring	River stage and streamflow	1951-present	
02176517	Early Branch	NAWQA Fixed/Integrator and CBES Study	River Stage,	1995-1998	1998-present
			Nutrients, pesticides, Bacteria, Suspended sediments, trace elements in bed sediments and biota	1995-1998	
02176518	Grays	CBES Study	River Stage		1995-present
			Nutrients, organic carbon, trace elements in bed sediments and biota.	1995-1998	

At the end of the NAWQA study period in 1998, USGS discontinued the monitoring at Early Branch and Grays stream gauging stations. Since then the Center for Forested Wetlands Research has been keeping up with the maintenance and servicing of these stream gauges and retrieval and management of their data.

An automatic weather station with an OMNIDATA datalogger has been installed in the middle of a large opening in the study site. The station has been continuously measuring rainfall, air temperature, relative humidity, wind speed and direction, and solar radiation. Also at that time, an identically equipped weather station was installed beneath the canopy near the center of the site, but was removed at the end of Phase 1 (1999). These data are archived at the Center for Forested Wetlands Research.

The Coosawhatchie Early Branch site was established as a NAWQA fixed and integrator site, fixed site being those that were the most intensively sampled and an integrator site because it represents an integration of multiple land covers (Maluk 2000). Water quality samples were collected monthly from the Coosawhatchie River sites from October 1995 through September 1997, as part of the USGS NAWQA program and were analyzed for nutrients, suspended organic carbon, dissolved oxygen, silica, phosphorus, several nitrogen species, trace metals and pesticides. Details of the methods, quality control procedures and results can be found in Mueller et al. (1997) and Maluk (2000).

RESULTS TO DATE:

- A reference wetland has been developed where the structure and functions of a representative bottomland hardwood forest have been quantified.
- Flooding pattern at the site was typical of blackwater rivers with relatively short duration; floodwaters may be deep and widespread, followed by extensive periods of low discharge.
- Groundwater discharge is the dominant hydrological condition, but recharge can occur during extremely high flows. Hydroperiod was variable both within and among years. The substantial drying pattern of hydroperiods in last decade compared to the long-term data was attributed to municipal and industrial water use by the towns of Beaufort and Savannah. This change may well influence changes in vegetation community dynamics that depend upon hydroperiods.
- The annual streamflow is among the smallest of southeastern coastal plain rivers, and the sediment load is relatively slight (5-25 mg/l) compared with other coastal plain rivers, including other blackwater rivers (Hupp 2000), and is similar in suspended sediment concentrations to another blackwater river, the Edisto (Maluk 2000).
- The Coosawhatchie River exhibited a seasonal trend in the nutrient concentrations with low concentrations in the winter and significantly higher concentrations in the summer, possibly due to low amounts of total organic nitrogen present in the form of detritus during the winter. Nitrate concentrations in the river were low, as was expected for forested watersheds. Dissolved phosphorus concentrations in the Coosawhatchie River were among the highest in the Basin.
- Forest litter decay rates were comparable to rates reported in similar floodplains.
- Observed differences in community structure among the four floodplain communities appeared to be inversely related to the number and duration of flood events.

NEXT STEPS:

- A water management model like DRAINMOD may be used to evaluate the short and long-term hydroperiods on these forested lands to determine wetland hydrology.
- A comprehensive hydrologic model can be used to address the issue of potential impact of groundwater use on flood plain resources including vegetation in the region.
- To conduct studies impacts of harvesting and regeneration of BLH.

4. Study on High Intensity Short Rotation Woody Crop site at Trice Farm, SC

STUDY SITE

A study at Trice forest (intensively managed short-rotation woody crop SRWC) site, owned and managed by International Paper Company in the Upper Coastal Plain of South Carolina, (Fig. 1) was conducted in 1997 as part of Oak Ridge National Laboratory's Agenda 2020 to provide a bridge between smaller-scale plot studies and larger-scale nutrient cycling models. The study site (~300 acres) is located on an International Paper (IP) research forest (Trice) approximately 1 mile southwest of Mayesville in Sumter County, South Carolina (Figs. 1 and 8 left). The site on the Upper Coastal Plain region was historically planted with cotton, soybeans and wheat, with a small portion of land in pasture and natural pine/hardwood forest. The first rotation of SRWC (sycamore and sweetgum) was planted on the study catchments in February 1997. The soils on the site are predominantly loamy sand or sandy loam at the surface and much of the area had been artificially drained with ditches for agricultural use.

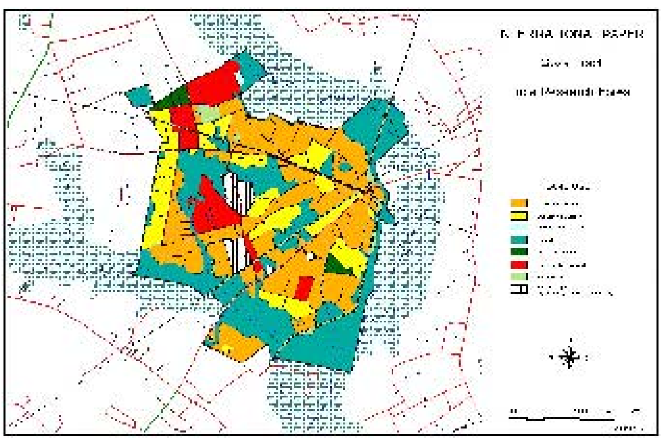

Figure 4. Layout map of IP's Trice Forest near Sumter, Upper Coastal Plain of SC.

OBJECTIVES:

- To determine the effects of SRWC systems on soil chemical and physical properties, and nutrients in surface and subsurface runoff.
- To understand the hydrologic and nutrient cycling processes of SRWC plantations.
- To examine the potential benefits of alternative management practices in terms of productivity, soil sustainability, and off-site movement of nutrients and chemicals using both monitoring and modeling approach such as process-based hydrologic model, WATRCOM (Parsons et al., 1991) and biogeochemical model, NuCM.
- To evaluate the potential of SRWC systems to sequester carbon.

METHODS:

The study site was designed at a watershed scale because many processes are manifested differently at plot (0.4 ha) and stand (> 2 ha) scales. The watershed scale accommodates the conditions necessary for understanding productivity and sustainability at an operational level.

Measurements were taken at two levels: a large watershed scale and a smaller catchment scale. Measurements of flow, soil moisture, weather and nutrient parameters were done at six experimental catchments (4-6 ha) and a large 800 ha 'second order" watershed was instrumented for flow measurement to provide baseline data for assessing the long-term effects of SRWC on water quality and quantity.

A CR10X automatic weather station in the middle of the watershed continuously measures air temperature, humidity, wind speed and solar radiation needed for ET estimates. Precipitation is measured by a tipping bucket rain gauge attached to a HOBO datalogger adjacent to the weather station. Prefabricated plastic flumes with WL-15 and GL-300 dataloggers were used to estimate flow rates both at the catchment and watershed outlets.

Three treatments were designed for testing established practices at an operational scale (two replicate catchments per treatment): (1) Sweetgum, herbicide application, open drainage, (2) Sycamore, herbicide application, open drainage, and (3) Sycamore, cover crop, controlled drainage structure. These treatments represent commercially feasible combinations of tree species, fertilization, weed control and water management regimes. The detailed description of the site and treatments can be found elsewhere (Trettin and Davis, 2002).

RESULTS TO DATE:

- Sycamore was significantly more productive than sweetgum in the first five years. Sycamore treatments yielded significantly high N concentration in the soil and drainage water, but below drinking water standards.
- The **WATRCOM** model (Parsons et al., 1991) was successfully applied to this silvicultural system (Parsons and Trettin, 2001).
- The SRWC systems have positive benefits in terms of environmental considerations.
- The study/infrastructure and WATRCOM model provided a basis for long-term assessments of the nutrient cycling and transport from the SRWC system in the Upper Coastal Plain.
- The study also provided the operational scale assessment of SRWC and the development of tools needed to plan and manage these crops.

NEXT STEPS:

- To develop an empirical basis using monitoring approaches and modeling capabilities to evaluate the effects of changing agricultural land use to forests and short rotation woody crops with respect to hydrology and water quality, at the watershed scale.

5. Study of Depressional Isolated Wetlands (Carolina Bays) at Burch Farm, SC

SITE DESCRIPTION

The research site for the depressional (isolated) wetlands is located at Burch Fiber Farm, recently owned and operated by Mead-Westvaco near Olar in Bamberg County, South Carolina (Fig. 1 and Fig. 5). The depressional wetland referred to herein as Chapel Bay site has an area of 6 ha covered by bottomland hardwoods in the interior. Soils are poorly drained sandy loams.

Surrounding uplands are composed of crop lands, intensively managed hardwoods and natural pine stands. There are two other wetlands at the site: Cathedral Bay (22 ha) and Potato Bay (0.4 ha). Cathedral Bay, a preserved Carolina Bay with a pure stand of pond cypress, lies adjacent to the Burch farm. The surficial aquifer lies approximately 5 m below the ground surface at the site. The general stratigraphy of the site to approximately 10 m depth was assessed through well logs. Soil horizon layers A and E are composed mainly of sand in the upland areas and range from sandy loams to loamy sands within the wetlands. Horizon B is composed of sandy clay loams in the uplands and sandy clay loam and sandy clay within the wetlands. Soil layers below the horizons are altering clay and sand layers, characteristic of the surficial aquifer system. Detailed description of soil types and logging are described by Pyzoha (2003). The average annual rainfall at the site is 1200 mm and the average annual maximum and minimum temperatures are 74.1° F and 52.4° F, respectively.

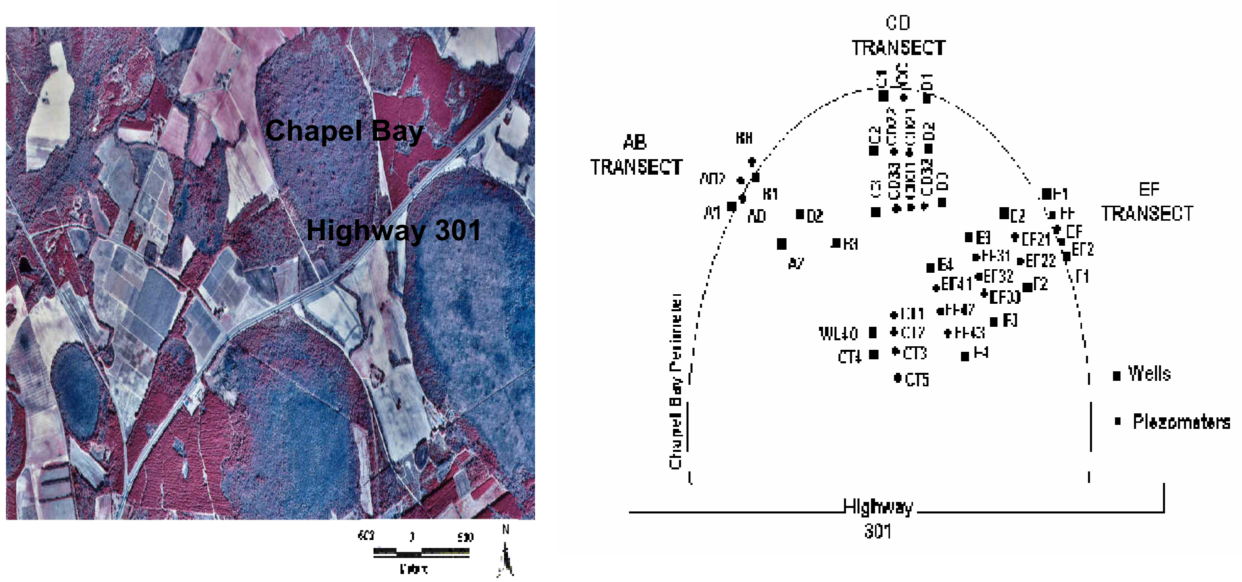

Figure 4. Location map (left side) and experimental layout of ground water wells at Chapel Bay.

OBJECTIVES

- To examine potential surface water and ground water interactions (first examined by Miwa et al., 2004) and thus identify the interaction between Carolina bays and the adjacent uplands (Fig. 4, left); and to assess the role of their interactions on the regional water balance using conceptual models.
- To test a distributed forest hydrologic model FLATWOODS (Sun et al., 1998a; 2004) for evaluating the surface and subsurface water flow pattern and their interactions with surrounding uplands.

METHODS

Precipitation and air temperatures were continuously measured with an automatic tipping bucket rain gauge and a temperature probe at the Burch Fiber Farm. Well logging was used to identify the stratigraphy to a 10 m depth. About 46 PVC and stainless steel pipe wells and PVC pipe piezometers (six with data loggers) were installed in three transects within Chapel Bay and two transects within Potato Bay to monitor water table levels since 1997 (Fig. 4, right). Surface flow, soil water, and shallow groundwater were monitored. In addition, three piezometers were installed in the upland area to assess interactions between Carolina Bays and their surrounding areas. Automatic digital recording wells equipped with dataloggers were also installed near the center of each of the bays. Wells and piezometers were measured monthly from February 2002 to December 2003 using a water level indicator. Water levels measured between 1997 and 1999 (Miwa et al., 2004) were also evaluated. Existing wells and piezometers were surveyed using a rotary laser level, Philadelphia rod, and GPS unit to ensure accuracy. In addition, a 700 m by 700 m area was surveyed for elevations needed for hydrologic modeling. Slug tests were performed to determine hydraulic conductivities. Details of field experimental procedures are described by Pyzoha (2003).

RESULTS TO DATE:

- Minimal surface and groundwater interactions occurred during dry periods, indicating that the bays are hydrologically isolated during these periods.
- During wet periods, the bays served as a storage regime for storm water, and perhaps as locations of groundwater recharge, interacting with surrounding regions (Fig. 5).
- The study suggested a need for reevaluation of Carolina Bays as isolated systems.
- Results of a distributed hydrologic model, **FLATWOODS** model (Sun et al., 1998a) applied to the study site suggested that Chapel Bay is a flow-through wetland, losing groundwater to the lower recharge area, especially during wet winter periods. The simulation study also suggested that groundwater flow direction is controlled by the gradient of the underlying restricted layer, not by the topographic gradient. Wetland position on the landscape is one important factor in determining the hydrologic interactions between the wetland and its surrounding upland. The results also suggested that the model is able to capture the spatial and temporal dynamics of shallow groundwater table in a heterogeneous landscape.

NEXT STEPS:

- To test DRAINMOD model with the data from this depressional wetland for its application on these poorly drained lands and compare the results with those from FLATWOODS model.
- To refine and evaluate these models for application in wetland hydrology, interactions of hydroperiods with soils and vegetation on the coastal forested landscapes.

SUMMARY

This paper summarized five different (long-term and short-term) eco-hydrologic studies being conducted by the Forest Service, Center for Forested Wetlands Research in Charleston, SC in the forested wetland landscapes of the Atlantic Coastal Plain. This paper did not summarize some of the hydrology and water management related works at Savannah River Site (SRS) being undertaken by the Center in collaboration with Department of Energy and watershed scale studies near Plymouth, NC (Figure 1, left) being conducted by North Carolina State University as an extension of the Carteret study. Based on the findings and recommendations from this work, it is evident that the scientific studies in the low-gradient coastal landscape (managed forests, depressional wetlands, bottomland hardwoods, riparian zones, other natural forests) are complicated by their hydrogeologic location, land development and management practices and climatic factors. Therefore, there are and will be many more problems and issues that may need consideration as the human population near the coastal waters continue to grow along with the increasing timber demand in the southeast. Better understanding about biogeochemical processes in soils and water affecting water quality together with the hydrology should be developed for the effective and viable land use and development including engineered or restored lands to enhance water quality and healthy forest ensuring a clean and stable water supply. One of the biggest tasks in this regard will be developing and applying ecohydrologic models capable of predicting the processes and management and climatic impacts in various spatial and temporal scales. Data from the existing complete weather stations at the coastal sites maintained by the Center together with its cooperators may well serve for ground truthing (field verification) of remotely collected data based on radar technology (precipitation) and remote sensing (temperature, radiation, albedo), which is becoming a part of the next generation eco-hydrologic modeling tool. The existing hydrologic studies and infrastructure at Forest Service Santee Experimental Forest near Charleston in South Carolina can well be a basis for the continuation of not only the long-term hydrologic studies but also other scientific studies including prescribed burning, regeneration and management of bottomland hardwoods, and carbon sequestration on the coastal forest ecosystems to provide the knowledge needed for their sustainable management. Therefore, the Center is seeking to expand collaboration with other area institutions, academia, industries, state and government agencies, private land owners and non-government organizations to build a long-term ecohydrological database, identify new prioritized issues, conduct experimental studies and implement the recommended science and technology using appropriate technology transfer approaches.

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References

Amatya, D.M., G.M. Chescheir, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. 2004. DRAINWAT-based Methods for Estimating Nitrogen Transport in Poorly Drained Soils. *In press, Transactions of the ASAE*, 43(3).

Amatya, D.M., G. Sun, C.C. Trettin, and R.W. Skaggs. 2003a. Long-term Forest Hydrologic Monitoring in Coastal Carolinas. *In Proc*. Renard, Kenneth G., McElroy, Stephen A., Gburek, William J., Canfield, H. Evan and Scott, Russell L., eds., *First Interagency Conference on Research in the Watersheds*, October 27-30, 2003. U.S. Department of Agriculture, Agricultural Research Service, pp:279-285.

Amatya, D.M., G. Sun, R.W. Skaggs, and C.C. Trettin. 2003b. Testing of DRAINMOD for Forested Watersheds with Non-Pattern Drainage. *ASAE Meeting Paper # 032046*, St. Joseph, MI.

Amatya, D.M., R.W. Skaggs, J.W. Gilliam, and J.E. Hughes. 2003c. Effects of an Orifice and a Weir on the Hydrology and Water Quality of a Drained Forested Watershed. *South. J. Appl. For.*, 27(2): 130-142.

Amatya, D.M., G.M. Chescheir, G.P. Fernandez, R.W. Skaggs, F. Birgand, and J.W. Gilliam. 2003d. Lumped Parameter Models for Predicting Nitrogen Transport in Lower Coastal Plain Watersheds. Report No. 347, Water Resources Research Institute of the University of North Carolina, Raleigh, NC, 118 p.

Amatya, D.M., G.M. Chescheir, R.W. Skaggs, and G.P. Fernandez. 2002. Hydrology of Poorly Drained Coastal Watersheds in Eastern North Carolina. *ASAE Paper No. 022034*, ST. Joseph, Mich.: ASAE.

Amatya and Skaggs. 2001. Hydrologic modeling of pine plantations on poorly drained soils. *Forest Science*, 47(1) 2001: 103-114.

Amatya, D.M., J.D. Gregory, and R.W. Skaggs. 2000. Effects of Controlled Drainage on the Storm Event Hydrology in a Loblolly Pine Plantation. J*. of the Amer. Water Resou. Assoc.* 36(1):175-190.

Amatya, D.M., J.W. Gilliam, R.W. Skaggs, M. Lebo, and R.G. Campbell. 1998. Effects of Controlled Drainage on Forest Water Quality. *Journal of Environmental Quality* 27:923-935(1998).

Amatya, D.M., R.W. Skaggs, J.D. Gregory and R. Herrmann. 1997. Hydrology of a Forested Pocosin Watershed. *Journal of American Water Resources Association* 33(3):535-546.

Amatya, D.M., R.W. Skaggs and J.D. Gregory. 1996. Effects of Controlled Drainage on the Hydrology of a Drained Pine Plantation in the North Carolina Coastal Plains. *J. of Hydrology*, 181(1996), 211-232.

Baker, T.T., B.G. Lockaby, W.H. Conner, C.E. Meier, J.A. Stanturf, and M.K. Nurke. 2001. Leaf Litter Decomposition and Nutrient Dynamics in Four Southern Forested Floodplain Communities. *Soil Sci. Soc. Am. J*. 65:1334-1347 (2001).

Blanton, C.D., R.W. Skaggs, D.M. Amatya, and G.M. Chescheir. 1998. Soil Hydraulic Property Variations during Harvest and Regeneration of Drained Coastal Pine Plantations. Paper no. 982147, *Amer. Soc. of Agr. Eng*., St. Joseph, MI.

Burke, M.K., S.L. King, D. Gartner, and M.H. Eisenbies. 2003. Vegetattion, Soil, and Flooding Relationships in a Blackwater Floodplain Forest. *Wetlands*, 23(4):988-1002.

Burke, M.K. and M.H. Eisenbies. 2000. The Coosawhatchie Bottomland Ecosystem Study: A Report on the Development of a Reference Wetland. *USDA Forest Service, Southern Research Station, General Tech. Rep. SRS-38*, 64 p.

Chescheir, G.M., M.E. Lebo, D.M. Amatya, J. Hughes, J.W. Gilliam, R.W. Skaggs, and R.B. Herrmann. 2003. Hydrology and Water Quality of Forested Lands in Eastern North Carolina. *Research Bulletin No. 320*, Raleigh, NC: North Carolina State University.

Chescheir, G.M., D.M. Amatya, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. 1998. Monitoring and Modeling the Hydrology and Water Quality of a Lower Coastal Plain watershed. *Proc. of the 1998 WEF Conference on "Watershed Management: Moving From Theory to Implementation"*, Denver, CO, May, 1998, pp:215-222.

Crawford, D.T., B.G. Lockaby, R.H. Jones, and L.M. Wright. 1992. Influence of Harvesting on Water Quality in Forested Wetlands. In *Proc. of the 13th Annual Conf. Society of Wetland Scientists*, M.C. Landin, ed., pp:818-822.

Dissmeyer, G.E. 1994. Evaluating the Effectiveness of Forestry Best Management Practices in Meeting Water Quality Goals or Standards. USDA Forest Service, Washington, D.C., *Misc. Publ. 1520*, 166 p.

Fernandez, G.P., G.M. Chescheir, R.W.Skaggs and D.M. Amatya. 2002. WATGIS: A GIS-based lumped parameter water quality model. *Trans. of the ASAE*. Vol. 45(3):593-600

Gartner, D. and M.K. Burke. 2001. Santee Experimental Watershed Database. 2001. *Unpublished data*, USDA Forest Service, SRS, Charleston, SC.

Grace III, J.M., R.W. Skaggs., H.R. Malcom, G.M. Chescheir, and D,K. Kassel. 2003. Increased Water Yields Following Harvesting Operations on a Drained Coastal Watershed. *ASAE Meeting Paper No. 032039*, St. Joseph, Mich.: ASAE.

Hupp, Cliff R. 2000. Hydrology, geomorphology and vegetation of Coastal Plain rivers in the south-eastern USA. *Hydrologic Processes* 14:2991-3010.

Lebo, M.E. and R.B. Herrmann. 1998. Harvest Impacts on Forest Outflow in Coastal North Carolina. *Journal of Environmental Quality*, 27:1382-1395 (1998).

Maluk, Terry L. 2000. Spatial and seasonal variability of nutrients, pesticides, bacteria, and suspended sediment in the Santee River Basin and Coastal Drainages, North and South Carolina, 1995-1997. *U. S. Geological Survey Water-Resources Investigations Report 00-4076*. Columbia, South Carolina.

McCarthy, E.J., R.W. Skaggs, and P. Farnum. 1991. Experimental determination of the hydrologic components of a drained forest watershed. *Trans. Amer. Soc. Agr. Eng*., 34(5):2031-2039.

McCarthy, E.J., J.W. Flewelling, and R.W. Skaggs. 1992. Hydrologic Model for Drained Forested Watershed. *ASCE J. of Irrigation & Drainage Engineering*, Vol. 118, No. 2, March/April, 1992, pp:242-255.

McCarthy, E.J. and R.W. Skaggs. 1992. Simulation and Evaluation of Water Management Systems for a Pine Plantation Watershed. *South. J. Appl. For.*, Vol. 16, No. 1, Feb. 1992, pp:48-56.

Miwa, M., C.C. Trettin, S.E. O'Ney, and M.H. Eisenbies. 2004. Hydrologic Processes in the Vicinity of a Carolina Bay. *In Review, Wetlands.*

Miwa, M., D.L. Gartner, C.S. Bunton, R. Humphreys, and C.C. Trettin. 2003. Characterization of Headwater Stream Hydrology in the Southeastern Lower Coastal Plain. *Project Report to US EPA,* USDA Forest Service, Charleston, SC.

Mueller, David K, Jeffery D. Martin, and Thomas J. Lopes. 1997. Quality-control design for surface-water sampling in the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 97-223. Denver, Colorado. 17 p. plus appendices.

NCASI. 1994. Forests as Nonpoint Sources of Pollution, and Effectiveness of Best Management Practices. National Council of Industries for Air & Stream Improvement, Inc., New York, NY, *Tech. Bull. No. 672*, 57 p.

Parsons, J.E. and C.C. Trettin. 2001. Simulation of Hydrology of Short Rotation Hardwood Plantations. *ASAE Meeting Paper No. 012108*, St. Joseph, Mich.: ASAE.

Parsons, J.E., R.W. Skaggs, and C.W. Doty. 1991. Development and testing of a three-dimensional water management model (WATRCOM): Development. *Trans. ASAE*, 34(1): 120-128.

Pyzoha, J.E. 2003. The Role of Surface Water and Groundwater Interactions Within Carolina Bay Wetlands. *M.S. Thesis*, College of Charleston, Charleston, SC. 121 p.

Richardson, C.J. and E.J. McCarthy. 1994. Effect of Land Development and Forest Management on Hydrologic Response in Southeastern Coastal Wetlands: A Review. *Wetlands*,14(1), pp:56-71.

Richter, D.D., C.W. Ralston, and W.R. Harms. 1983. Chemical Composition and Spatial Variation of Bulk Precipitation at a Coastal Plain Watershed in South Carolina. *Water Resources Research,* 19:134-140.

Riekerk, H. 1989. Influence of Silvicultural Practices on the Hydrology of Pine Flatwoods in Florida. *Water Resources Research*, 25(4):713-719.

Shepard, J.P. 1994. Effects of Forest Management on Surface Water Quality in Wetland Forests. *Wetlands*, 14:18-26.

Skaggs, R.W., G.M. Chescheir, G.P. Fernandez, and D.M. Amatya. 2003. Watershed Models for Predicting Nitrogen Loads from Artificially Drained Lands. *In Proc. of the ASAE 2nd Conf. On Watershed Management to Meet Emerging TMDL Environmental Regulations*, Albuquerque, NM, November 09-12, 2003.

Skaggs, R. W. 1978. A Water Management Model for Shallow Water Table Soils. Report No. 134. Raleigh, N.C.: *University of North Carolina, Water Resources Research Institute*.

SOFRA 2002. Southern Forest Resource Assessment. D.N. Wear and J.G. Greis (eds.), *USDA Forest Service, Southern Research Station*, Asheville, NC, September 2002.

Sun, G., T.J. Callahan, J. Pyzoha, C.C. Trettin, and D.M. Amatya. 2004. Modeling the Hydrologic Processes of a Depressional Forested Wetland in Coastal South Carolina, USA. In *Proc. Of the International Conference on Hydro-Science and Engineering*, Brisbane, Australia, May 30-June 03, 2004, ed. Altinakar et al., pp:331-334.

Sun, G., S.G. McNulty, J.P. Shepard, D.M. Amatya, H. Riekerk, N.B. Comerford, R.W. Skaggs, and L. Swift, Jr. 2001. Effects of Timber Management on Hydrology of Wetland Forests in the Southern United States. *Forest Ecology and Management*, 143(2001):227-236.

Sun, G., H. Riekerk, and L.V. Kornhak. 2000a. Ground-Water Table Rise After Forest Harvesting on Cypress-Pine Flatwoods in Florida. *Wetlands*, 20(1):101-112.

Sun, G., J. Lu, D. Gartner, M. Miwa, and C.C. Trettin. 2000b. Water Budgets of Two Forested Watersheds in South Carolina. In: *Proc. Of the Spring Spec. Conf., Amer. Wat. Res. Assoc.*, 2000.

Sun, H. Riekerk, and N.B. Comerford. 1998a. Modeling the Forest Hydrology of Wetland-Upland Ecosystems in Florida. J*. of the American Water Resources Association*, 34(4):827-841.

Sun, H. Riekerk, and N.B. Comerford. 1998b. Modeling the Hydrologic Impacts of Forest Harvesting on Florida Flatwoods. *J. of the American Water Resources Association*, 34(4):843-854.

Swank, W.T., Vose, J.M., Elliott, K.J. 2001. Long-term hydrologic and water quality responses following clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecol. and Management 143:163-178.*

Swindel, B.F., C.J. Lassiter, and H. Riekerk. 1982. Effects of Clearcutting and Site Preparation on Water Yields from Slash Pine Forests. *Forest Ecology and Management*, 4(1982):101-113.

Tajchman, S.J., H. Fu, and J.N. Kochenderfer. 1997. Water and energy balance of a forested Appalachian watershed. *Agric. and Forest Meteor.,* 84: 61-68.

Trettin, C.C. and A. Davis. 2002. Sustainability of High Intensity Forest Management with Respect to Water and Soil Quality and Site Nutrient Reserves. *Final Repot DOE #DE-AI05-97OR22560, USFS # OO-IA-113301135-222*., Vols. I and II., Oakridge National Laboratory, Oakridge, TN, June 2002.

Ursic, S.J. 1991. Hydrologic Effects of Clearcutting and Stripcutting Loblolly Pine in the Coastal Plain. *Water Resources Bulletin*, 27(6):925-937.

Wynn, T.M., S. Mostaghini, J.W. Frazee, P.W. McClellan, R.M. Shaffer, and W.M. Aust. 2000. Effects of Forest Harvesting Best Management Practices on Surface Water Quality in the Virginia Coastal Plain. *Trans. Of the ASAE*, 43(4):927-936.

Xu, Y.J., J.A. Burger, W.M. Aust, S.C. Patterson, M. Miwa, and D.P. Preston. 2002. Changes in Surface Water Table Depth and Soil Physical Properties after Harvest and Establishment of Loblolly Pine (Pinus taeda L.) in Atlantic Coastal Plain Wetlands of South Carolina. *Soil & Tillage Research*, 63(2002):109-121.

Young, C, E., Jr. 1967. Streamflow – An important factor in forest management in the coastal plain. South. *Lumberman Christmas Issue*. 215(2680):109-110.

Young, C.E., Jr. and Klaiwitter, R.A. 1968. Hydrology of wetland forest watersheds. *Proc. Of CUCOH Hydrol. Conference*. Clemson University, March 28-29, 1968, pp:29-38.