Development of Watershed Hydrologic Research at Santee Experimental Forest, Coastal South Carolina

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Managing forested wetland landscapes for water quality improvement and productivity requires a detailed understanding of functional linkages between ecohydrological processes and management practices. Watershed studies are being conducted at USDA Forest Service Santee Experimental Forest, South Carolina, to understand the fundamental hydrologic and biogeochemical processes and their linkages with soils, vegetation, topography, climate, and management practices in the low gradient forested landscapes of the South Carolina Coastal Plain. This study presents an overview of and builds on the long-term watershed hydrologic research begun in 1964 by our predecessors at this experimental forest. Monitoring and modeling studies using a paired watershed approach are being conducted to describe the effects of management practices on two first-order, forested watersheds. Long-term flow data from two 160-ha first-order, one 500-ha second-order, and one 4,500-ha third-order watersheds, provide an opportunity to evaluate the flow dynamics and hydrologic effects of scale, land use distribution, and climate on these coastal watersheds. DRAINMOD-based models are being tested with these data for their applicability as a water management tool on these poorly drained natural forested watersheds. The long-term information on hydro-meteorology, water quality and water table levels from these watersheds has also provided baseline data on the eco-hydrologic processes that are useful to researchers, planners, land owners and industries for the assessment of land management and climatic impacts. Such information for poorly drained low gradient coastal watersheds is becoming increasingly important for sustainable development as population pressure and timber demand continue to rise in the southeastern United States.

Keywords: *poorly drained soils, forested wetlands, forest management, outflow (runoff), water budget, water quality, hydrologic modeling, DRAINMOD*

Introduction

Historical Development Before Hurricane Hugo (1989)

In the early 1960s, limited information on hydrologic processes, flooding patterns, and water balance components was available for the low gradient, forested wetlands of the humid coastal plain of South Carolina, though similar information and data were continuously becoming available for upland forests through the US Forest Service Coweeta Experimental Forest in North Carolina. With continuing growth in the timber industry, the public and landowners started to become concerned about impacts of forest management (harvesting, thinning, etc.) on runoff, soil moisture, and flooding on these low gradient poorly drained coastal plains in the southeastern United States. In order to address these issues, a first-order experimental watershed (WS 77) with a drainage area of 160 ha (~400 acres) was created in 1963 within the US Forest Service's 2468-ha Santee Experimental Forest (SEF), under the leadership of Dr. Cortland E. Young, Jr., and Dr. Ralph A. Klaiwitter at the US Forest Service Southeastern Forest Experiment Station in Charleston, South Carolina. The SEF was established in 1938, some 55 km northwest of Charleston (Figure 1; Appendix A) for scientific studies (Table 1). The main objectives of the first study were to quantify the evapotranspiration (ET) of a typical coastal plain pine forest, and evaluate the excess soil moisture status using detailed measurements of water budget components. In 1964 another, much larger, watershed (WS 78, 5000 ha [~ 12000 acres]) was added to study the precipitation-runoff relationships of two different-sized watersheds in coastal forest systems (Figure 1). Forest Service scientists, assisted by hydrologists at the U.S. Geological Survey in

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Figure 1. Location of experimental watersheds 77, 78, 79, and 80 within Francis-Marion National Forest, South Carolina (from 1964 map). Note that watersheds 77, 79, and 80 are within the 2468-ha Santee Experimental Forest, established in 1938.

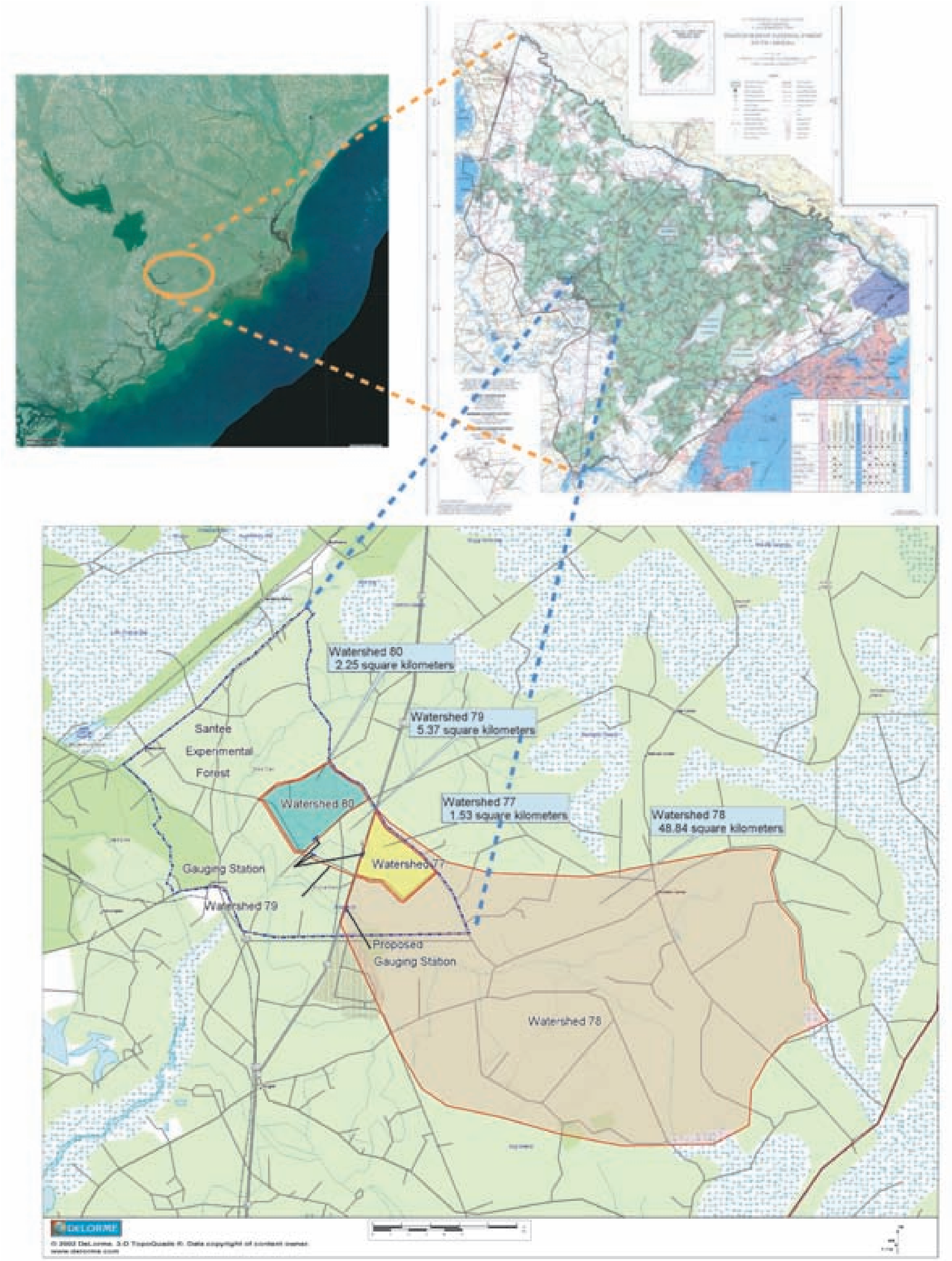

Table 1. Types and descriptions of infrastructure for each of the four watersheds at the Santee Experimental Forest, South Carolina.

Watershed No.	Drainage Area	Period of Record	Design of the Outlet	Associated Data	Condition	Needs
77 (Treatment) (First order, Fox Gully)	160 ha	1963-81; 1989 - present	Compound V-weir	Stage, Soil moisture, Water quality, GW levels, Met station	Good, monitoring continuing (No data 1981- 1989)	Analysis and publications of old data. Some ongoing.
78 (Turkey Creek)	5000 ha	1964-84; 2005 - present	Outlet in a dam	Stage, Velocity, Flow rates	Discontinued in 1984	Analysis and publications; Monitoring water quantity and quality is starting soon.
79 (Second order, Fox Gully)	500 ha	1966-73; 1989-90; 2003 - present	V-weir and 3-box culvert	Stage, Water quality	Good, monitoring continuing	Processing data analysis, Publications
80 (Control)	206 ha 155 ha since November 2001	1968-81; 1989- present	Compound weir	Stage, Water quality, GW levels, Met station, Throughfall	Good, monitoring continuing (No data 1981-1989)	Analysis of old data and publications ongoing.

Columbia, SC, installed a stream gaging station on WS 78 and collected data from 1964 to 1984 (Table 1).

Building upon the excellent cooperation between National Forest and Experimental Station, in 1965 Young and Klaiwitter added an additional gaging station on a 500-ha (~1200-acre) second-order watershed (WS 79) (Table 1, Figure 1, Appendix A). This provided an opportunity for Forest Service scientists and researchers to compare the effect of watershed size on precipitation-runoff relationships for these coastal forested wetlands, which would have been very difficult with only the original two watersheds (WS 77 and WS 78). While these studies were still ongoing, Young and Klaiwitter capitalized on the opportunity provided by the construction of Yellow Jacket Road by the Francis-Marion National Forest in 1968, by adding another 200-ha (~500-acre) experimental watershed (WS 80) draining to Fox Gully Branch (Figure 1; Appendix A). With the establishment of a flow gaging station in 1968 (Table 1), these four watersheds of varying sizes could be used to study not only the soil moisture and runoff processes, but also the effects of different types of treatments such as eradication of understory, clearcut, thinnings, drainage, and impoundments. A paired watershed approach was suggested with the fourth watershed (WS 80) as a control and the first watershed (WS 77) as a treatment for studying the effects of various silvicultural management treatments. The outlet systems on these watersheds were designed with compound v-notch weirs to accommodate high floods, as well as to hold sufficient water to support other management objectives such as timber, wildlife, forage and aquatic biota (Klaiwitter 1970). Some of the main objectives of these proposed studies on forested wetlands and their water resource and water management issues were outlined in the Southern Research Station (SRS) report (USDA FS 1963). All of these experimental watersheds were included in the inventory prepared by the American Geophysical Union (AGU 1965).

Monitoring was discontinued on the first-order, paired watersheds WS 77 and WS 80 in November 1982, and on the large watershed, WS 78, in November 1984. Data recording on the second-order watershed (WS 79) was not available after 1978. No further monitoring except for the weather station at the Santee Headquarters was conducted until October 1989, when Hurricane Hugo struck these experimental watersheds and forests. The chronology of activities on these watersheds is given in Table 2.

Developments after Hurricane Hugo (1989)

After Hurricane Hugo hit the experimental watersheds in late September 1989, the treatment watershed (WS 77) was salvage harvested. The control (WS 80) was not salvaged, with most of the trees, stumps, and branches left undisturbed in the forest. At the same time, recognizing a need to understand the hydrologic and water quality

Table 2. Chronology of watershed activities at Santee Experimental Forest.

Year	Description
1937	Santee Experimental Forest established
1946	Weather station for rain and temperature measurements established at Santee Headquarters
1963	Watershed WS 77 established as a treatment watershed
1964	Watershed WS 78 established as a large fourth-order watershed
1966	Watershed WS 79 established as a second-order watershed
1968	Watershed WS 80 established as a control watershed
1968	Flow monitoring initiated in November
1963 - 1968	Young and Klaiwitter studies
1974 - 1977	Binstock (1978) Study on WS 77 and WS 80
1976	Water quality monitoring initiated
1980	Richter (1980) and Richter et al. studies on WS 77 and WS 80
1981	Flow and water quality monitoring discontinued on all but WS 78
1984	Flow monitoring discontinued on watershed WS 78
1989	Hurricane Hugo damages the forest in September
1989	Both flow and water quality monitoring reactivated in November on watersheds WS 77, 79 and WS 80
1990	WS80 is non-salvage harvested (all roots, stumps, branches left intact on the watershed)
1990	Rain and temperature measurements established at Met25
1992	Manual wells established on WS 80 and WS 77
1994	Plots established for growth study (Hook et al. 1991)
1996	Automatic recording WL40 wells established on WS 80 and WS 77
1996	Electronic data loggers installed at Met25 (rain and temperature), CR10 Campbell Scientific data logger installed at Santee Headquarters weather station
1999	Long-term study of vegetation dynamics initiated (Burke 1998)
2000	Sun et al. study on WS 77 and WS 80
2001	Binkley (2001) study; Secondary outlet unplugged, reducing WS80 drainage area to 160 ha
2003	Miwa et al. study; Amatya et al. studies; WS 77 undergoes prescribed burning on 10 May; Throughfall monitoring on WS 80 begins; Backup flow meter installed on WS 79 and 80; Harder study begins on WS 80.
2004	A collaborative project to reinitiate monitoring of WS 78 on Turkey Creek and its hydrological study begins; Harder study completed with 2003-04 data.
2005	Streamflow monitoring on Turkey Creek begins in January; A collaborative study with Florida A&M University begins on this watershed; A new study on biomass removal by prescribed fire begins on WS 77, 79, and WS 80.

impacts of hurricanes and other natural disturbances, monitoring of both the water quantity (outflow) and quality were resumed.

Streamflow gaging stations on both the first-order (WS 77 and WS 80) and second-order (WS 79) watersheds were upgraded with automatic GL3150 (Global Water)[1] sensors with pressure transducers for recording stage height to estimate flow rates. Flow monitoring at the large fourth-order watershed (WS 78) was not resumed. A fully automatic CR10 (Campbell Scientific) weather station was installed in 1996 at the Santee Headquarters to monitor air temperature, humidity, wind speed and solar radiation needed for the estimates of evapotranspiration (ET). An additional sensor to measure net radiation was added in 2003. Watersheds WS 77 and WS 80 were also equipped with automatic stations – precipitation recorders in 1990, additional sensors to measure air and soil temperature in 1995. Several manual monitoring wells were installed on both of the first-order watersheds in 1990. Two shallow automatic recording wells were installed on WS 77 and one on WS 80 in 1992 (Appendix A). One additional deep automatic well was installed on WS 80 in 2003. Throughfall gages were also installed across watershed WS 80 in July-August 2003. A chronology of various activities that took place on these watersheds is shown in Table 2.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Other Planned Monitoring

- To re-install the evaporation pan and monitoring device to measure pan evaporation at the weather station at Santee Headquarters.

- To install backup data loggers at WS 77 and WS 79 to insure against loss of flow data.
- To install piezometers on the control watershed (WS 80) to examine the deep groundwater fluxes in this system.
- To measure leaf area index (LAI) and stomatal conductance of the pine-hardwood stand on the control watershed (WS 80).
- To install the Eddy Flux tower to quantify the carbon and water fluxes on WS 80 with mixed pine-hardwood stands.

Data Analysis and Management

Most of the strip chart and magnetic tape data from the rain gages and flow recorders used on the watersheds before the Hurricane Hugo were sent to Coweeta Hydrologic Laboratory in North Carolina for digitizing into electronic formats. Precipitation, weather, flow (for WS 77, WS 79, and WS 80) and water table data were converted to digital formats. Accordingly, all data from 1964 through July 1999 have been checked for appropriate QA/QC (Gartner and Burke 2001) and then archived in a single Microsoft Access database. Efforts are underway to append the database with data from August 1999 to date. These data are currently being stored at the Center for Forested Wetlands Research in Charleston, South Carolina. Also based on a recent Memorandum of Understanding with Atlanta-based Tetra-Tech, Inc., flow data from watershed WS 78 for the period of 1964 to 1973 has been converted into digital formats. Data from 1974 to 1976, processed at Coweeta Hydrologic Laboratory, were already in digital formats, and no data have yet been found for 1977 to 1984. Only the field service records on paper formats are available through May 1984. The recorded stage heights taken every two to four weeks of the service period may be used to derive the discharges using the stage discharge relationship created in 1964.

The Center for Forested Wetlands Research (CFWR) at Southern Research Station Unit 4103 has recently participated in an Internet-based hydrologic data sharing program (HYDRODB 2004) developed by Oregon State University under the sponsorship of the US Forest Service and the National Science Foundation's Long Term Ecological Research (LTER) program (*http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm*). CFWR has also posted hydrologic and metadata from Santee Experimental Forest watersheds WS 77 and WS 80 on HYDRODB for internet based data sharing where researchers and users can download data for inter-site comparisons and various other research and study purposes.

Results To Date

Only a limited amount of information was published from data measured between 1964 to 1982 on these experimental watersheds. Young and Henderson (1965, 1966) published the procedures for measurement of soil moisture and pan evaporation, respectively, at the study site. Young (1966) reported a two-year water budget for the treatment watershed (WS 77), concluding that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base flow generated from this natural watershed. Young (1967) also described the flooding pattern, flashiness, and effects of storage on these forested lands in controlling the outflow processes. The limited records then showed that the Santee watershed (WS 77) tended to release rainfall more quickly than do other forested areas in the Southeast. Young and Klaiwitter (1968) found the total runoff varying between 427 to 869 mm for three above-average rainfall years, yielding 38% on average of the total rainfall lost to runoff from WS 77. Young et al. (1972) also presented an analog version of a hydrologic model for a wetland forest at this site. Significant works evaluating the hydrologic and water quality effects of prescribed burning using the paired watershed approach on WS 77 and WS 80 were published by Binstock (1978), Richter (1980) and Richter et al. (1983a, 1983b). Binstock (1978) found no significant effects on the water quality or the soil chemistry of the experimental watershed following a prescribed winter burn. Richter (1980) found an average annual outflow to precipitation ratio of 27% (with a range of 15% to 43%) for 1965 to 1978 for WS 77, while an average ratio of 20% (with a range of 12% to 30%) was found on the control, WS 80, from 1970 to 1978. No published information has yet been found on the fourth-order Turkey Creek watershed (WS 78) and the second-order Fox Gully Creek watershed (WS 79) (Figure 1).

Hook et al. (1991) published some information on the impacts of Hurricane Hugo. Sun et al. (2000) evaluated the water budgets and water table pattern of the two experimental watersheds, finding average annual outflow to precipitation ratios of 30% for WS 80 and 23% for WS 77. Later, Binkley et al. (NCASI 2001) published water chemistry data from these two watersheds in their study of the nutrient concentrations of over 300 streams in small, forested watersheds across the continental United States. Miwa et al. (2003) studied the stream flow dynamics and hydrograph characterization of these watersheds. They demonstrated that headwater stream flow was highly responsive to rain events and that the stream processes are regulated by rainfall intervals, antecedent soil moisture, vegetation, soil types, and physical characteristics of the watershed including topography and surface water storage.

More recently, Amatya et al. (2003a) compared the six-year hydrology of the control watershed (WS 80) with that of an artificially drained watershed in eastern North Carolina. Results showed that WS 80 had much shallower water table depths with higher frequency outflows as compared to the North Carolina watershed, even though WS 80 had lower average annual rainfall. Amatya et al. (2003b) also tested a DRAINMOD hydrology model developed for poorly drained soils to evaluate the hydrology and water budget of WS 80, and demonstrated the potential of the model to accurately describe the hydrology of natural forested wetland given reliable inputs of soils and weather data. Most recently, Harder (2004) completed a study characterizing the detailed water budget of the control watershed (WS 80).

Because of the extended period of near-surface water table elevations caused by large storm events in 2003, with the highest annual rainfall (1671 mm) in 14 years (1990-2003), the stream runoff for the control watershed accounted for as much as 48% of the total rainfall. The results of the study served both to characterize hydrologic processes (runoff, water table response to rainfall, ET and soil moisture dynamics), and to quantify the water budget for a wet year (2003) and dry winter/spring season (2004) of the first-order forested watershed. Harder also provided a most comprehensive review of the studies conducted so far on this watershed. Some of the information on the Santee experimental watersheds is also reported in a recent publication by Amatya et al. (2004a).

Recent Ongoing Studies

Recent studies on the Santee Experimental Forest watersheds aim to:

- Use the historical flow and water quality data from the first-order control watershed (WS 80) and sample storm events from the second-order watershed (WS 79), for estimating reference loads for comparison with developed watersheds in the region, and also for developing a Total Maximum Daily Load (TMDL) for Charleston Harbor, in collaboration with Atlanta-based Tetra-Tech, Inc. and Charleston-based JJ&G Engineering Consultants (Miller and Amatya 2004).
- Use the historical data from three experimental watersheds (WS 79, WS 80, and WS 78) for the comparison of rainfall-runoff relationships, flow duration curves and flood frequency analyses (Amatya and Radecki-Pawlik 2005).
- Test the hydrology of the control watershed (WS 80) using a physically-based distributed model (MIKE-SHE) and apply the model for evaluation of management impacts in collaboration with the US Forest Service, Southern Global Change Program.
- Use field-measured data and water budget from the control watershed (WS 80) to refine the testing of DRAINMOD model and compare results with the Thornthwaite water balance model (Thornethwaite and Matther 1955).

Rationale for Continuing Future Studies

The hydrologic and water quality effects of silvicultural management practices including prescribed burning, harvesting and thinning have been a major area of research in the southeastern United States. The Southern Forest Resource Assessment (SOFRA 2002) emphasized a need for research to assess the long-term cumulative non-point source impacts of silvicultural activities on water quality and overall watershed health. The dominant water quality issues are sediment, roads (as sources of sediment), nutrients, fires, (as sources of sediment and nutrients), pesticides and water temperature (Jackson et al. 2004). Although studies to address some of these issues have been done in the past (Riekerk 1989; Ursic 1991; Shepard 1994; Amatya et al. 1997; Sun et al. 2000, 2001; Xu et al. 2002; Amatya et al. 2004b), these studies were either mostly limited to hydrology or covered only a shorter period.

Prescribed burning as a forest management tool, as developed in the Atlantic Coastal Plain (Richter et al. 1982), specifically at the Santee experimental watersheds, was shown to have insignificant effects on the quality of ground and surface water. It reduces fuel loads, controls certain tree pathogens, improves wildlife habitat, and restores desired ecosystems. Few data are available, however, on the effects of this management tool on the hydrology and water quality of wetlands (Jackson et al. 2004). Similarly, solid data on forest fertilization effects and the effects of various best management practices (BMPs) on water quality are lacking for poorly drained coastal forests.

In order to understand and assess these impacts on forested wetlands as affected by year-to-year variation in climate, it is necessary to develop water and nutrient budgets using long-term data. Long-term hydrologic data are essential for understanding hydrologic processes, as baseline data for assessment of impacts and conservation of regional ecosystems. At the same time, they are also very crucial for developing and testing hydrologic and water quality models for answering questions that are difficult to investigate by monitoring, either due to spatial and temporal scale issues, or to complex interactions of parameters on these poorly drained low-gradient systems.

A large quantity of data for wet pine flats (managed plantations) and their impacts on hydrology and water quality in the coastal North Carolina exists in the literature (Amatya et al. 2004b). These systems are established on artificially drained lands, and also intensively managed for timber production. However, little information is available on naturally drained forests of pine mixed with hardwood stands. The forests at the Santee experimental watersheds are managed and operated by the Francis-Marion National Forest for forest and wildlife conservation practices, reducing risks of wild fire, and also for timber management.

A recent study comparing an artificially drained managed pine forest with conventional ditches (25 ha) in coastal North Carolina with a naturally drained less managed mixed (pine-hardwood) forest (200 ha) in coastal South Carolina showed that the latter had much shallower water table depths with higher frequent outflows as compared to the artificially drained one, even though the latter had lower average annual rainfall (Amatya et al. 2003b). This suggests that drainage alone does not necessarily determine total outflow, which may also depend upon the soil type and the argillic horizon. Therefore, data from these headwater coastal forested watersheds, which are distinct from the drained, managed pine forests, are extremely valuable and need analysis and interpretation for scientific studies and assessment of impacts.

As envisioned by earlier Forest Service researchers in the 1960s, the information on water budgets and effects of watershed sizes on precipitation-runoff relationships, hydrograph shapes, flow patterns (magnitudes and distributions) can be very useful for planners and designers in forest management, water and nutrient management, flood control structures, wetland restoration and conservation in the naturally drained low gradient forested lands of the coastal plain. Such data are becoming even more vital as the population pressure and development near the coastal waters continues to increase in the southeastern U.S. The long-term data available for these experimental watersheds for 20 years or more can serve as a reference for evaluating impacts of developing these coastal forests and also as a basis for developing predictive equations in similar ungaged basins in the region (Wagener et al. 2004). Furthermore, these data can be used to analyze the trend of outflows as affected by changes in land use and climatic variation. As an example, flow and water chemistry data from the experimental control watershed (WS 80) for the period 1976-81 and 1989-92 and the recent (2004) storm event sampling data on the second-order watershed (WS 79) are being used as a baseline for reference, undeveloped watershed loads for comparing loads from developed lands in the Charleston Harbor watershed, for which a water quality model is being developed (Lu et al. 2005). These experimental watersheds are also continuously being used as a field laboratory for learning forest hydrogeologic research by students at the College of Charleston, South Carolina.

With the support from the US Forest Service, Southern Research Station, the Center is doing its best to keep up these experimental watersheds as the only long-term coastal forest experimental station in the Southeast for continuing eco-hydrologic studies, along with other scientific studies including prescribed burning, regeneration and management of bottomland hardwoods, restoring wetland hydrologic functions, and carbon sequestration on the coastal forest ecosystems to provide the knowledge needed for their sustainable management. These objectives are consistent with the recommendations of a recent workshop to discuss the role of coastal zone in global biogeochemical cycles (Siefert 2004), and may also help advance hydrologic science in the 21st century (CUAHSI 2003). Most importantly, continuing research at Santee Experimental Forest will help realize the visions of our Forest Service predecessors who installed the experimental watersheds in 1963 as a pilot laboratory for South Carolina and adjacent states (Young 1967).

Future Planned Studies

Future research efforts at the Santee experimental watersheds will:

- Compare the hydrology and water quality of two first-order watersheds (WS 77, treatment) and (WS 80, control) using data before and after Hurricane Hugo.
- Use both the first-order paired (WS 77, WS 80) and part of the second-order (WS 79) watersheds for studying both the plot- and watershed-scale effects of biomass removal by thinning and prescribed burning on nutrient cycling and transport.
- Study the water quality effects of partial prescribed burning on the treatment watershed (WS 77) using the paired watershed approach with WS 80 as a control.
- Revitalize the watershed-scale study on the third-order Turkey Creek Watershed (WS 78). This is consistent with one of the Forest Service goals (2004-08) to monitor water quality impacts of activities on National Forest lands.

Revitalization of the Watershed-Scale Study on Turkey Creek Watershed (WS 78)

As a result of continued collaborative efforts to develop and expand the studies on existing experimental watersheds at Santee Experimental Forest, a recent study proposal to revitalize the abandoned watershed-scale study at Turkey Creek watershed (WS 78) (Figure 1) was funded by the Forest Service Southern Research Station Challenge Cost Share Program matching the funds provided by National Council of Air and Stream Improvement (NCASI), Inc. The 5,000-ha watershed has 52% forest cover (mostly within the Francis-Marion National Forest), 28% wet shrubs and scrub, 14% wetlands and water, with the remaining 6% developed for agricultural lands, roads and open areas (Figure 2).

The main objectives of the study are to resume the hydrologic monitoring of the watershed, followed by water quality sampling. The data from past and current monitoring will be used: (a) to compare the flow dynamics among three experimental watersheds of various sizes; (b) to examine the pre- and post-hurricane flow dynamics; (c) to study the effects of land use change and, possibly, the climatic variation on the water yield and flow dynamics (Figure 2); (d) as baseline data for evaluating impacts; and (e) to develop and test DRAINMOD-based and other watershed scale hydrologic models for these poorly drained sites to predict the flow dynamics, water budget and impacts on hydrology and water quality. These modeling studies will also be able to specifically address questions about the cumulative effects of harvesting, thinning, prescribed burning, and biomass removal on hydrology and water quality. Other benefits may include predicting the spatial and temporal distribution of surface and groundwater tables, wetland hydrologic functions, and nutrient and sediment exports. The results will help the national forest manage its lands, roads and trails for operational purposes such as reducing fire hazards, restoration, water management, and transportation needs. The watershed may also be a potential site for studying effects of various forest BMPs, land management practices, and ecological and biogeochemical processes including carbon sequestration and methane (CH_4) gas flux dynamics. Furthermore, the site may be a candidate for testing new monitoring technologies such as ADV (Acoustic Doppler Velocity) measurement on slow-moving streams, remote sensing for deriving LAI for over- and under-story vegetation, temperature, soil moisture, and albedo, and Doppler-based precipitation, as needed for large scale hydrology modeling.

The current supporters and collaborators in this study include: the US Forest Service, Southern Research Station, for funding support; National Council of Air and Stream Improvement (NCASI), Inc., for partial funding support; Center for Forested Wetlands Research, SC, as principal investigator (PI); College of Charleston, South Carolina, as Co-PI, research collaborator; University of Krakow, Poland, as a research collaborator; Francis-Marion National Forest, SC, for watershed GIS database and other information support; the US Geological Survey, SC, for installation, servicing and data collection at stream gaging station; Tetra-Tech, Inc., Atlanta, Georgia, as a cooperator in data digitizing and sharing, and South Carolina Department of Transportation for giving access for installation of the gaging station.

Preliminary Work on Turkey Creek Watershed

So far, work on the Turkey Creek experimental watershed (WS 78) has encompassed the following activities:

1. Processing and analysis of daily flow data from the watershed for 1964 to 1976.

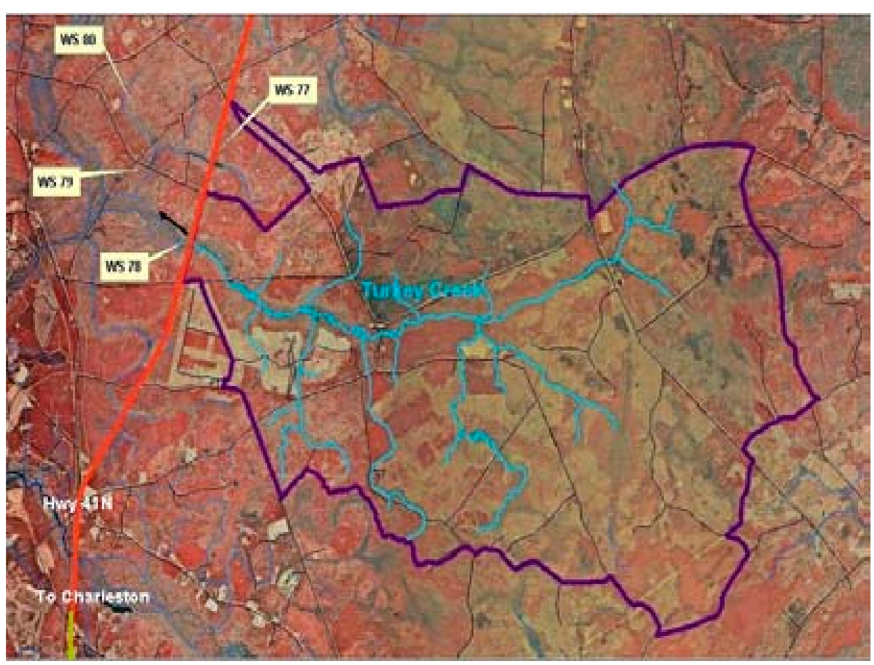

Figure 2. Land use distribution map of 5,000-ha Turkey Creek watershed (WS 78).

2. Flow frequency duration analysis.

3. Development of flood frequency curves and comparison with smaller watersheds (WS 80 and WS 79) in the vicinity.

4. Determination of rainfall-runoff relationships and comparison with WS 80 and WS 79 (Figure 3).

5. A collaborative agreement with the Agricultural University of Krakow, Poland for conducting the hydrologic study on Turkey Creek watershed.

6. A paper documenting the preliminary results of comparison of stream flow dynamics of watersheds (WS 77, WS 80, and WS 79) for the 2005 ASAE Annual conference (Amatya and Radecki-Pawlik 2004).

7. Acquisition of satellite imagery, aerial photographs, and GIS data layers on topography, hydrography, soils, and land use (US Forest Service, Francis-Marion and Sumter National Forest Office, SC).

8. Acquisition of similar GIS data layers from Berkeley County Office, SC.

9. Acquisition of historic aerial photographs, GIS layers and data base on forest management practices within Turkey Creek watershed (Francis-Marion National Forest).

10. A cooperative agreement between the Center and College of Charleston for the installation of a stream gaging station at the outlet of Turkey Creek watershed and for a student assistant for data processing and field work.

11. A cooperative agreement between the College of Charleston and USGS District Office in Columbia for the complete installation, servicing and real-time data retrieval, QA/QC and data sharing through the Internet.

12. An agreement between USGS and the South Carolina Department of Transportation (DOT) for the installation of and access to the monitoring gage within the right-of-way of the new bridge being built at Turkey Creek on Highway 41N.

13. A first cooperators' project meeting took place on 9 December 2004. The USGS collaborator reported that the gaging station on Turkey Creek will be installed by January 2005. Questions and discussions on multiple hydrology related research issues such as spatial moisture predictions, flooding, ET estimates, sampling for mercury, assessment of geomorphological characteristics, etc., were raised by the cooperators.

14. A temporary stream gaging station and a rain gage were installed on 16 December 2004. They will collect data until the permanent gages are installed after the construction of the new bridge on Highway 41 (Turkey Creek).

15. A PhD candidate from the Civil and Environmental Engineering Department at Florida A&M University has planned to conduct his field research related to wetland hydrologic functions on this watershed.

16. A fourth project cooperators' meeting is planned for 27 July 2006.

17. Turkey Creek Watershed initiatives were recently featured in Forest Service Southern Research Station's Compass Magazine (From Mountain Headwaters to the Sea), Issue 5, Spring 2006.

The re-initiation of the large, forested watershed study (5,000 ha) on the South Carolina coastal plain, with support from the USFS Southern Research Station and the NCASI, Inc., completes the development of a multi-scale hydrology and ecosystem monitoring framework. The current milestone, re-initiating the gaging of the Turkey Creek Watershed, represents the fulfillment of a gaging network encompassing 1st-, 2nd- and 3rd-order streams; thereby facilitating the examination of the interactions of land use or disturbance regime with streamflow and nutrient export dynamics at multiple scales. For example, historic stream flow data prior to Hurricane Hugo (1989) may be examined with post-disturbance data. The Turkey Creek Watershed Study is a multi-collaborator effort, with precipitation and stream flow data being collected continuously as a part of the US Geological Survey's real-time stream monitoring network. The College of Charleston has installed deep groundwater table wells, and the Francis Marion National Forest is helping to install multiple shallow wells to enable the assessment of surface-subsurface flow interactions, and stream water quality sampling stations will be installed by the Forest Service in cooperation with the USGS during summer 2006.

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Literature Cited

Amatya, DM, AR Pawliki. 2004. Long-term flow dynamics of three coastal experimental forested watersheds. [Abstract} Accepted for presentation at the 2005 American Society of Agricultural Engineers Annual Meeting, Tampa, FL.

Amatya, DM, RW Skaggs and JD Gregory. 1997. Evaluation of a watershed scale forest hydrologic model. *Journal of Agricultural Water Management* 32:239-258.

Amatya, DM, G Sun, CC Trettin, RW Skaggs. 2003a. Long-term forest hydrologic monitoring in coastal Carolinas. In:

KG Renard, SA McElroy, WJ Gburek, et al., eds. Proceedings, First Interagency Conference on Research in the Watersheds, October 27-30, 2003. U.S. Department of Agriculture, Agricultural Research Service: 279-285.

Amatya, DM, G Sun, RW Skaggs, CC Trettin. 2003b. Testing of DRAINMOD for Forested Watersheds with Non-Pattern Drainage. Paper No. 032046, St. Joseph, MI: American Society of Agricultural Engineers. 17 p.

Amatya, DM, CC Trettin, RW Skaggs, et al. 2004a. An overview of hydrologic studies at Center for Forested Wetlands Research, USDA Forest Service. Paper No. 04-2132. St. Joseph, MI: American Society of Agricultural Engineers. 21 p.

Amatya, DM, RW Skaggs, JW Gilliam, JE Nettles. 2004b. Effects of regeneration on hydrology and water quality of a managed pine forest. Paper No. 042217, American Society of Agricultural Engineers, St. Joseph, MI. 16p.

American Geophysical Union [AGU]. 1965. Inventory of representative and experimental watershed studies conducted in the United States. AGU and IASH and UNESCO, Sep 28-Oct 05, 1965, Budapest, Hungary, pp:122-123.

Binkley, D. 2001. Patterns and processes of variation in nitrogen and phosphorus concentrations in forested streams. Technical Bulletin No. 836, National Council for Air and Stream Improvement (NCASI), Inc., December 2001, (47 p + Appendices).

Binstock, DA. 1978. Effects of a prescribed winter burn on anion nutrient budgets in the Santee Experimental Forest ecosystem. Durham, NC: Duke University. 184 p. Ph.D. dissertation.

Burke, MK. 1998. Long-term vegetation dynamics in two forested communities impacted by Hurricane Hugo. Study Plan FS-SRS-4103. Asheville, NC: USDA Forest Service, Southern Research Station.

CUAHSI. 2003. Advancing hydrologic science in the 21st century. Consortium of the Universities for the Advancement of Hydrologic Science, Washington, DC. June 2003. (*http://www.cuahsi.org*).

Gartner, D, and MK Burke. 2001. Santee Experimental Watershed Database. 2001. Charleston, SC: USDA Forest Service, Southern Research Station. Unpublished data.

Harder, SV. 2004. Hydrology and water budget of a first order forested coastal plain watershed, South Carolina. M.S. Thesis, College of Charleston, Charleston, SC. 168 p.

Hook, DD, MA Buford and TM Williams. 1991. Impact of Hurricane Hugo on the South Carolina Coastal Plain. *Journal of Coastal Research*, Ft. Lauderdale, FL, SI 8:291-300.

HYDRO-DB. 2004. Hydrological Data Base - An Internet based data sharing protocol. Santee Experimental Forest Watersheds Metadata Report. Corvallis, OR: Oregon State University. (*http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm*).

Jackson, CR, G Sun, DM Amatya, WT Swank, M Riedel, J Patric, T Williams, JM Vose, CC Trettin, WM Aust, S Beasely, H Williston and G Ice. 2004. Fifty years of forest hydrology research in the southeast - Some lessons learned. In: J Stednick and G Ice, Eds. A Century of Forest and Wildland Watershed Lessons, Bethesda, MD: Society of American Foresters: 33-112).

Klaiwitter, RA. 1970. Water regulation on forest land. *Journal of Forestry* 68(6): 338-342.

Lu, S, DM Amatya and J Miller. 2005. Development of watershed and reference loads for a TMDL in Charleston Harbor System, South Carolina. In: Proceedings of the American Society of Agricultural Engineers 3rd TMDL Conference, Atlanta, Georgia, 2-4 March 2005.

Miller, J, DM Amatya. 2004. Development of watershed and reference loads for a TMDL in Charleston Harbor, SC. [Abstract] Accepted and paper in preparation for the ASAE 3rd TMDL Conference in Atlanta, GA , March 02-04, 2004.

Miwa, M, DL Gartner, CS. Bunton, R Humphreys, and CC Trettin. 2003. Characterization of headwater stream hydrology in the southeastern Lower Coastal Plain. Final Report to US EPA. Charleston, SC: USDA Forest Service, Southern Research Station.

Richter, DD. 1980. Prescribed fire: Effects of water quality and nutrient cycling in forested watersheds of the Santee Experimental Forest in South Carolina. Durham, NC: Duke University. 194 p. Ph.D. dissertation..

Richter, DD, CW Ralston and WR Harms. 1982. Prescribed fire: effects on water quality and forest nutrient cycling. *Science* 215:661-663.

Richter, DD, CW Ralston, WR Harms. 1983a. Chemical composition and spatial variation of bulk precipitation at a coastal plain watershed in South Carolina. *Water Resources Research* 19:134-140.

Richter, DD, CW Ralston, WR Harms. 1983b. Prescribed fire: Effects on water quality and forest nutrient cycling. *Science* 215: 661-663.

Riekerk, H. 1989. Influence of silvicultural practices on the hydrology of pine flatwoods in Florida. *Water Resources Research* 25(4):713-719.

Shepard, JP. 1994. Effects of forest management on surface water quality in wetland forests. *Wetlands* 14:18-26.

Siefert, RL. 2004. The role of coastal zones in global biogeochemical cycles. *EOS* 85(45):469.

SOFRA 2002. Southern Forest Resource Assessment. DN Wear and JG Greis (eds.), Asheville, NC: USDA Forest Service, Southern Research Station, September 2002.

Sun, G, J Lu, D Gartner, M Miwa, CC Trettin. 2000. Water budgets of two forested watersheds in South Carolina. In: Proceedings, Spring Spec. Conf., American Water Resources Association, 2000.

Ursic, SJ. 1991. Hydrologic effects of clearcutting and stripcutting loblolly pine in the Coastal Plain. *Water Resources Bulletin* 27(6):925-937.

U.S. Dept. of Agriculture, Forest Service [USDA FS]. 1963. The Wetlands - watershed management's new frontier. Asheville, NC: USDA Forest Service, Southern Forest Experiment Station. 6 p.

Wagener, T, M Sivapalan, J McDonnell, et al. 2004. Predictions in ungauged basins as a catalyst for multidisciplinary hydrology. *EOS* 85 (44):451, 457.

Xu, YJ, JA Burger, WM Aust, SC Patterson, M Miwa and DP. 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* 63:109-121.

Young, CE Jr. 1966. Water balance on a forested watershed in the flatwoods. In: Proceedings, Assoc. of South. Agric. Workers 63rd Annual Conv. Jackson, MS, February 7-9, 1966: 69.

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

Young, CE Jr, and JE Henderson. 1965. A method for sealing soil moisture access tubes. *Soil Science* 99(3):213-214.

Young, CE Jr, and JE Henderson. 1966. An overflow system for a standard U.S. weather bureau evaporation pan. Research Note SE-60. Charleston, SC: USDA Forest Service, Southeastern Forest Experiment Station.

Young, CE Jr, and RA Klaiwitter. 1968. Hydrology of wetland forest watersheds. Proc. of CUCOH Hydrol. Conference. Clemson University, March 28-29, 1968: 29-38.

Young, CE Jr, RA Klaiwitter, and JE Henderson. 1972. Hydrologic model of a wetland forest. *Journal of Soil and Water Conservation* 27(3):122-124.

Appendix A. Santee Experimental Paired Watersheds Characteristics

a. Established in 1965 within the US Forest Service's Francis-Marion National Forest, South Carolina
b. A paired watershed approach on flat, poorly drained soils of lower Atlantic coastal plain
c. WS 80: 200 ha – Control; WS 77: 160 ha – Treatment, WS 79: 500 ha – 2nd-order watershed
d. On 1st-order headwater streams - Tributary of Turkey Creek within the Cooper River Basin
e. Surface elevations from 4.0 to 10.0 m above mean sea level
f. Soils: Primarily loams strongly acidic characterized by seasonally high water tables and argillic horizons at 1.5 m depth
g. Vegetation: Loblolly pine (*Pinus taeda*), longleaf pine (*Pinus palustris*), baldcypress (*Taxodium distichum*) and sweet gum (*Liquidambar styraciflua*)
h. Mean annual rainfall: 1220 mm; Mean annual temperature: 18°C

Satellite image of three experimental watersheds (77, 79, and 80) draining to Turkey Creek (a new watershed scale study) within Santee Experimental Forest with gaging stations (triangular symbols) and Santee Headquarters Weather Station.

Watershed related Web sites:
http://www.srs.fs.usda.gov/charleston/santee.html
(For general information)
http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm
(For metadata and data harvesting)
The monitoring and watershed studies are maintained by US Forest Service, Southern Research Station, Center for Forested Wetlands Research (SRS-4103), 2730 Savannah Highway, Charleston, SC 29414. For further information about the study sites contact: Dr. Devendra M Amatya, Ph.D., P.E., Research Hydrologist, Tel: 843-769-7012; damatya@fs.fed.us