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Five Hydrologic Studies

Conducted by or in Cooperation with the Center for Forested Wetlands Research, U.S. Department of Agriculture Forest Service

D.M. Amatya, C.C. Trettin, R.W. Skaggs, M.K. Burke, T.J. Callahan, G. Sun, J.E. Nettles, J.E. Parsons, and M. Miwa

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Abstract

The U.S. Department of Agriculture Forest Service Center for Forested Wetlands Research has conducted or cooperated in studies designed to improve understanding of fundamental hydrologic and biogeochemical processes that link aquatic and terrestrial ecosystems. Five of these studies are discussed here. The first is based on observations made on long-term experimental watersheds established in the 1960s on the Forest Service Santee Experimental Forest in South Carolina. It quantifies the soil moisture dynamics, flow regimes, and water chemistry of low-gradient forested wetlands. The second study is being conducted in cooperation with North Carolina State University. It is a long-term project aimed at quantifying the effects of various water management and silvicultural management practices on hydrology and water quality at the Weyerhaeuser Company's managed pine forest in Carteret County, North Carolina. The third study is a long-term ecosystem study on MeadWestvaco's Coosawhatchie River bottomland hardwood site in South Carolina. It addresses questions related to public concerns about the need for protection, restoration, and sustainable management of forested wetlands. The fourth study, which was conducted between 1997 and 2000, examined the hydrology and water quality of intensively managed short-rotation woody crop plantations on International Paper's Trice experimental forest in the upper Coastal Plain of South Carolina. A fifth study was conducted between 1996 and 2004 at MeadWestvaco's Carolina bay site in the South Carolina upper Coastal Plain; it assessed the surface-water and ground-water interactions between Carolina bays and their surrounding uplands. Recommendations are provided for using knowledge gained through these and other studies as a basis for expanding needed hydrologic research with collaborators to address four major areas of water-related issues in the Southeast.

Keywords. Forested wetlands, management impacts, models, vegetation, water management, water quality, watershed.

Introduction

Managing forested wetland landscapes to improve water quality, water quantity, and productivity requires a detailed understanding of functional linkages between ecohydrologic processes and management practices, which in turn requires an accurate understanding of landscape hydrologic and nutrient cycling processes. Watershed-level hydrologic and nutrient cycling processes are complicated by the presence of varied land features such as forests, wetlands, riparian buffers, uplands, and water bodies, and multiple land uses increase this complexity still further. Scientists recognize that long-term ecohydrologic monitoring of watersheds is necessary if they are to understand the basic physical processes of natural and anthropogenic disturbance and the impact of management practices on these processes. Long-term monitoring provides baseline data for assessing this impact, conservation of regional ecosystems, generation of scientific hypotheses, and testing of hydrologic and water-quality models. The Southern Forest Resource Assessment (Wear and Greis 2002) emphasized that there is a need for research that will enable us to predict the long-term cumulative nonpoint-source impacts of silvicultural activities on water quality and overall watershed health.

To understand the ecohydrologic role of forested wetlands in a landscape, it is necessary to develop water and nutrient budgets and to quantify the long-term hydroperiod dynamics of those wetlands. Long-term hydrologic data from small, paired, forested watersheds at Coweeta Hydrologic Laboratory in North Carolina (NC) provide basic understanding of ecohydrologic processes for regional upland watersheds (Swank and others 2001). Tajchman and others (1997) report the water and energy balance of a 39-ha central Appalachian watershed with forest cover of 80-year-old upland oaks and cove hardwoods using 40 years of hydrologic data. However, only a few such observational studies have been done for the forested landscapes of the lowlands of the Southeastern Coastal Plain. These landscapes consist of natural and managed forests, depressional wetlands, pine flatwoods, riparian buffers, and bottomland hardwoods on brackish waters. They are characterized by poorly drained high-water-table soils, wet sites, and low topographic relief. Some of these wetlands have been drained artificially to lower water tables for trafficability and reduction of excessive moisture for increased crop growth. Hillslope processes dominate the hydrology of upland watersheds, but hydrologic processes on relatively low-gradient, poorly drained Coastal Plain sites 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 at the surface or a shallow water table is present. This means that total outflow depends on the frequency and duration of flooding and on the dynamics of the water table (hydroperiod), which are driven by rainfall and evapotranspiration (ET). Although potential ET is primarily controlled by solar energy, ET is also dependent on soil type, vegetation type, and seasonal dynamics. This complicates the task of quantifying the water budget components of these wetland systems, and the need to account for the use of various water and silvicultural management practices and interactions with surrounding uplands makes the job even more challenging. Only a few studies have documented hydrology and water budgets for depressional wetlands, bottomland hardwoods, pine flatwoods, pocosins, and pine plantations and their interactions with surrounding uplands (Amatya and others 1996, 1997; Burke and Eisenbies 2000; McCarthy and others 1991; Pyzoha 2003; Riekerk and others 1979; Skaggs and others 1990; Sun and others 2000a; Young 1968[1]; Young and Klaiwitter 1968).

In the last two decades, there has been 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, nutrient cycling, and export processes of forested wetlands. The extent of commercial forestry operations is predicted to increase in the South over the next 20 years (Wear and Greis 2002), and this expectation increases the need to document the impact of silviculture on water quality in order to satisfy the public's desire to maintain high-quality water sources and industry's commitment to water-quality precepts under the Sustainable Forestry Initiative. Silvicultural practices include harvesting, site preparation, bedding, fertilization, regeneration, and thinning. Timber harvesting reduces ET, thus elevating the ground-water level (Grace and others 2003, Sun and others 2000b, Xu and others 2002) and increasing the water yield from a forested site until the canopy is regenerated. These increases in water volume can change both storm and base flow, and without proper management of both volume and flow rate, may increase flow energy throughout the harvested watershed. High-energy water can move farther, transport more sediment and nutrients to downstream water bodies, and even affect the sensitive brackish habitats essential for juvenile development of many marine fish and shellfish species. However, studies in NC have shown that controlled drainage can be used to manage the highest energy runoff at hydrograph peaks, reducing nutrient and sediment loads in water from intensively managed pine plantations on poorly drained soils. Other studies have shown that riparian buffers provide similar impact reduction (Dissmeyer 1994, NCASI 1994, Wynn and others 2000). However, additional studies are needed, especially concerning the water-quality effects of increasingly intensive forest management treatments (Wear and Greis 2002).

Recent studies document some effects of silvicultural practices on soil properties, hydrology, and water quality in the poorly drained lowlands of the Atlantic Coastal Plain (Amatya and others 1997, Blanton and others 1998, Crawford and others 1992, Grace and others 2003, Lebo and Herrmann 1998, Riekerk 1989, Sun and others 2001, Swindel and others 1982, Ursic 1991, Xu and others 2002). Shepard (1994) reviewed studies quantifying the effects of silvicultural practices on the quality of water from nine wetland forest sites and found that harvesting timber raised nutrient concentrations above "natural" level for 1 to 4 years after harvest. Sun and others (2001) in their synthesis study of effects of timber management on wetland forests reported that the hydrologic effects of various forest management practices across the Southern United States are variable, but generally minor, especially when forest best management practices are adopted. The authors suggested that in addition to soils, wetland types, and management options, climate is an important factor controlling hydrology and magnitude of disturbance. Chescheir and others (2003) reported the baseline outflow and nutrient characteristics of pine forest watersheds in NC. Recently, researchers have been investigating the use of short-rotation woody crop (SRWC) methods to produce hardwoods in the Southeast. There has been only limited study of the effects of SRWC forestry on hydrology and water quality.

Data from various forested ecosystems are essential for developing and testing models that can be used to evaluate the effects of new management practices, climate change, and landscape processes at spatial and temporal scales at which monitoring is impractical (Amatya and Skaggs 2001; Amatya and others 2003a; McCarthy and Skaggs 1992; McCarthy and others 1992; Sun and others 1998a, 1998b). However, few existing models are properly applicable to address the complex processes of the low-gradient coastal forests at field or watershed scales.

The main objective of this paper is to provide an overview of five major experimental studies that have been or are being conducted by the U.S. Department of Agriculture Forest Service (Forest Service) Center for Forested Wetlands

[1] Young, C.E., Jr. 1968. Water balance of a forested coastal plain watershed on the Santee Experimental Forest. Unpublished Progress Report, Study W-2. On file with: USDA Forest Service, Southern Research Station, Center for Forested Wetlands Research, 2730 Savannah Highway, Charleston, SC 29414.

Research (CFWR) at Charleston, SC (http://www.srs.fs.usda.gov/charleston/), in collaboration with various area institutions, forest industries, and other agencies. These studies employ scientific monitoring and modeling approaches to address issues discussed above. The studies are (1) long-term studies conducted at first-order headwater streams at Santee Experimental Forest, South Carolina (SC); (2) long-term studies conducted in managed (drained) pine forest at Carteret County, NC; (3) the long-term Coosawhatchie Bottomland Ecosystem Study (CBES) in SC; (4) an experimental study on a high-intensity SRWC site at Trice Farm, SC; and (5) an experimental study of depressional wetlands and their interactions with uplands at Burch Fiber Farm, SC. For each study, the overview includes the site description, methodology, results to date, and next steps recommended or being planned. The paper concludes with recommendations for new ecohydrologic studies to address the important scientific questions and management challenges in the forested wetlands of the Southeast.

Long-Term Studies on Naturally Drained Watersheds at Santee Experimental Forest, South Carolina

Site Description

This naturally drained site is located at latitude 33°N. and longitude 80°W. in the Santee Experimental Forest, which is part of Francis Marion National Forest near Charleston, SC (fig. 1, left). In 1963, the Forest Service designated a 160-ha experimental forested watershed (WS 77) at this location (fig. 1, right) as a site for studies of hydrologic processes, flooding pattern, water balance components (especially ET and drainage), and effects of management practices for the low-gradient, forested wetlands of the humid Coastal Plain. This is one of the paired watersheds (with 206-ha watershed, WS 80, established later in 1968) on the headwater stream draining to Turkey Creek on the lower Atlantic Coastal Plain (fig. 1, right). During 1964 to 1968 the Forest Service expanded the experimental study at this site by adding two larger watersheds to it. These additional watersheds are designated as WS 78 and WS 79. Watershed 78 has an area of about 5000 ha and is drained by a third-order stream, Turkey Creek (outlet in fig. 1, right, but full boundary not shown). Watershed 79 has 500 ha of drainage area on a second-order stream and contains both WS 77 and WS 80. The Center continues to maintain long-term hydrologic monitoring of WS 77, WS 79, and WS 80. Information about these watersheds is summarized in table 1.

The study site of interest here (WS 77 and WS 80) is on a marine terrace of the Pleistocene epoch.[2] The area has low relief with surface elevations ranging from 4.0 to 10.0 m above mean sea level. Loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* P. Mill.), cypress (*Taxodium distichum* L.), and sweetgum (*Liquidambar styraciflua* L.) are

[2] Gartner, D.; Burke, M.K. 2001. Santee Experimental Watershed database. 32 p. Unpublished report (Revised from April 29, 1999). On file with: USDA Forest Service, Southern Research Station, Center for Forested Wetlands Research, 2730 Savannah Highway, Charleston, SC 29414.

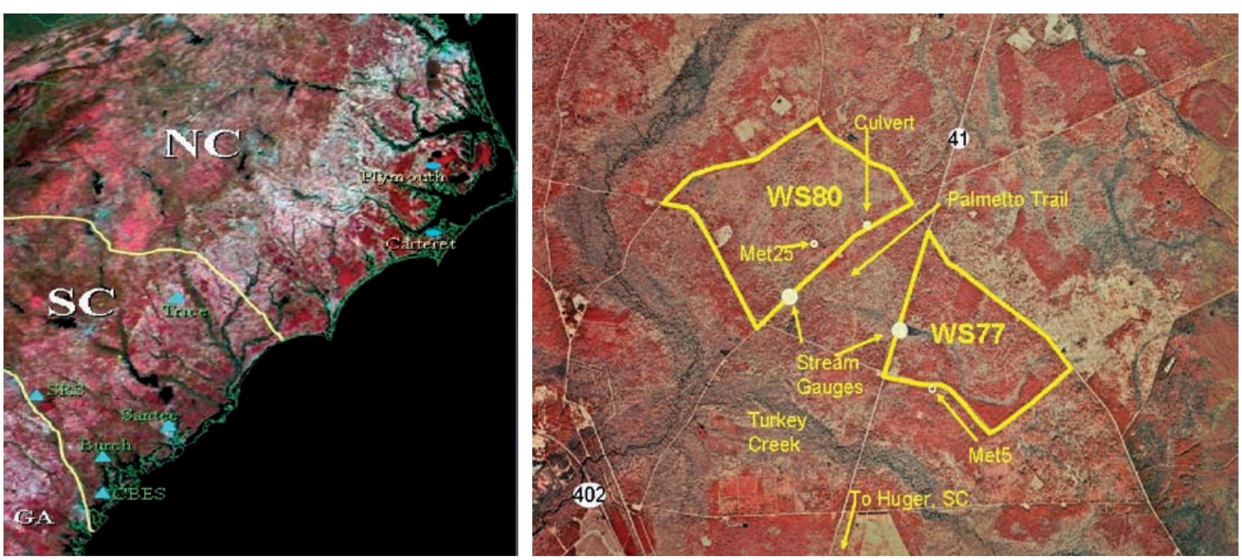


Figure 1—Left: locations of the five study sites. Right: two experimental watersheds at Santee Experimental Forest in coastal South Carolina.

Table 1—Santee Experimental Forest watersheds 77, 78, 79, and 80: infrastructures, data collection, and research needs

Watershed number	Drainage area	Estab-lished	Outlet design	Condition of infra-structure	Associated data	Status of monitoring	Needs
77 (Treatment; first order, Fox Gully)	160 ha	1963	Compound V-weir	Good	Stage, soil moisture, water quality, GW levels, meteorological station	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	Monitoring discontinued in 1984	Digital processing of old data, resume monitoring of water quantity and quality, analysis and publications
79 (second order, Fox Gully)	500 ha	1965	V-weir and 3-box culvert	Good	Stage, water quality	Monitoring continuing	Processing, data analysis, publications
80 (control)	206 ha initially; 160 ha now	1969	Compound V-weir	Good	Stage, water quality, GW levels, meteorological station, throughfall	Monitoring continuing (no data 1981-1989)	Digitizing 1992-95 data, analysis of old data and publications

— = not applicable; GW = ground water.

dominant forest species in the watershed (Sun and others 2000b). Watershed 77 (treatment) was salvage harvested soon after Hurricane Hugo in September 1989; WS 80 (control) was not salvaged. Watershed 77 supports a naturally regenerated stand of pine trees and has recently had understory burning. Soils are primarily loams and strongly acid, infertile Aquults characterized by seasonally high water tables, argillic horizons at 1.5 m depth, and low base saturation (see footnote 2). The climate of the research area is humid subtropical with long hot summers and short mild winters (Sun and others 2000b). Mean annual precipitation is about 1350 mm with highest rainfall in July and August and lowest rainfall in November to April. Winter storms are generally of low intensity and long duration, and summer storms are generally of high intensity and short duration.

Objectives

- To quantify the hydrologic processes, flow dynamics, and baseline water and nutrient budgets for forested watersheds draining Coastal Plain streams.
- To evaluate the effects of management on hydrology and water quality.
- To develop and test hydrologic models for these naturally drained coastal forests. These models will help explain interactions among soils, vegetation, and hydroperiods and will be useful in evaluating management and climatic impacts.
- To conduct long-term ecohydrological studies of 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 (fig. 1, right, and table 1) for quantifying water nutrient budgets, flow, and water table dynamics of these low-gradient forested watersheds. Watershed 77 is gauged with a flow-recording station upstream of a compound V-notch weir that spans the stream. Watershed 80 has a stream-gauging station at the outlet. This station consists of a compound V-notch and a flat concrete weir with a recording gauge inside a stilling well. The flow measurement structure on WS 79 is a recording gauge upstream of a V-notch weir. There is a concrete box culvert on either side of this weir, and the bases of these culverts are at the same level as the top of the V-notch. Flow measurements on all three watersheds were interrupted between 1981 and 1984 and did not start again until after Hurricane Hugo in September 1989. Recording of flow data on the largest watershed, WS 78, was discontinued in 1984. Automatic ISCO-3210 flow data loggers were installed on WS 77 and WS 80 only in 1996. Flow data are missing for intermittent periods for all watersheds. Water tables were measured using manual wells at several locations in WS 77 and WS 80 until 1995. One automatic recording well (WL 40) was installed on WS 80 in late 1995, and two were installed on WS 77 at that time (table 1).

Meteorological data (daily maximum and minimum air temperatures and precipitation) have been collected since 1964 at a station designated as Met-5, which is located on WS 77, and since 1976 at Met-25 on WS 80. A complete weather station measuring maximum and minimum air temperatures, humidity, solar radiation, wind speed, and wind direction was installed in 1996 at Santee Headquarters, which is within 4 km from the watersheds. Only air temperature data were available prior to 1996. Several rain gauges were installed initially within and around the large watershed (WS 78), but their use was discontinued later.

Long-term data for daily precipitation, air temperature, and streamflow from WS 77 and WS 80 are being made available through HYDRO-DB, a Web-based data sharing and harvesting server hosted by Oregon State University and sponsored by the Forest Service and National Science Foundation's Long-Term Ecological Research network. The site is located at http://www.fsl.orst.edu/climhy/hydrodb/, where hydroecological data from various participating sites are posted.

Results to Date

- Young (1967): Excess water in the form of surface runoff and subsurface drainage did not appear to be a problem on WS 77. Baseflow from the watershed was undependable. Reliability of water balance ET varied depending on the temporal scale. Twenty percent of the annual rainfall, on average, became stormflow, depending on seasonal soil moisture storage.
- Binstock (1978): A prescribed winter burn did not significantly deplete or enrich mineral soil, or significantly increase concentrations of dissolved nutrients in the streamwater.
- Richter and others (1983, 1982) and Richter (1980): Hydrologic fluxes of nitrogen, phosphorus, sulfur, and basic cations from burned pine litter to ground water and streamwater are not likely to have appreciable effects on water quality in the Atlantic and Gulf Coastal Plain.
- Sun and others (2000b): Annual streamflow was 25 to 30 percent of annual precipitation. However, simulations using the MRSWARM model showed stream outflow values as great as 50 percent depending on annual rainfall pattern. Salvage logging after Hurricane Hugo greatly increased annual streamflow on WS 77.
- Binkley (2001): Some nutrient concentration data from these first-order watersheds was reported as part of a nationwide assessment of nitrogen and phosphorus concentrations in forested streams. Binkley reported that nitrogen and phosphorus concentrations were generally much lower for forest streams than for streams draining agricultural or urban land.
- Miwa and others (2003): Headwater streamflow on these watersheds is highly responsive to rain events and is also influenced by vegetation and topography. Quantitative separation of baseflow is difficult in these flat coastal watersheds.
- Amatya and others (2003b): A test of DRAINMOD's (Skaggs 1978) predictions of daily streamflows of WS 80 was encouraging. Available data were employed, and model calibration was minimal.
- Amatya and others (2003a): A 6-year hydrologic comparison study of naturally drained WS 80 and an artificially drained watershed in NC found a wide variation in annual outflows affected by water-table position, which depends on both rainfall and ET. Average annual rainfall was lower at the SC site, but the water table was shallower and outflows greater and more frequent there than at the NC site. Site-to-site differences in soil and vegetation types may have contributed to these differences.

Next Steps

- A study now underway will quantify the water budget of WS 80 (the control). Both monitoring of rainfall, throughfall, outflow, PET, and water-table depth and modeling are being employed. DRAINMOD will be tested further with measured field data on soil hydraulic properties and weather parameters.

- Sun is testing the capability of a distributed hydrologic model called MIKE-SHE to predict the hydrology of WS 80.
- Long-term flow data from the first-order watersheds are being used for preliminary analyses of baseline loading calculations for a Charleston Bay water-quality model being developed by Tetra-Tech, Inc. (Lu and others 2005).
- Tetra-Tech, Inc., is sampling event water quality at WS 79 in connection with development of the Charleston Bay water-quality model.
- Researchers are analyzing data on outflow concentrations of nutrients from control WS 80 and treatment WS 77 as a means of comparing the effects of natural regeneration and prescribed understory burning on WS 77.
- Researchers have recently resumed hydrologic monitoring of WS 78 and will evaluate streamflow dynamics there. This project is supported by the Forest Service Southern Research Station Challenge Cost-Share Program and the National Council for Air and Stream Improvement, Inc. (NCASI). The cooperators in this project are the College of Charleston, the U.S. Geological Survey, the Francis Marion National Forest, the University of Cracow, Tetra-Tech, Inc., and the SC Department of Transportation.
- Existing long-term flow data for WS 78 may be analyzed to compare that watershed's water budget and flow dynamics with those of WS 79 and WS 80.
- A DRAINMOD-based watershed-scale model (Amatya and others 1997, 2004a) for evaluating the effects of various management practices may be tested on WS 78.

Long-Term Studies on Managed Pine Forest at Carteret County, North Carolina

Site Description

In early 1988, the Weyerhaeuser Company and N.C. State University (http://www.bae.ncsu.edu/soil_water/scarteret.htm) initiated a long-term study designed to quantify potential impacts of silvicultural and water management practices on downstream hydrology and water quality at a site in Carteret County, NC. Since 2002, the Center has been collaborating with NC State University in this long-term study, which has been supported primarily by NCASI. The study site (figs. 1 and 2) is located at approximately latitude 34°48'N. and longitude 76°42'W. and is owned and managed by Weyerhaeuser Company. The research site consists of three artificially drained experimental watersheds, each

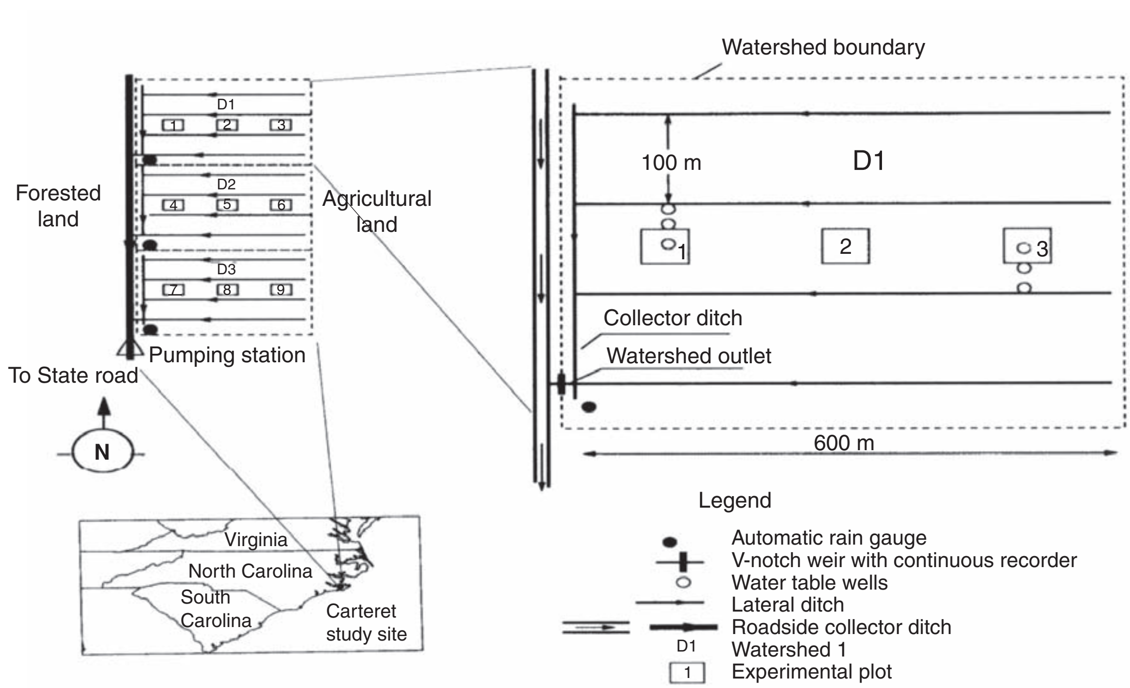


Figure 2—Location map and layout of experimental watersheds (D1, control; D2 and D3, treatment watersheds) at Carteret County, NC.

about 25 ha in size and planted to loblolly pine in 1974. The site is flat, located at an elevation of about 3 m a.m.s.l., and its soils have shallow water tables. The soil is a hydric series, Deloss fine sandy loam (a fine-loamy mixed Thermic Typic Umbraquult). Each watershed is drained by four parallel lateral ditches, which are 1.4 to 1.8 m deep and spaced 100 m apart. These drain to a roadside collector ditch, which ultimately drains to an estuary about 3 km downstream (fig. 2). Long-term average annual precipitation at the site is 1330 mm. The climate is typical of the Atlantic Coastal Plain; summers are hot and humid, and tropical storms and hurricanes are common.

Objectives

- To conduct long-term field studies of the effects 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 and other related models as tools for predicting and evaluating hydrology, water quality, productivity, and climate change for the drained forested watersheds.
- To apply the results of field-scale research (both data and models) to assess cumulative impacts of alternative land uses and management practices on the hydrology and water quality of large coastal watersheds.

Monitoring

Data on hydrology and water quality and 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 data logger in an open area on the western side of each watershed. Air temperature, relative humidity, wind speed, and net radiation were measured continuously by an automatic weather station located at the center of the treatment watershed (D2). An adjustable-height 120° V-notched weir located in a water-level control structure at a depth nearly equal to that of the bottom of the outlet ditch was used to measure drainage outflow in each watershed. A water-level recorder and an automatic data logger were installed upstream of each weir and measured water levels at 6-minute intervals. An additional recorder was placed downstream from the weirs (not shown) to determine whether weir submergence occurred and to provide data that could be used to correct flows in case of submergence. 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 each of two locations midway between the lateral ditches for each watershed (not shown). The parameters being measured and the method and the frequency of measurements are presented in table 2. McCarthy and others (1991) carried out an interception study of the 14-year-old pine forest. McCarthy and others (1991) and Amatya and others (1996, 2000a) provide detailed descriptions of the site and measurements, including the history of the loblolly pine stand planted in 1974. Amatya and others (1998, 2003c) have documented details of procedures for laboratory water-quality sample analysis. The chronology of various site treatments is shown in table 3.

Results to Date

- Evapotranspiration was the dominant component of the water budget (~70 percent of annual rainfall) followed by drainage outflows (Amatya and others 1996, McCarthy and others 1991). Interception was estimated to be 15 percent of the average annual rainfall. Lateral seepage amounted to nearly 4 percent of the total rainfall. Seasonal loss through ET was as much as 96 percent of the rainfall depending on the season.
- Controlled drainage consisting of a raised weir on a flash-board riser during the summer-fall period on treatment watershed D2 helped store the water in the soil profile for periods of high tree growth and ET (Amatya and others 2000a). Controlled drainage with a raised weir during the spring on treatment watershed D3 also substantially reduced freshwater outflows, minimizing offsite impacts on the downstream water quality of the estuarine ecosystem. Similarly, use of an orifice-weir at the outlet of treatment watershed D3 significantly reduced outflows compared to free drainage from control watershed D1 (Amatya and others 2003c).
- Water management with controlled drainage with a weir on D2 and D3 reduced the export of nitrogen, phosphorus, and sediment, primarily by reducing drainage outflows (Amatya and others 1998). Controlled drainage with an orifice-weir reduced the export of phosphorus and sediment, but despite the reduced outflows, nitrogen export did not decrease (Amatya and others 2003c).
- Blanton and others (1998) found that the 1995-96 harvesting, bedding, and site preparation for regeneration on treatment watershed D2 reduced drainable porosity in the top 60 cm of the profile by approximately 50 percent, resulting in a significant change in storm outflow hydrographs.
- Amatya and others (2004b) found that water-table elevations and water-quality parameters returned to baseline levels (levels observed in control watershed D1) approximately 6 years after planting of pine trees in 1997 for regeneration on treatment watershed D2. However, due to

Table 2—Parameters being measured at the Carteret study site, North Carolina

Parameter	Method of measurement	Location	Monitoring interval	Units	Remarks/ datalogger	Measurement period
			Hydrology			
Precipitation	Automatic tipping bucket	Open area	Event	mm	OMNIDATA	1988-2000
					Texas Electronic	2000 to date
	Manual gauge	Open area	2-3 weeks	mm	Standard	1988 to date
Outflow	Continuous stage	Outlet	12-min	cm	OMNIDATA	1988-2000
					INFINITY	2001 to date
	120° V-weir	Outlet	12-min	m^3hr^{-1}	Weir Equation	1988 to date
Water table	Continuous well	Midfield	1 hour	cm	OMNIDATA infinity	1988 to date
	Manual well	Transect	2-3 weeks	cm		1988-1995
Soil moisture	Various depths	Midfield	3-4 weeks		Neutron probe	1988-1994
	Various depths	Midfield	3-4 weeks		TDR	1995 to date
Throughfall	Manual troughs	Midfield	Event	mm		1988-1990
Stemflow	Plastic semi-tubes	Midfield	Event	mm		1988-1989
			Weather[a]			
Air temperature	Automatic and manual		Half-hourly	°C	CAMPBELL	1988 to date
Relative humidity	Automatic and manual		Half-hourly	%	SCIENTIFIC	1988 to date
Wind speed	Anemometer	At the middle	Half-hourly	$m\ sec^{-1}$	CR-21 (until 1997)	1988 to date
Wind direction	Anemometer	of watershed	Half-hourly	Degrees		1988 to date
Solar radiation	Pyranometer	D2	Half-hourly	$W\ m^{-2}$	CAMPBELL	1988 to date
Net radiation	Net radiometer		Half-hourly	$W\ m^{-2}$	SCIENTIFIC	1997 to date
Soil temperature	Sensor		Half-hourly	°C	CR-10X (from	1997 to date
Soil heat flux	Heat flux plates		Half-hourly	$W\ m^{-2}$	1997 to date	1999-2000
			Water quality			
NO_3+NO_2, NH_4	Composite and grab	Outlet	Time			
TKN, TP, PO_4	samples		proportional	$mg\ L^{-1}$	ISCO	1988 to date
TSS,						
pH, turbidity	Manual meters	Outlet	2-3 weeks	Various	HYDROLAB	1988 to date
DO, temp						
Cations, metals	Composite and grab	Outlet	2-3 weeks	$mg\ L^{-1}$	ISCO	1988-1994
			Tree physiology			
Height	Measuring pole	Midfield	Yearly	m		1988 to date
DBH	Dendrometer band	Midfield	Yearly	cm		1988 to date
Leaf Area Index	Litterfall traps	Midfield	3-4 weeks			1988-1994
Leaf Area Index	Leaf area analyzer	Midfield	4-6 weeks		Li-COR (2000)	1995 to date
Stomatal conductance	Porometer	Midfield	3-4 weeks	moles $m^{-2}s^{-1}$	Li-COR (1600)	1988-1994

[a] All weather data from 1988 to 1997 were measured on an hourly basis by a CR-21 Campbell Scientific weather station located about 800 m west of the study site.

Table 3—Chronology of water and silvicultural treatments on three experimental forested watersheds at Carteret site, North Carolina[a]

Year	Watersheds D1 (24.7 ha)	D2 (23.6 ha)	D3 (26.7 ha)	Management scenarios
1974		Study began		
1987	Experiment or 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 drainage (calibration period)			Fertilizer application and 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 preparation/ bedding in October	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1997	Free drainage (control)	Planted for regeneration (February)	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1998	Free drainage (control)	1-year-old pine trees	Orifice-weir outlet	Silvicultural treatment (D2) and water management (D3)
1999	Free drainage (control)	2-year-old pine trees	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	Free drainage	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

[a] Pine trees on all three watersheds (D1, D2, and D3) were planted in 1974 with a precommercial thinning in 1980 and fertilizer application in 1981 (after Amatya and others 1996). Most of these studies are being supported by NCASI, Inc.

frequent weir submergence on treatment watershed D2 during large events, the results for the drainage outflows were somewhat inconclusive.

- On the basis of 100 site-years of outflow data for forested watersheds in the Coastal Plain of eastern NC, including the data from control watershed D1, Chescheir and others (2003) reported a median hydrologic response factor of 31 percent, with an interquartile range of 26 to 35 percent. For most study sites, nutrient concentrations in forest outflow were lower than typical values for other land uses.
- Amatya and others (2003a) studied annual outflows from naturally drained watershed WS 80 in SC and artificially drained watershed D1 in NC. They found that annual outflows varied widely and were affected by water-table position, which is dependent upon both rainfall and ET. Naturally drained WS 80 in SC had much shallower water-table depths and more frequent outflows than did watershed D1, even though average annual rainfall was lower at the SC site. Site-to-site differences in soil and vegetation types may have contributed to this.
- Using data from control watershed D1 and many other sites in the Southern United States, Lu and others (2003) developed a long-term annual ET model with four independent variables: annual precipitation, latitude, elevation, and forest coverage. The model may be used to examine the spatial variability of water availability and effects of land use change on water availability.
- Sun and others (2002) concluded that streamflows from flatwoods watersheds like the one at the Carteret site generally are discontinuous in more years than are streamflows from upland watersheds. The stormflow peaks in these low-gradient coastal watersheds were smaller than those in the upland watersheds except under extremely wet conditions.
- Amatya and others (1995) used weather data from the Carteret site and two other coastal stations to evaluate five methods of estimating PET. The Penman-Monteith method was employed as a reference. Amatya and others (2000b) studied the relationships between net and solar radiation for three vegetation canopies (emerging wetland vegetation at the Carteret site and grass and young pine trees elsewhere) in coastal NC.
- McCarthy and others (1992) used data from this study to develop and test the forest hydrologic model DRAINLOB, which is based on DRAINMOD (Skaggs 1978). DRAINLOB was modified for use at the watershed scale (Amatya and others 1997) and was successfully applied to data for large coastal watersheds with pine forest cover (Amatya and others 1997, 2003d).
- Data from this site were used to test the capability of DRAINLOB to model various water and silvicultural management practices. (Amatya and Skaggs 1997, McCarthy and Skaggs 1992, Richardson and McCarthy 1994). The model was further tested with long-term data from the study site (Amatya and Skaggs 2001).
- Measured data and the DRAINLOB model modified for an orifice-weir outlet were used to develop preliminary guidelines for the design of an orifice-weir outlet for managing water and offsite impacts (Amatya and others 1999).
- Using a PnET-II ecosystem process model, Sun and others (2000c) predicted a significant increase of drainage (6 percent) and forest productivity (2.5 percent) for a pine forest on the control watershed in Carteret County, NC, as a result of future climate change scenarios predicted by the General Circulation Model HADCM2.
- The study at the Carteret site, together with a large watershed-scale experimental study near Plymouth, NC, resulted in a long-term database 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 and others 1997, 2002, 2004a; Chescheir and others 1998; Fernandez and others 2002; Skaggs and others 2003).

Next Steps

- A final study is underway to evaluate the hydrologic and water-quality impacts of harvesting and subsequent planting for regeneration on watershed D2.
- Similarly, monitoring is continuing to evaluate the hydrology and water-quality impacts of a second commercial thinning of mid-rotation pine trees on watershed D3.
- A long-term water budget and trends in water-quality parameters (nutrients and sediment) of control watershed D1 under conventional “free” drainage is being evaluated during the growth cycle of the pine stand.
- A study is planned to compare downstream water-quality effects of fertilizer treatments on the 6- to 7-year-old young pine stand on watershed D2 and the 30-year-old mature thinned stand on watershed D3 with that of control watershed D1.
- There are plans to study the long-term hydrology of a drained pine forest throughout that forest’s life cycle (from planting to harvest). Modeling outputs obtained by applying DRAINLOB to 40 years of weather data and 16 years (1988-2003) of observation data may be used to describe the forest’s water and nutrient balances and processes.

The Coosawhatchie Bottomland Ecosystem Study, South Carolina

Site Description

The CBES site (fig. 1) is a 350-ha tract owned by Mead-Westvaco Corporation and located in Jasper County, SC, at latitude 32°40'N., longitude 80° 55'W., just above tidal influence on the Coosawhatchie River (fig. 3A). The river is a fourth-order, anastomosing, blackwater stream that drains a 1012-km^2 watershed (Abrahamsen 1999). The Coosawhatchie River valley is on the Wicomico and Pamlico marine terraces and was formed by erosion and downcutting during the Pleistocene-Holocene. The flood plain, which is 1.6 km wide on the study site, is relatively small and immature compared to those of some other rivers in the lower Coastal Plain (Murray and others 2000) but is representative of the formerly numerous blackwater river flood plains along the Atlantic Coast that were drained for agriculture or intensively logged.

There are two weakly developed terraces on the site, and these are distinguished by surface sand size and flooding frequency. Soils of the lower terrace consist of variable loamy and clayey Pamlico and recent fluvial sediments over sandy fluvial beds. Most are in the Brookman series of fine mixed thermic Typic Umbraqualfs. In much of the flood plain there is a confining layer of clay at a depth between 30 and 100 cm (Murray and others 2000). The flood plain's less scoured soils are in the Meggett series, which consists of fine, mixed, thermic Typic Albaqualfs. Approximately 20 percent of the lower terrace consists of six other soil series; these are characterized by underlying calcareous marine sediments. The higher second terrace is a fine-loamy siliceous thermic Typic Umbraqualf.

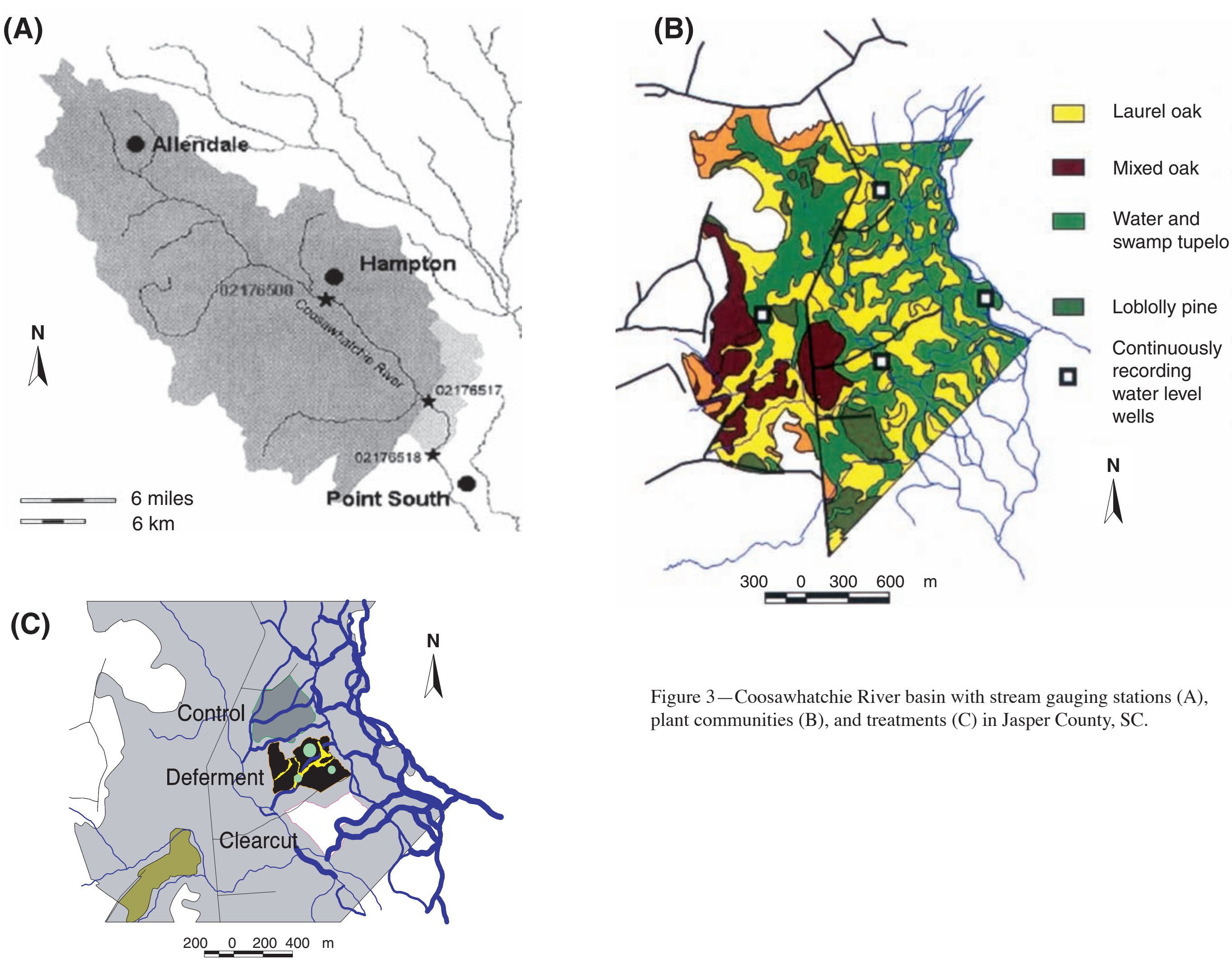


Figure 3—Coosawhatchie River basin with stream gauging stations (A), plant communities (B), and treatments (C) in Jasper County, SC.

There is approximately 2 m of relief on the study site, and the distinct microtopography is convex hummocks and scoured swales with sandy channel bars and small natural levees (Murray and others 2000). The hydroperiod is relatively unaltered, as the river has not been channelized and dams and levees are not present on the river (Eisenbies and Hughes 2000). Land use in the watershed is mainly agriculture (42 percent), forestry (30 percent), and wetlands (24 percent) (Maluk 2000). Although not cleared and drained for agriculture, the study site was high-graded, most recently around 1950. There are five forest community types on the site. These types are named for the dominant tree species in each community: water tupelo (*Nyssa aquatica* L.), swamp tupelo [*Nyssa sylvatica* var. *biflora* (Walter) Sargent], laurel oak (*Quercus laurifolia* Michaux), overcup oak (*Q. lyrata* Walter), and mixed oak (Burke and others 2003) (fig. 3B).

The CBES is part of two larger studies; it is one of three sites in the Southern Forested Wetland Research Initiative and one of the fixed and integrator sites for the United States Geological Survey's (USGS) National Water Quality Assessment (NAWQA) program for the Santee River basin and coastal drainages of NC and SC. In the former program, several Federal and State agencies, universities, and forest industry are collaborating to develop reference bottomland hardwood forests in the South. The latter program is a USGS-led multi-agency study of the spatial distribution of water quality and quantity and of the mechanisms by which human activities and natural factors affect water quality.

The CBES is a study of ecosystem structure and processes in a hydrologically linked terrestrial and aquatic ecosystem. It was initiated to address recent public concerns about the need for sustainable management, restoration, and protection of forested wetlands. The multi-investigator study consists of two phases. Phase 1 was the baseline calibration period (1994-99) during which the site was developed as a reference or model wetland for comparison purposes. Phase 2 (2000-05) is a study of the influence of three alternative regeneration methods on ecosystem processes (fig. 3C).

Objectives

- To characterize the hydrology of the site for reference purposes.
- To quantify hydroperiods across the site and relate hydroperiods to forest community structure.
- To develop hydrologic models for predicting changes in water level across the site and for estimating historic hydroperiods on the site.
- To produce long-term hydrologic and meteorological databases for the site for use in ecosystem and hydrologic models.
- To test the influence of three regeneration methods on ecosystem processes influenced by hydroperiod.

Monitoring

Soil was cored deeply to identify the depth and composition of deposits and the existence of aquifers on the site. Long-term river-stage data from 24 km upstream (Hampton Station), 8 km upstream (Early Branch Station), and at the lowest part of the study site (Gray's Station) (fig. 3, table 4) were used in conjunction with three additional continuously recording water-table wells on the site (fig. 3) and 18 manual PVC wells installed in permanent productivity plots (Burke and others 2000) to monitor the elevation of the water table. In addition, eight piezometers in and adjacent to the river channels were used to determine the recharge-discharge relations between the ground water and surface water.

Individual regressions were calculated for water-table elevations on the flood plain. Water-table elevations for observation wells were used as the dependent variable, and river stage (at the Hampton, Early Branch, and Gray's stations) and water-table elevations for three additional continuously recording wells were used as independent variables. The observation wells were monitored manually, and the best regressions were used to model water levels in the four major communities during the 4 years during which stage data were collected. These models were used in conjunction with the 50-year database from the Hampton station to estimate long-term hydroperiod on the site. Recharge and discharge relations between the ground water and surface water were determined by monitoring the piezometers during a range of river stages.

Two automatic weather stations with an OMNIDATA data logger were installed in the middle of a large opening and under the canopy on the study site. These stations continuously measured rainfall, soil and air temperatures, relative humidity, wind speed and direction, and solar radiation since 1994. The weather station under the canopy was removed at the end of phase 1 (1999). The data from this station are archived at the CFWR for general use.

The Early Branch gauging station and river reaches between the Early Branch and Gray's stations were established as NAWQA fixed and integrator sites in 1995. Fixed sites are those that were sampled most intensively during the 3 years of the NAWQA study, and the integrator sites are those that represented an integration of multiple land covers (Maluk

Table 4—Three stations on the Coosawhatchie River used in Coosawhatchie Bottomland Ecosystem Study (Burke and Eisenbies 2000): function, information collected, period of operation, and responsibility for operation

USGS station number	Station name	Function	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	Gray's	CBES study	River stage	—	1995-present
			Nutrients, organic carbon, trace elements in bed sediments and biota	1995-1998	—

— = not applicable; USGS = United States Geological Survey; NAWQA = National Water Quality Assessment; CBES = Coosawhatchie Bottomland Ecosystem Study

2000). In addition to stage information, numerous water-quality indicators were monitored by USGS from October 1995 to September 1997. Details of methods, quality-control procedures, and results can be found in Mueller and others (1997) and Maluk (2000). After September 1997, USGS discontinued the monitoring at the Early Branch and Gray's stream gauging stations, and the CFWR assumed responsibility for maintenance, servicing, data retrieval, and data management for these stations. The USGS continues to manage the Hampton station.

The Coosawhatchie Early Branch site was established as a NAWQA fixed and integrator site. Water-quality samples were collected monthly from the Coosawhatchie River sites from October 1995 through September 1997, as part of the USGS NAWQA program. These samples were analyzed for nutrients (phosphorus and several nitrogen species), suspended organic carbon, dissolved oxygen, silica, trace metals, and pesticides. Details of methods, quality-control procedures, and results can be found in Mueller and others (1997) and Maluk (2000).

Results to Date

- Deep coring at the site revealed that the surficial aquifer is about 9 m thick and consists of alluvial sand and clay deposited by the Coosawhatchie River and older Pleistocene sand and clay. These deposits are underlain by a confining unit that is 12 m thick, which in turn overlies the Floridan aquifer, which is about 21 m deep (Eisenbies and Hughes 2000).
- Hydrology on the site was typical of blackwater rivers: flooding is of relatively short duration and may be followed by extensive periods of low discharge, floodwaters may be deep and widespread, and droughts also occur (Burke and Chambers 2003).
- Long-term hydrologic records showed that hydroperiods were variable both within and among years and that duration of flooding was shorter in recent years than formerly (Burke and others 2003).
- The potentiometric surface of the Floridan aquifer is approximately 0.5 m above land surface at the study site. This represents a decline of approximately 5 m during the last decade and is the result of ground-water withdrawals for municipal and industrial water supplies (Hughes and others 1989). The documented drop in potentiometric surface is consistent with the shortened duration of flooding measured in recent years. These observations suggest that the site is becoming drier and that withdrawal of water from the aquifer may be affecting wetlands (Burke and others 2003).
- Discharge of ground water is the dominant hydrological condition on the study site, but recharge can occur during extremely high flows.

- The river generally crests 3 to 4 days after rain events in the watershed. Crests at the Gray's station are 2 to 3 days after crests at the Hampton station (Eisenbies and Hughes 2000), so regressions using river stages were used in predictive models of ground water.
- Regressing water-table elevations for observation and continuously recording wells on river stages yielded correlation coefficients that ranged from 0.56 to 0.97. Water levels in wells closest to the river generally correlated best with river stage (Eisenbies and Hughes 2000).
- The forest communities had distinct hydrologic regimes. Sites could be ranked from wettest to driest by percentage of time flooded on both water year and growing season (March 15 to October 1) bases. For the previous 50 years (1951-2000), the mean time flooded during the growing season was 79 percent for water tupelo, 68 percent for swamp tupelo, 38 percent for laurel oak and overcup oak, and 19 percent for mixed oak (Burke and others 2003). Also, ground cover and species diversity values were inversely correlated to flooding frequency (Billups and Burke 1999).
- Hydrologic connectivity (degree of flow-path connection to the main channel) affected sedimentation rates. Highest deposition rates occurred near sloughs and their anabranches that have a direct flow path to the river (Hupp 2000).
- The annual streamflow is among the smallest for southeastern Coastal Plain rivers, and the sediment load is relatively light (5 to 25 mg L^{-1}) compared with that of other Coastal Plain rivers, including other blackwater rivers (Hupp 2000). Concentrations of suspended sediment in the Coosawhatchie River are similar to those in another blackwater river, the Edisto (Maluk 2000). The flood plain appears effective at removing suspended sediment (24.5 kg ha^{-1} yr^{-1}) via sediment deposition (0.02 to 0.20 cm yr^{-1}) (Hupp 2000).
- The Coosawhatchie River exhibited a seasonal trend in nutrient concentrations, with low concentrations in winter and significantly higher concentrations in summer, possibly because total organic nitrogen present in the form of detritus was lower during the winter. Nitrate concentrations in the river were low, as is expected for forested watersheds. Dissolved phosphorus concentrations in the Coosawhatchie River were among the highest in the basin.

Next Steps

- Evaluate the short-term and long-term hydroperiods on these forested lands using hydrologic models like DRAINMOD to determine wetland hydrology.
- Address the potential impact of ground-water use on flood plain resources, including vegetation in the region, using a comprehensive hydrologic model.
- Conduct studies on impacts of harvesting and regeneration of bottomland hardwoods.
- Study impacts of upland management practices on hydrology and water quality.

Study on High-Intensity Short-Rotation Woody Crop Site at Trice Farm, South Carolina

Site Description

A study on a hardwood plantation forest, which is owned and managed by the International Paper Company and located in the upper Coastal Plain of SC (fig. 1), was initiated in 1997 as part of the U.S. Department of Energy's Agenda 2020 Program to provide a bridge between small-scale plot studies and large-scale assessment models. The study is a collaborative effort of Oak Ridge National Laboratory, the International Paper Company, NC State University, the University of Nevada, the College of Charleston, and the Forest Service.

The plantation forest, which was previously a farm, is now used for research on intensively managed SRWC and operational plantations. The forest is located on the upper Coastal Plain, approximately 1.6 km southwest of Mayesville in Sumter County, SC (fig. 4). It was historically planted with cotton, soybeans, and wheat, with a small portion of land in pasture and natural pine-hardwood forest. Some natural forest is present at this time, primarily in headwater reaches and riparian zones. The study site occupies ~120 ha. It is located on former agricultural fields that are situated in a way that facilitates the measurement of all inputs and outputs from the system. The first rotation of SRWC sycamore (*Platanus occidentalis* L.) and sweetgum (*Liquidambar styraciflua* L.) was planted on the study catchments in February 1997. The soils on the site are typified by the Goldsboro, Norfolk, Coxville, and Rains soil series, which are characteristic of the upper Coastal Plain, and they have been drained artificially.

Objectives

- To determine the effects of operational SRWC plantations on soil chemical and physical properties and on nutrients in surface and subsurface runoff.
- To determine the hydrologic and nutrient cycling processes of SRWC plantations.

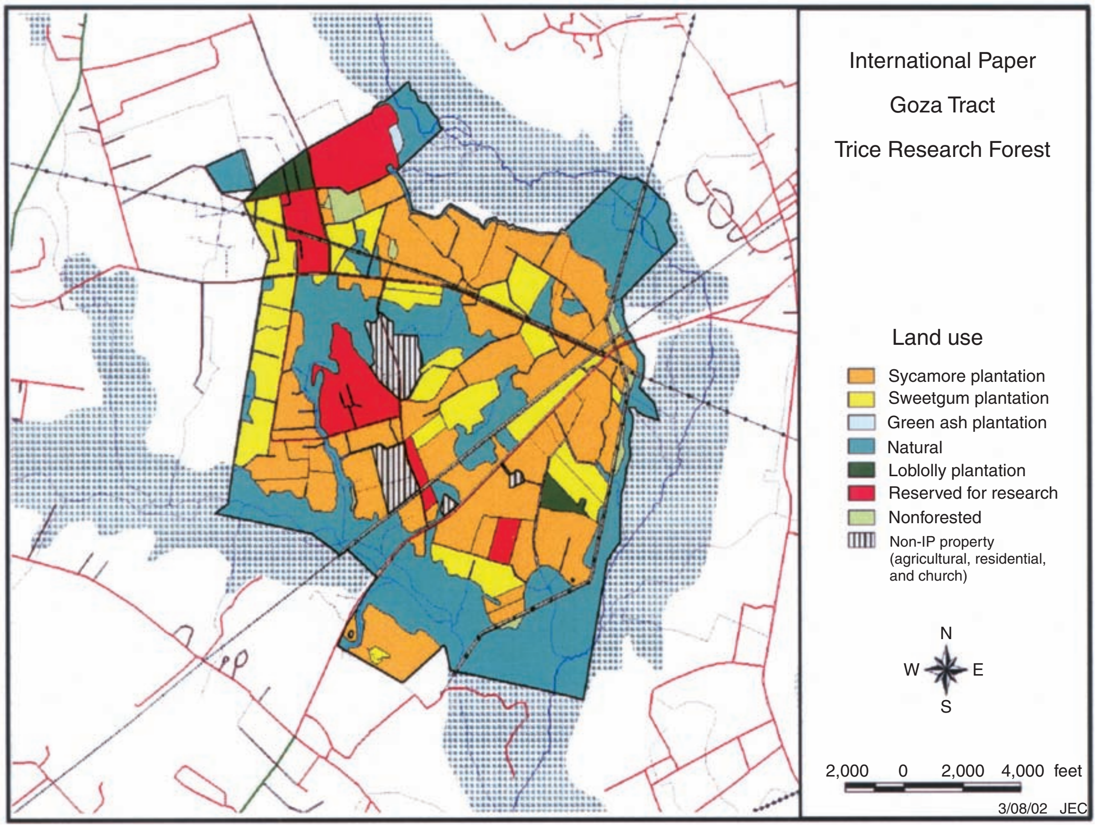


Figure 4—Layout of International Paper's Trice Forest in the upper Coastal Plain near Sumter, SC.

- To determine the potentially beneficial effects of alternative management practices on productivity, soil sustainability, and offsite movement of nutrients and chemicals. Both field instrumentation and modeling are employed. The models used are a process-based hydrologic model, WATRCOM (Parsons and others 1991), and a biogeochemical model, NuCM.
- To evaluate the potential of SRWC systems to sequester carbon and enhance soil tilth.

Methods

The study 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 provides the conditions necessary for understanding productivity and sustainability at an operational level. The presence of adjacent natural forests, which can be used as a reference system, also facilitates the assessment of the conversion of agricultural land into intensively managed woody crop plantations.

Measurements were taken at a large watershed scale and a smaller catchment scale (table 5). Measurements of flow, soil moisture, weather, and nutrient parameters were done at six experimental catchments (4 to 6 ha), and an 200-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. Detailed studies of nitrogen mineralization and organic matter decomposition have been conducted.

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

Three treatments were designed to represent established practices of SRWC culture (with 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

Table 5—Summary of meteorological, hydrologic, water quality, soil and vegetation data used to assess treatment responses and cumulative development of the watersheds and catchments

Data type	Measurement	Method	Scale	Sample period
Meteorological	Temperature	Thermocouple	Watershed	Continuous
	Precipitation	Gauge	Watershed	Continuous
Hydrologic	Stream stage	Water level recorders (electronic and chart types)	Watershed and catchment	Continuous
	Stream flow	Trapezoidal flumes and V-notch weirs	Watershed and catchment	Continuous
	Water table elevation	Deep (4.6 m) and shallow (1.8 m) well pairs	Catchment	1997-2002: monthly
Water quality	Soil water analysis: PO_4, NH_4, NO_3, Mg, K, Ca	Hanging-column tension lysimeters (1 m deep)	Catchment	1998-2002: monthly
	Stream water analysis: TN, TP, NO_3, NH_4, Ca, Mg, K, sediment	ISCO 3700 portable samplers	Watershed and catchment	1998-2002: storm event samples plus weekly composite samples
Soil chemical properties	Extractable cations, TC, TN, N-mineralization	Cores (15-75 cm)	Plot	1997-1999, 2001
		Sequential cores	Plot	2001-2002
	Decomposition	Litter bags	Plot	2001-2004
Soil physical properties	Bulk density	Cores	Catchment	1998-2001: annual
	Infiltration	Single-ring infiltro-meter, cores	Catchment	1998
Vegetation	Tree growth above ground	Diameter tapes, calipers, telescoping poles	Plot	1997-2002: annual
	Tree mortality	Visual	Plot	1997-2002: annual
	Below-ground biomass	Cores	Catchment	1997-2002: periodic
	Litter	1.25 m^2 collectors	Plot	1997-2002: monthly

management regimes. Detailed description of the site and treatments can be found elsewhere (Trettin and Davis 2002).

Results to Date

- Sycamore has been significantly more productive than sweetgum over the first 6 years, averaging 40 Mg ha^{-1} biomass compared to 15 Mg ha^{-1} for sweetgum in 6 years. Use of the controlled drainage system has not affected sycamore productivity, probably because an extended drought occurred during the first 4 years following plantation establishment.
- The WATRCOM model (Parsons and others 1991) was successfully applied to this silvicultural system (Parsons and Trettin 2001). Simulations demonstrated that the controlled drainage should be effective in increasing available soil water during periods with normal precipitation.
- Short-rotation woody crop management systems had no deleterious effects on water quality. Sycamore treatments

were associated with significantly higher nitrogen concentrations in the soil water and drainage water, but these concentrations were well below the allowable maximum for drinking water. Applied pesticides had minimal effect on water or the aquatic organisms in the channel.

- The first-order channels and second-order streams are extremely "flashy," and this demonstrates the importance of effective riparian zone management.
- The SRWC systems improve soil tilth (Tolbert and others 2000), enhance wildlife habitat (Tolbert and others 2002), and improve water quality.
- The study and its infrastructure, and the WATRCOM model, provide a basis for long-term assessments of nutrient cycling and transport from the SRWC system in the upper Coastal Plain.
- The study also provides for the operational scale assessment of SRWC and the development of tools needed to plan and manage these crops.

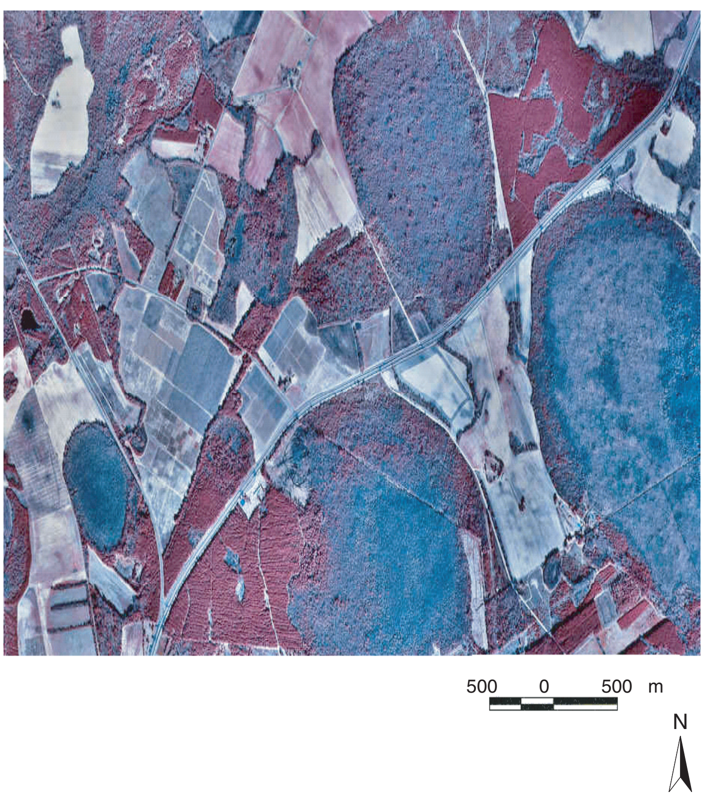
Next Steps

- Use monitoring and modeling to determine the effects of changing land use from agriculture to forests and SRWC on hydrology and water quality at the watershed scale.
- Use hydrologic data from the catchments at this study site to test and compare results obtained by using DRAINMOD and WATRCOM.
- Test the validity of remotely sensed data that characterize plant productivity and soil conditions.
- Continue to monitor soil processes to determine the rates of carbon sequestration and nitrogen turnover in the managed plantations.

Study of Depressional Isolated Wetlands (Carolina Bays) at Burch Fiber Farm, South Carolina

Site Description

The research site for the depressional isolated wetlands is located at Burch Fiber Farm, which is near Olar in Bamberg County, SC, and is owned and operated by MeadWestvaco (figs. 1 and 5). The depressional wetland referred to herein as Chapel Bay has an area of 6 ha. Bottomland hardwoods occupy its interior. Soils are poorly drained sandy loams. Surrounding uplands consist of croplands, 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 owned by



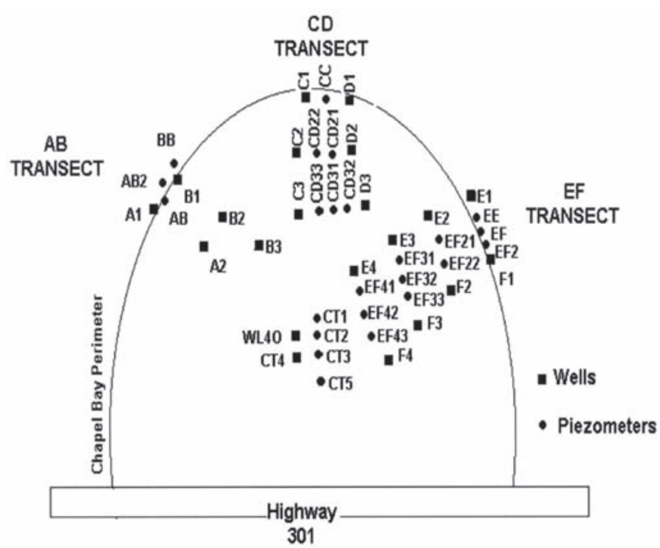


Figure 5—Location map (left side) and experimental layout of groundwater wells at Chapel Bay, near Olar, SC.

the SC Heritage Land Trust, supports a pure stand of pond cypress and is adjacent to the Burch farm. The surficial aquifer lies approximately 5 to 8 m below the ground surface at the site. The general stratigraphy of the site to approximately 10 m depth was determined by examining 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 alternating clay and sand layers, which is characteristic of the surficial aquifer system. Pyzoha (2003) describes the soil types and logging in detail. Average annual rainfall at the site is 1200 mm, and the average annual maximum and minimum temperatures are 23.4 °C and 11.3 °C, respectively.

Objectives

- To examine potential surface-water and ground-water interactions (first examined by Miwa and others 2004[3]) and thus identify the interaction between Carolina bays and the adjacent uplands (fig. 5, left), and to assess the effects of the interactions between Carolina bays and adjacent uplands on the regional water balance by means of conceptual models.
- To test the performance of the distributed forest hydrologic model FLATWOODS (Sun and others 1998a, 1998b, 2004) in evaluating the surface and subsurface waterflow patterns and their interactions with surrounding uplands.

Methods

Precipitation and air temperatures were measured continuously with an automatic tipping bucket rain gauge and a temperature probe at the Burch 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 (6 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. 5, right). Surface flow, soil water, and shallow ground water 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 data loggers were also installed near the center of each of the bays. Water levels were measured monthly from February 2002 to December 2003. Water levels measured between 1997 and 1999 (Miwa and others 2004) were also evaluated. Positions of existing wells and piezometers were determined using a rotary laser level, Philadelphia rod, and GPS unit. 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 ground-water interactions occurred during dry periods, indicating that the bays are hydrologically isolated during these periods (Pyzoha 2003).
- During wet periods, the bays served as a storage site for stormwater, and perhaps as locations of ground-water recharge, interacting with surrounding regions (fig. 5).
- The study suggested that Carolina bays may not be isolated systems.
- The distributed hydrologic model FLATWOODS (Sun and others 1998a) suggests that Chapel Bay is a flow-through wetland, losing ground water to the lower recharge area, especially during wet winter periods (Sun and others 2004). The simulation study also suggests that ground-water flow direction is controlled by the gradient of the underlying restricting 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. Testing also suggests that the model is able to capture the spatial and temporal dynamics of a shallow ground-water table in a heterogeneous landscape.

Next Steps

- Test the applicability of DRAINMOD (Skaggs 1978) to Carolina bays by running the program with data from the Burch farm and comparing the results with those obtained by running FLATWOODS.
- Refine and evaluate these models for application to wetland hydrology and to interactions of hydroperiods with soils and vegetation on coastal forested landscapes.

Summary and Recommendations

Five long-term and short-term ecohydrologic studies are being conducted by the Forest Service Center for Forested Wetlands Research (Charleston, SC) in the forested wetlands of the Atlantic Coastal Plain. These studies have contributed to our understanding of the hydrologic and nutrient cycling processes that occur on naturally drained and artificially drained low-gradient coastal forested watersheds. The knowledge that has been gained is being used to reduce offsite impacts and maintain productivity on this forested landscape.

[3] Miwa, M.; Trettin, C.C.; O'Ney, S.E.; Eisenbies, M.H. 2004. Hydrologic processes in the vicinity of a Carolina bay. On file with: International Paper Company, 719 Southland Road, Bainbridge, GA 39819.

The low-gradient coastal landscape is a mosaic of managed forests, depressional wetlands, bottomland hardwoods, riparian zones, and other natural forests. Its character is further complicated by site-specific hydrologic factors, pressures for land development, management practices, and climatic factors. The Southern Forest Resource Assessment (Wear and Greis 2002) clearly depicted the challenges to sustaining the environmental quality and social values of this landscape. The need to understand and manage the region's water resources is a critical challenge. To meet this challenge, we recommend the following:

- Additional emphasis is needed on hydrologic studies of forests, wetlands, and riparian zones on the flat coastal landscapes drained by low-gradient streams and rivers. These lands are a vital source for clean water, forest products, carbon sequestration, and wildlife habitat, but the influences of hydrology on these outputs have not been adequately addressed to meet the current and projected management needs.
- Studies are urgently needed that consider the effects of land use change (for example, from forest cover to urban, or agriculture to forest) on ecohydrologic and biogeochemical processes. Better understanding of the biogeochemical processes that affect water quality is needed to guide land use and development, including the development of engineered or restored lands to enhance water quality and healthy forests to provide a clean and stable water supply. One of the biggest challenges will be developing and applying ecohydrologic models capable of predicting the processes and the effects of management and climatic factors at various spatial and temporal scales. Data from the existing weather stations maintained by CFWR and its cooperators may be used for ground truthing (field verification) of radar data and other remote sensing data (for example, temperature, radiation, albedo, vegetation type, LAI), which are becoming a part of the next generation of ecohydrologic modeling tools.
- Studies at the large watershed scale or basin scale are needed to examine the interactions of uplands and lowlands, in-stream processes, land management and land use change, climate, and social factors. The empirical studies discussed in this report can provide the basis for such large-scale assessment. Critical attention must be given to the uncertainties associated with scaling issues in both the monitoring and modeling phases.
- Long-term (> 10-year) studies are needed to support hydrologic research. This is because hydrology is influenced by temporal and spatial variation in climate, soils, vegetation, and topography. The existing hydrologic studies and infrastructure at the Forest Service Santee Experimental Forest near Charleston, SC, can be a basis for the continuation of the long-term hydrologic studies and studies of prescribed burning, regeneration and management of bottomland hardwoods, and carbon sequestration in coastal forest ecosystems. Similarly, the current long-term database and ongoing activities associated with the CBES provide a reference system and a basis for increasing our knowledge of hydroperiod, vegetation dynamics, and biogeochemical processes, as they relate to bottomland hardwood forests. Also, the site of the ongoing long-term study on a managed pine forest at Carteret County, NC, can be another site for expanding research on impacts of forest management on the lower Coastal Plain.

The most effective way to address the numerous scientific questions and management challenges relative to water resources in the Southeast is through collaboration among academia, industries, State and Federal government agencies, private land owners, and nongovernmental organizations to build and share a long-term ecohydrological database, identify new prioritized issues, conduct experimental studies, and implement the recommended science and technology using appropriate technology transfer approaches. The facilities mentioned provide an excellent foundation for building those collaborative efforts. In this context, CFWR has been updating its hydrometeorologic database from the experimental watersheds on the HYDRO-DB, a Web-based data sharing and harvesting site (http://www.fsl.orst.edu/climhy/hydrodb/). We hope that this type of database and our long-term hydrologic research facilities can increase the level of collaboration and our collective abilities to address the many water resource issues facing the Southeastern United States.

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The U.S. Department of Agriculture Forest Service Center for Forested Wetlands Research has conducted or cooperated in studies designed to improve understanding of fundamental hydrologic and biogeochemical processes that link aquatic and terrestrial ecosystems. Five of these studies are discussed here. The first is based on observations made on long-term experimental watersheds established in the 1960s on the Forest Service Santee Experimental Forest in South Carolina. It quantifies the soil moisture dynamics, flow regimes, and water chemistry of low-gradient forested wetlands. The second study is being conducted in cooperation with North Carolina State University. It is a long-term project aimed at quantifying the effects of various water management and silvicultural management practices on hydrology and water quality at the Weyerhaeuser Company's managed pine forest in Carteret County, North Carolina. The third study is a long-term ecosystem study on MeadWestvaco's Coosawhatchie River bottomland hardwood site in South Carolina. It addresses questions related to public concerns about the need for protection, restoration, and sustainable management of forested wetlands. The fourth study, which was conducted between 1997 and 2000, examined the hydrology and water quality of intensively managed short-rotation woody crop plantations on International Paper's Trice experimental forest in the upper Coastal Plain of South Carolina. A fifth study was conducted between 1996 and 2004 at MeadWestvaco's Carolina bay site in the South Carolina upper Coastal Plain; it assessed the surface-water and ground-water interactions between Carolina bays and their surrounding uplands. Recommendations are provided for using knowledge gained through these and other studies as a basis for expanding needed hydrologic research with collaborators to address four major areas of water-related issues in the Southeast.

Keywords. Forested wetlands, management impacts, models, vegetation, water management, water quality, watershed.