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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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

- 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

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

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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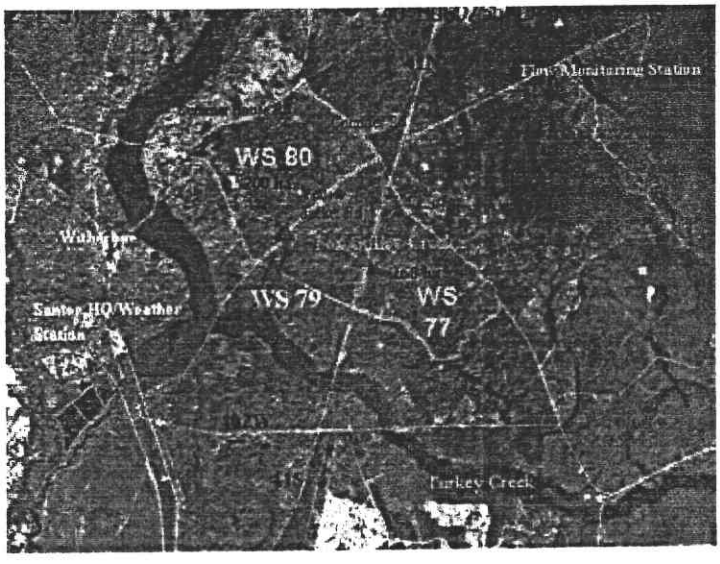
Appendix A. Santee Experimental Paired Watersheds Characteristics

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