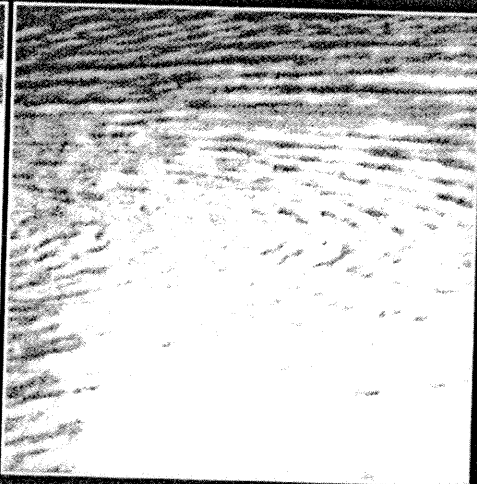




A CENTURY OF FOREST AND WILDLAND WATERSHED LESSONS

George G. Ice and John D. Stednick
Editors



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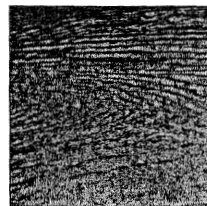
Kenneth M. Gale,
www.forestryimages.org



Dave Powell,
USDA Forest Service,
www.forestryimages.org



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Fifty Years of Forest Hydrology in the Southeast

C. Rhett Jackson, Ge Sun, Devendra Amatya, Wayne T. Swank, Mark Riedel, Jim Patric, Tom Williams, Jim M. Vose, Carl Trettin, W. Michael Aust, R. Scott Beasley, Hamlin Williston, and George G. Ice

ABSTRACT: The forests of the southeastern United States are incredibly valuable and diverse, both for timber production and for the aquatic habitat they provide. These overlapping values and diverse conditions have spawned numerous studies to assess how forest management affects hydrology and water quality. In the mountains, key watershed studies include those conducted at USDA Forest Service research facilities at Coweeta Hydrologic Laboratory in North Carolina and Fernow Experimental Forest in West Virginia. Research on hilly topographies includes work from the Oxford Hydrologic Laboratory in Mississippi and Grant Forest in Georgia. The South also has vast tracts of forested flatwoods and wetlands that represent poorly drained sites, which are not commonly studied in other regions. Hydrologic research is made difficult in these sites because of conditions such as shallow relief, poorly defined drainages, and periodic inundation. Some key research on these types of sites include the IMPAC study in central Florida, the Santee Watershed Study in South Carolina, the Belle Baruch Hydrologic Institute in South Carolina, the North Carolina State Wetland Research Program, and the Mobile-Tensaw River Delta Study in Alabama. The lessons of watershed research in the South are that site-specific conditions that influence hydrologic and water quality response must be properly identified to apply appropriate management practices and interpret water quality impacts from forest operations. Although roads represent a major source of sediment in upland sites, they sometimes have proven to be minor sources in poorly drained locations. Management practices that disturbed wetland forest soils and would be expected to dramatically accelerate sediment loss from comparable upland sites instead have been found to increase sediment trapping efficiency. Water quality assessed as impaired for one site may be typical of natural conditions for another. Rapid recovery from disturbance is often seen, as these productive forest sites revegetate in response to disturbance. Connecting all these varied responses to forest management and our desire to interpret them is a basic requirement to understand the hydrologic cycle, determine how water pathways lead to runoff, and measure how water interacts with watershed physical and biological processes, including evapotranspiration. Extensive literature citations guide further investigation of these issues.

KEYWORDS: best management practices (BMP), bottomland hardwood, dissolved oxygen, evapotranspiration, flatwoods, herbicides, nutrients, pocosin, roads, runoff, sediment, site preparation, slash burning, stream temperature, timber harvesting, water quality, water yield, wetland

Introduction

The forests of the southeastern United States — defined broadly as everywhere east of the Mississippi River and south of the Ohio River and Pennsylvania, with the addition of Arkansas, Louisiana, and west Texas — are among the most productive and diverse in the world. These diverse conditions have led to a rich aquatic fauna. The southeastern United States is reported to have the world's greatest diversity of temperate freshwater fish, with more than 500 species (more than half of the freshwater fish species in North America) (USGS 2003). Ninety percent (nearly 300) of the freshwater mussel species in the United States occur in this region. Overlapping these important aquatic resources is a vibrant timber industry: The South is estimated to produce 60 percent of the nation's forest products (Ware and Greis 2002). Fittingly, the area has been home to numerous forest hydrology research programs, many involving long-term watershed studies. Extensive collaboration between land-grant universities, the USDA Forest Service, and wood products companies has marked these research programs. Much of the basic knowledge of forest hydrologic processes and forestry best management practices (BMP) has been developed in the southeastern United States. As a result of the numerous hydrologic research activities in the Southeast, a brief review of southeastern forest hydrology research must overlook many studies and details of interest to hydrologists. The goals of this chapter are to provide a general overview of hydrologic knowledge developed in the Southeast and to serve as a bibliographic reference for many keystone research papers by southeastern forest hydrologists.

Regional Setting: Climate, Topography, and Hydrology

The southeastern United States encompasses a broad array of physiographic regions in which differences in soils, geology, topography, and climate cause variations in hydrologic behavior and create different water quality issues for forest management. Climate, geology, and topography are three major factors that dictate regional hydrologic patterns, soil development, and forest structure and functions. Any attempt to project impacts of management practices on hydrology must consider these three factors as background controls. Most southern forests are located in the climate system described as humid forest, with cool winters and warm-to-hot summers (Muller and Grymes 1998). Topography and elevation in the southern United States alter this pattern greatly, however, and result in a variety of hydrologic and water quality conditions.

There are many ways to define the South to describe overall forest hydrologic conditions and the driving forces behind them. Wolock and McCabe

(1999) use nine major ecoregion provinces that support forest ecosystems as a spatial framework to describe hydrology in the South. Table 3-1 contrasts hydrologic behavior — in terms of total annual runoff amount, runoff-to-precipitation ratio, and seasonal distribution of runoff — using regional long-term hydrometeorological databases (The Ouachita and Ozark ecoregion provinces are combined in the table.) Another method is Bailey's (1995) ecoregion classification system (Figure 3-1). Each of the 10 major provinces occurring within the southern geographic region has unique hydrologic characteristics as affected by climate, topography, soils, and vegetation covers.

Table 3-1. Comparison of Hydrologic Characteristics of Major Southeastern Physiographic Regions (Wolock and McCabe 1999)

Physiographic Province	Topography	Climate and Hydrology	Forest Management Concerns
Outer Coastal Plain — mixed forest	Poorly drained flat lands; elevation <100 m	High precipitation (PPT) (>1,200 mm yr ⁻¹); warm temperature; high evapotranspiration (ET) (>65% of PPT); variable runoff (300–800 mm yr ⁻¹); low runoff ratio (<30% most areas); slow-moving streams	Impacts on forested wetland hydroperiod and water quality; high water tables; artificial surface drainage essential; rutting; soil compaction
Southern — mixed forest	Upper coastal plain and piedmont; elevation 100–300 m	PPT 1,200–1,400 mm yr ⁻¹ ; moderate runoff (200–800 mm yr ⁻¹); moderate runoff ratio (20–60%)	Sedimentation due to new ground disturbance during harvest and site preparation; historical land uses (channel alteration due to deposition or erosion)
Central Appalachian — broadleaf forest, coniferous forest, meadow (Blue Ridge)	Steep hillslopes at high elevation (300–2,000 m)	High PPT (1,100–2,000 mm yr ⁻¹); high runoff (400–1,200 mm yr ⁻¹); high runoff ratio (>50%); low ET due to low air temperature	Sedimentation due to new forest road construction and historical land uses; trout habitat
Eastern Broadleaf Oceanic Province	Rugged topography; long, narrow valleys and ridges; elevation 300–800 m	PPT 1,000–1,600 mm yr ⁻¹ ; high runoff ratio (>40%)	Sedimentation from roads and skid trails for hardwood forest harvesting
Eastern Broadleaf Continental Province (Cumberland Plateau)	Dendritic drainage with winding narrow-crested ridges and deep, narrow valleys; elev. 100–400 m	PPT decreased from 1,400 to 1,000 mm yr ⁻¹ northward; runoff (500–700 mm yr ⁻¹) and runoff ratio (35–45%) decreased westward	Sedimentation from road and harvesting operations
Lower Mississippi — riverine forest	Alluvial plains; elevation <50 m	High precipitation (1,200–1,500 mm yr ⁻¹) with decreasing south-north gradient; low runoff (450–550 mm yr ⁻¹); low runoff ratio (<35%)	Harvesting impacts on wetland water quality and site productivity; soil compaction
Ouachita Mixed Forest — Meadow and Ozark Broadleaf Forest	Rugged topography with relief over 300 m; narrow valleys and floodplains	Precipitation decreasing northwestward from 1,500–400 mm yr ⁻¹ ; runoff 400–550 mm yr ⁻¹ ; runoff ratio (>45%) highest on high elevations of the Ouachita and Boston Mountains	Impact of forestry activities on water quality and site productivity
Prairie Parkland (subtropical)	Flat with elevation <5 m in the Coastal Plain to 500 m in the western Great Plains	Low but variable precipitation decreased dramatically westward (700–1,100 mm yr ⁻¹); high ET; low runoff (50–300 mm yr ⁻¹); runoff ratio (5–25%).	Impact of intensive pine forest management effects on sedimentation

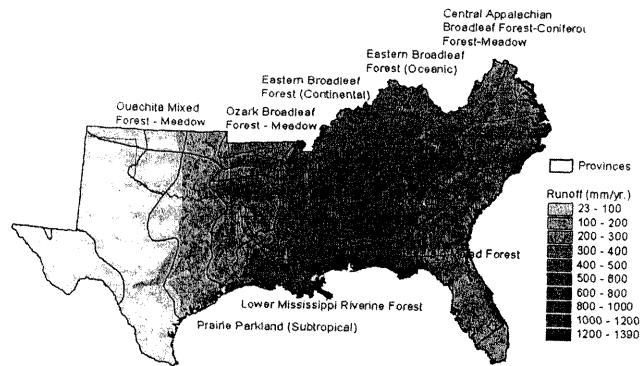


Figure 3-1.
Bailey's ecoregion
classification
system for the
Southeast.

Seasonal dynamics of stream runoff depend on the balances of precipitation (PPT) input, evapotranspiration (ET) loss, and soil moisture storage capacity. Across the southeastern United States, potential evapotranspiration generally is higher than precipitation in the summer but lower in other seasons. Therefore, streamflow is the highest in the winter and lowest in the summer. Flatlands, with lower precipitation and less-defined drainage networks, tend to display lower runoff than steep hill and mountain regions. These differences of hydrologic characteristics define all aspects of the water quantity and quality responses to management and the design of BMPs.

Early Research on Hydrologic Processes

Prior to the 1960s Horton overland flow was the dominant process used to explain stormflow generation. Horton overland flow occurs when precipitation rates exceed soil infiltration rates and the excess runs over the ground surface (Horton 1933). Although many hydrologists, starting in the 1940s, understood that the Horton model did not fit observations of runoff and streamflow from forested basins very well, there had been little development of alternative conceptual models for streamflow and stormflow generation.

Today forest hydrologists explain runoff patterns using the "variable source area" concept and our understanding of subsurface flow. Although these concepts were semi-independently developed by several researchers around the world (Betson 1964; Tennessee Valley Authority 1964; Hewlett and Hibbert 1967; Ragan 1967; Dunne and Black 1970a, 1970b), they were championed by southeastern forest hydrologists — principally Roger Betson, John Hewlett, and Alden Hibbert. The variable source area concept (Hewlett and Hibbert 1967) describes the changing source area or portion of a watershed that contributes to runoff. This dynamic, shrinking and expanding source area is a product of both watershed and storm characteristics. Portions of the landscape (e.g., wetlands, low floodplains,

hillslope hollows), where the water table occurs near the ground surface for much of the year or where subsurface flows converge, frequently are source areas. Depending on antecedent moisture conditions, these areas can saturate quickly during rainfall and, when connected to the stream network, will contribute to stream runoff. Interflow refers to shallow lateral subsurface flow moving through surface soils with high hydraulic conductivities and moving over layers with restrictive conductivities. In terrain with moderate and steep slopes and low-conductivity layers near the ground surface, interflow is an important contributor to storm hydrographs. Preferential subsurface flow pathways also are important in many forest sites where animal burrows, root channels, and other macropores can literally pipe flow downslope. As rainfall continues, the area of saturated soils and the area contributing subsurface flow expands. This expanding and shrinking contributing portion of the watershed is termed the variable source area.

Several key studies in the Southeast advanced these concepts and theories. In the early 1960s Roger Betson, a scientist for the Tennessee Valley Authority, attempted to fit a mathematical model of Horton overland flow to runoff data from mixed-cover basins in western North Carolina and eastern Tennessee (Betson 1964). Betson found that "runoff usually originates from a small, but relatively consistent, part of the watershed." Betson had accidentally discovered the importance of variable source areas in stormflow generation. Betson's data and model indicated that only 5–40 percent of watersheds were contributing stormflow, and he called these "effective runoff producing areas." Betson's results demonstrated why previous efforts to calculate effective infiltration rates based on watershed response rarely agreed with in situ measurements of soil infiltration capacities.

Hewlett and Hibbert (1967) separated stormflows out of long-term hydrographs from 24 southeastern and eastern streams and calculated two forms of watershed response factors characterizing the amount of precipitation that became stormflow within each watershed. These response factor metrics were fairly robust and could be calculated with an accuracy of better than plus or minus 15 percent accuracy from six years of data. For 15 of the 24 streams, the rainfall that became stormflow was <10 percent, and for 23 of the 24 streams, it was <20 percent. Hewlett and Hibbert linked watershed responsiveness metrics to the concept of variable source areas.

Hewlett (1961b) and Hewlett and Hibbert (1963) pioneered the study of interflow with a series of inclined trough experiments conducted at the USDA Forest Service Coweeta Hydrologic Laboratory. Interflow is the lateral downslope subsurface movement of water in saturated or unsaturated soil above a soil or bedrock layer that impedes vertical drainage. Hewlett and Hibbert sought to explain sustained interstorm baseflow in mountain streams in basins where saturated groundwater aquifers did not exist. They built and instrumented a 45-ft-long and 3-ft-deep soil-filled concrete trough inclined on a 40 percent slope, and they measured outflow for 150 days

following saturation of the slope. Whereas large pores drained in only 1.5 days, unsaturated interflow sustained outflow from the slope for the entire 150-day drainage period. Hewlett and Hibbert's work demonstrated the importance of interflow as a mechanism for redistributing soil moisture and maintaining baseflows in steep topography underlain by relatively impermeable layers.

Mountain Upland Watershed Research in the Southeast

An unusual aspect of forest hydrology research in the Southeast has been the number of high-quality, long-term watershed studies, including many paired watershed studies evaluating hydrologic effects of timber harvest. This section provides an overview of the major long-term watershed studies located mainly in the mountains of the South. The Appalachian, Ouachita, and Boston Mountains are sites where high-value streams and abundant precipitation can occur. Slope steepness also can lead to higher erosion potentials, although erosion also is influenced by soil and geology.

Coweeta Hydrologic Laboratory, North Carolina

The Coweeta Hydrologic Laboratory was formally established in 1934 and, as noted by Odum (1988), represents the longest continuous environmental study on any landscape in North America. Coweeta is located in the Nantahala Mountain Range of western North Carolina, within the Blue Ridge Physiographic Province. The 2,185 ha laboratory comprises two adjacent, east-facing, bowl-shaped basins. The 1,626 ha Coweeta Basin has been the primary site for watershed experimentation; the 559 ha Dryman Fork Basin has been held in reserve for future studies, including projects currently being planned.

Elevations range from 675 m in the administrative area to 1,592 m at Albert Mountain; this relief produces gradients in hydrologic, climatic, and vegetation characteristics. There are about 73.4 km of streams within the laboratory; 75 percent of the total stream length is composed of first- and second-order streams (Wallace 1988). Two fourth-order streams, Ball Creek and Shope Fork, drain the Coweeta Basin and join within the laboratory boundary to form Coweeta Creek, a tributary that flows 7 km east to the Little Tennessee River.

The climate at Coweeta is classified as marine, humid temperature because of high moisture and mild temperatures (Swift, Cunningham, and Douglass 1988). Mean annual precipitation ranges from 180 cm at low elevations to 250 cm at high elevations, and less than 5 percent of the annual precipitation occurs as snow. Precipitation is somewhat uniformly distributed throughout the year. A detailed description of Coweeta climate is provided by Swift, Cunningham, and Douglass (1988). Geology is dominated by metamorphic formations including schists, gneisses, and metasediments (Hatcher 1988). Soils fall into two orders: immature Inceptisols and older, developed Ultisols. The Inceptisols include Umbric Dystrochrepts and Typic Dystrochrepts. The Ultisols are represented by

Typic Hapludults, which cover the largest area of any soil group at Coweeta, and Humic Hapludults. Vegetation of the region is composed of mixed mesophytic forests; the four major forest types have been described by Day, Phillips, and Monk (1988) and are characterized by considerable diversity of tree species (Elliott et al. 1997).

Since the establishment of Coweeta, 32 weirs have been installed on streams in the laboratory, but many weirs are no longer operational (see Figure 3-2). Currently 16 streams are gaged. Eight watersheds have remained relatively undisturbed since the establishment of the laboratory and serve as controls in paired watershed experiments. A wide range of management prescriptions and/or experimental treatments has been applied over the years to Coweeta watersheds. Detailed descriptions can be found in individual papers, which focus on each watershed (see discussion below).

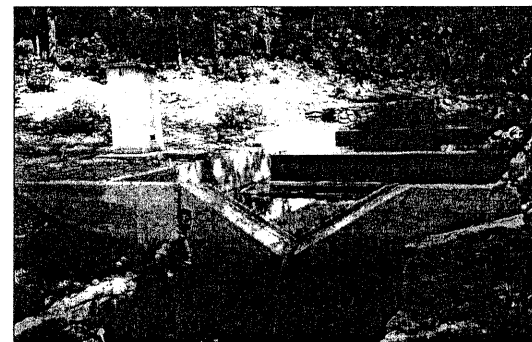


Figure 3-2. Newly constructed (1934) 120-degree sharp-crested V-notch weir at Coweeta. Pictured is Richard A. Hertzler, who developed the discharge rating equation for the 120-degree notch while he was employed at Coweeta. (Photo courtesy Coweeta Hydrologic Laboratory, Southern Experiment Station, USDA Forest Service.)

A baseline network for precipitation and stream chemistry measurements was initiated in 1968 and expanded to the entire basin by 1972. Routine analyses for the major inorganic constituents are conducted for eight precipitation-gaging sites, two dry deposition sites, eight streams draining control watersheds, and nine streams draining treated watersheds. Coweeta has been a site in the National Atmospheric Deposition Program since 1980, which involves a variety of analyses of precipitation and air chemistry.

An annotated bibliography of publications is available for research conducted at Coweeta and/or studies utilizing Coweeta data (Stickney, Swift, and Swank 1994); with an addendum, this compilation through December 2002 includes 1,265 entries.

Research Program at Coweeta

The research program at Coweeta represents a continuum of theory, experimentation, and application using watersheds as landscape units for study. An underlying philosophy guiding the research approach at Coweeta is that the quantity, timing, and quality of streamflow provide an integrated measure of success or failure of land management practices.

Hydrologic response to disturbance frequently has been used as a research tool for interpreting ecosystem behavior. An interdisciplinary research approach has been a key characteristic of the program. Previous papers have documented the establishment and early research history of Coweeta (Douglass and Hoover 1988). Subsequent long-term ecological research at the laboratory has been reviewed (Swank, Meyer, and Crossley 2002), and a book highlights some of the major scientific information derived from forested watershed research at Coweeta (Swank and Crossley 1988b). In the following sections, we summarize these past and present research contributions.

Early Research at Coweeta

Charles R. Hursh was principally responsible for the initial development of the research program at Coweeta. His template for research was the hydrologic cycle, which he considered fundamental to determine the principles underlying the relation of forest cover to the supply and distribution of meteorological water (Douglass and Hoover 1988). Following the establishment of an extensive network of climatic and stream gaging stations and subsequent collection of records in the early 1930s, experimental treatments were implemented on four watersheds between 1939 and 1941. In three of the experiments, effects on the flow regime, erosion and stream sedimentation of conversion from forest to mountain farming (cornfield and pasture), cattle grazing in woodlands, and exploitative logging were demonstrated (Lieberman and Hoover 1948a, 1948b; Johnson 1952; Dils 1953; Sluder 1958). Findings from these experiments contributed to improved land-use practices in the southern Appalachians. In the fourth experiment, all trees were felled on a watershed (logs not yarded off watershed) to determine changes in the hydrologic cycle (Kovner 1955, 1957). Concurrent studies and analyses examined runoff processes and soil hydrologic characteristics (Hursh and Brater 1941; Hursh and Fletcher 1942; Hoover and Hursh 1943), which provided insights into basic relations of forests and runoff.

In the years after World War II until the late 1950s, several management practices and vegetation manipulation experiments were conducted at Coweeta to further examine the effects of different cutting prescriptions and vegetation type conversions on the quantity, quality, and timing of streamflow. Findings from these studies provided new information in syntheses that were to follow.

The 1960s and 1970s

Earlier watershed experimentation demonstrated the general effects of land-use practices and vegetation manipulation on the quantity and quality of streamflow, but responses were highly variable and quantitatively unpredictable. It was clear that more detailed studies of hydrologic processes were needed to explain cause-and-effect relationships and provide a foundation for the development of hydrologic models.

During the succeeding two decades, significant advances were made in forest hydrology at Coweeta. Based on the early work of Hursh and Brater (1941) and Hoover and Hursh (1943), Hewlett (1961a) refined the concepts of streamflow generation for forested hillslopes — i.e., saturated/unsaturated drainage from soil profiles are the processes generating stormflow and base flow feeding Coweeta streams. This refinement was in sharp contrast to the previously held Hortonian concept of overland flow as the process for streamflow generation. Hewlett's concept was demonstrated and verified by Hewlett (1961b) and Hewlett and Hibbert (1963) using large, sloping, artificially packed soil models. Hewlett and Troendle (1975) subsequently expanded these findings to develop the variable source area model for first- and second-order watersheds. A more complete history on the development of this topic is given by Hibbert and Troendle (1988).

The quantification and importance of rainfall interception in the hydrologic balance was a major contribution emerging from Coweeta. This research included studies on interception loss in white pine (Helvey 1967) and loblolly pine (Swank, Goebel, and Helvey 1972) forests; hardwood forest litter interception (Helvey 1964); design criteria for interception studies (Helvey and Patric 1966); comprehensive literature reviews and development of general equations for estimating interception parameters for eastern hardwoods (Helvey and Patric 1965) and conifer forests (Helvey 1971); and development of a model to predict water content and evaporation for hardwood leaf litter (Moore and Swank 1975). This body of research has been used extensively by investigators to interpret hydrologic and nutrient cycling responses to management and vegetation manipulation practices.

Studies on the spatial and temporal distribution of soil moisture for steep forested land were an important contribution from Coweeta. On the basis of extensive soil moisture sampling in the first 2 m of soil over a seven-year period, Helvey and Hewlett (1962) showed that soil water content followed a sine curve, with long-term maxima and minima at the beginning of spring and autumn, respectively. The long-term annual cycle of soil moisture was almost perfectly correlated with the annual cycle of streamflow. Scientists at Coweeta evaluated the use of the neutron meter for measuring soil moisture (Hewlett, Douglass, and Clutter 1964) and developed improved techniques for using this instrumentation (Douglass 1962, 1966). The technique subsequently was used in studies to show the source and rates of soil moisture use by forest trees (Patric, Douglass, and Hewlett 1965) and annual patterns of soil moisture content in relation to topographic positions at a regional scale (Helvey, Hewlett, and Douglass 1972). More specific details of both interception and soil moisture research at Coweeta are provided by Helvey and Patric (1988).

Syntheses of watershed studies at regional and global scales for forest treatment effects on water yield provided generalities on the relationships

between forests and streamflow. In a review of 39 studies available at the time, Hibbert (1966) concludes that removal of or reduction in forest stands increases water yield and that reforestation decreases water yield. Using experimental cutting data for hardwood forests in the Appalachian Highlands, Douglass and Swank (1972, 1975) derived equations for predicting the first-year yield increase and the total volume of water following cutting. This empirical model, which is based on only two variables (percent basal cut and radiation load for the watershed), has proven useful for evaluating the effects of alternative management practices on both annual and intra-annual streamflow. Implementation of the model was facilitated through methods developed by Swift and Knoerr (1973) for estimating radiation on mountain slopes.

Other long-term watershed studies at Coweeta on the effects of vegetation conversions on evapotranspiration and streamflow have yielded original results. The first watershed-scale evidence that species conversion from hardwood to white pine reduces water yield was reported for two Coweeta watersheds (Swank and Miner 1968). Subsequent research strengthened this finding and showed annual flow reductions of 20 percent, greater evapotranspiration, and a characteristic monthly distribution of streamflow reductions for conversion of hardwood to pine (Swank and Schreuder 1973, 1974; Swank and Douglass 1974). Other analyses showed that conversion to pine reduced the frequency of both high and low flows by 30–60 percent (Swank and Vose 1994). In another original vegetation conversion study, Hibbert (1969) described water yield changes after a Coweeta forested watershed was converted to grass. When grass production was high, water yield was about the same as expected from the original forest, but as grass productivity declined, water yield gradually increased until it exceeded yield from the forest by about 15 percent. In years of low grass production, the frequency of flows below a minimum discharge decreased and base flow increased (Burt and Swank 1992).

In another long-term study, a clearcutting treatment first applied to a mixed hardwood-covered watershed in 1940 was replicated in 1963. The flow recovery response in association with structural characteristics of the successional vegetation provided evidence, for the first time at a watershed scale, of the need to include leaf area index as a parameter in estimating evapotranspiration of forests (Swank and Helvey 1970). These findings were subsequently used in the development and testing of an evapotranspiration model at Coweeta (Swift et al. 1975; Huff and Swank 1985); the hydrologic model also was validated across a wide range of forested sites (Vose and Swank 1992).

The most definitive study at Coweeta on the effects of forest cutting on the storm hydrograph was conducted by Hewlett and Helvey (1970). After an 18-year calibration period, the mixed hardwood forest on a 44 ha watershed was clear-felled but not removed; there were no roads on the watershed. The objective was to assess the basic effects of a forest cover on

reducing peak discharge and stormflow volume. Forest harvest increased stormflow volumes (average 11 percent) and slightly increased peak flow rates (7 percent at mean peak flow). Volume increases were larger for larger storms. Other research at Coweeta has examined the effects of commercial harvesting on storm hydrograph characteristics (Douglass and Swank 1976; Swank, Douglass, and Cunningham 1982). Details of changes in water yield and timing of stream flow for watershed disturbances at Coweeta are given by Swank, Swift, and Douglass (1988).

The impacts of forest cutting on stream temperatures have been studied extensively at Coweeta. When streamside vegetation is cut, large increases in maximum stream temperature occur (Swift and Messer 1971), but temperature declines toward baseline values in about five years as streamside vegetation regrows (Swift 1973). The effectiveness of a narrow buffer strip of uncut trees and shrubs in maintaining normal stream temperatures also has been demonstrated (Swift and Baker 1973).

As reviewed by Swift (1985), forest access road design and construction and their effectiveness in reducing soil loss have been important areas of research since the establishment of the laboratory. Many of the principles and guidelines for forest roads have been drawn from Coweeta studies and adapted by government and industry groups. The broad-based dip — sometimes referred to as the Coweeta dip (Hewlett and Douglass 1968) — probably has found the widest acceptance. Research on other specific road features has been reported by Swift (1984a, 1984b, 1986). Douglass (1974) reported on methods for sizing bridges and culverts for streams draining forested land in the southern Appalachians.

A pathfinding experiment was initiated in the Coweeta basin in 1962 to demonstrate the concept of multiple-use management (Hewlett and Douglass 1968). The compatibility of managing timber, water, wildlife, and recreation was evaluated and provides an on-the-ground forum to view and discuss long-term results of multiple management goals (Douglass and Swank 1976; Swank 1998). This watershed-based study demonstrates that southern Appalachian forests can be managed successfully for a variety of uses. Many of the findings from this project have been factored into forest management planning and practice.

Federal and state environmental legislation in the 1970s posed new opportunities and needs for watershed research. Issues related to non-point-source pollution led to studies outside the Coweeta basin, which were highly focused and of shorter duration. New information on the effects of mechanical site preparation (Douglass and Swift 1977; Douglass and Goodwin 1980), herbicides (Neary, Bush, and Douglass 1981, 1983; Neary 1983; Neary et al. 1985; Neary, Bush, and Grant 1986), and fire (Douglass and Van Lear 1983; Douglass, Van Lear, and Valverde 1983) on water quality was obtained and strongly influenced management decisions of the era.

Another major shift in research focus was the initiation in 1968 of mineral cycling research in a cooperative effort between Coweeta and the Institute of Ecology at the University of Georgia. The original objective was to investigate the effects of experimental manipulations on nutrient cycles and forest productivity, as revealed by nutrient and water budgets (Johnson and Swank 1973).

1980s to Present

Nutrient cycling and associated ecological research at Coweeta has received continuous funding from the National Science Foundation (NSF). Swank, Meyer, and Crossley (2002) provide a programmatic description of the research. In 1980 Coweeta was selected as one of the first six sites in the Long-Term Ecological Research (LTER) network funded by NSF; it continues to participate in the program.

Long-term research on precipitation and stream chemistry for control watersheds at Coweeta provides a firm basis for evaluating the biogeochemistry function of southern Appalachian forest ecosystems and evaluation responses to forest management practices and natural disturbances (Swank and Waide 1988). Precipitation chemistry is dominated by H^+ and SO_4^{2-} ions with a mean annual pH of 4.6. Streamwater chemistry of low-elevation watersheds is dominated by Na^+ and HCO_3^- ; for high-elevation watersheds, SO_4^{2-} replaces HCO_3^- . Analyses of long-term trends of mean annual precipitation and stream chemistry show no significant trends of increasing or decreasing acidity (Swank and Waide 1988). Seasonal trends in concentrations and export of solutes are regulated mainly by watershed discharge. Differences in net budgets (input minus output) among control watersheds reflect differences in bedrock geology within the Coweeta basin and in the hydrologic responses and biological characteristics of high- and low-elevation watersheds.

Long-term measurements of solutes have been made for streams draining many of the disturbed watersheds at Coweeta (Swank 1988). Comparisons of annual nutrient budgets for control versus disturbed watersheds illustrate the importance of evapotranspiration processes in regulating biogeochemical cycles. Chemical budget data, combined with process research, also demonstrate the importance of biological processes (decomposition, net primary production, uptake, and storage of nitrate by vegetation) in regulating nutrient retention and loss from forest ecosystems. Relative to some forested regions of the United States, increases in streamwater nutrients are small in the Coweeta watersheds, even for the most drastic vegetation disturbances, and have no adverse impact on water quality for municipal water supplies or downstream fisheries.

The effects of natural disturbances on stream chemistry also have been observed at Coweeta for outbreaks by two different insects (Swank et al. 1981; Swank 1988), extensive tree blowdown from hurricanes (Swank and Vose 1997), and ozone damage to vegetation (Swank and Vose 1990/91).

Other syntheses of watershed ecosystem studies at Coweeta evaluated the long-term changes (20 years) in vegetation, hydrology, and water quality parameters following commercial clearcutting (Swank, Vose, and Elliott 2001; Elliott, Boring, and Swank 2002); assessed stages of watershed nitrogen saturation in the context of altered nitrogen cycles and stream responses to disturbance (Swank and Vose 1997); and documented long-term forest management effects on soil carbon and nitrogen (Knoepp and Swank 1997a) and soil cations (Knoepp and Swank 1997b).

The collaborative, interdisciplinary research program at Coweeta has produced a wealth of new knowledge in many areas of forest ecosystem science — much too extensive to describe in this chapter. Perhaps the most relevant topic is the considerable research on stream biota, organic matter, and nutrient dynamics that has been conducted at Coweeta over the past three decades. Several summary papers contain specific findings on this topic, including Wallace (1988); Webster et al. (1988, 2000); Wallace, Grubaugh, and Whiles (1996); Webster and Meyer (1997); Meyer, Wallace, and Eggert (1998); and Wallace et al. (1999).

Coweeta also has been a cooperator in several additional large, interdisciplinary projects over the past two decades. In one correlated study of forests across seven states, watersheds were used to evaluate the effects of whole-tree harvesting on soil cation budgets (Johnson et al. 1988; Mann et al. 1988). Subsequent analyses examined the long-term effects of management on soil carbon (Johnson et al. 2002). In another effort, the Integrated Forest Study evaluated the effects of atmosphere deposition on nutrient cycling at 17 forested sites in the United States, Canada, and Norway (Johnson and Lindberg 1992). Two watersheds at Coweeta (mixed deciduous and white pine forest types) were included in the study. A major focus of the research was testing of hypotheses regarding the effects of atmospheric sulfur and nitrogen deposition on forest nutrient cycles; the project was noteworthy for its incorporation of state-of-the-art methods for measuring dry and cloud water deposition in addition to wet deposition. A nutrient cycling model (NuCM) derived from the effort was subsequently modified and validated through simulation of soil and stream chemical responses of several Coweeta watersheds (Johnson, Swank, and Vose 1993, 1995; Johnson, Susflak, and Swank 1998; Johnson et al. 1999). Results from this research provide confidence and guidance in applying the model to assess a variety of environmental issues associated with atmospheric deposition effects on forest soils and streamwater quality.

Ecosystem management is an operating philosophy of the USDA Forest Service. The object of ecosystem management is to use ecological approaches to achieve broader multiple-use objectives. A demonstration project on ecosystems management was initiated in 1994 on Wine Spring Creek, a 1,820 ha watershed near Coweeta (Meyer and Swank 1996; Swank 1998). This project provides an integrated, interdisciplinary ecosystem approach to research, planning, and management. Partners in the study

include more than 60 scientists and land managers in six research units in the Southern Research Station, National Forest System, and eight universities, along with conservation and environmental groups, state agencies, and the public (Swank and Tilley 2000). The project is organized around themes of ecosystem restoration, forest sustainability, human and economic values, and ecosystem structure and function. These multifaceted studies are providing new knowledge, technology transfer, and management benefits. More than 50 papers and reports document the findings from this research. These papers include topics of environmental responses in the use of fire to restore pine-hardwood ecosystems (Vose et al. 1999) and vegetation dynamics following burning (Elliott et al. 1999); diversity of riparian forests in rhododendron thickets (Baker and Van Lear 1998); salamander and small mammal responses to silviculture practices (Bartman et al. 2001; Ford et al. 2001); response of forest floor microarthropods to burning (Crossley, Hansen, and Lamoncha 1997); trout use of woody debris and habitat in Wine Spring Creek (Flebbe 1999); the effect of riparian zones in structuring small mammal communities (Laerm et al. 1997); and analytical tools for synthesizing the multiple values of the watershed (Swank and Tilley 2000).

The use of fire as a management tool in southern Appalachian forests and its effects on vegetation, soil, water, and air quality represent a major new research thrust and management contribution at Coweeta. Comprehensive experimental assessments have been conducted on alternative prescribed burning techniques to restore pine-hardwood ecosystems in the region (Clinton, Vose, and Swank 1993, 1996; Vose 1994; Vose et al. 1997; Clinton et al. 1998; Vose et al. 1999) and emissions from forest burning in the southeastern United States (Vose et al. 1996). Current research efforts are focusing on three areas: determination of the historical role of fire in shaping ecosystem structure and function; long-term effects of restoration burning in xeric pine-hardwood ecosystems; and effects of restoration burning on mesic forest community types. Considerable debate surrounds the historical role of fire in shaping ecosystem structure and function. Increased information on historical uses (e.g., when? where? how often?) will provide considerable insight into effective reintroduction of fire in the southern Appalachians. Coweeta is remeasuring permanent plots in watersheds burned several years ago and conducting new watershed-scale studies on the effects of prescribed fire on midslope and cove forest ecosystem processes. In addition, the scope of Coweeta's fire research is expanding throughout the South. Fire can play a significant role in runoff, sediment yield, and nitrate transport in aquatic and terrestrial ecosystems. Coweeta is measuring and modeling the effects of wildfire and prescribed burning on forest hydrology in the mountain, piedmont, and coastal plain regions of the southern United States.

Groundwater pollution is a major problem in many areas of the United States. Conventional cleanup methods, such as pumping and treating

groundwater, are costly. Coweeta is engaged in a multiagency collaborative project to evaluate the use of trees to accumulate and metabolize pollutants in shallow groundwater — a process called phytoremediation. To be an effective tool, vegetation must transpire a substantial quantity of water from the location of the pollutant plume (such as the soil horizon and/or groundwater). Coweeta has quantified transpiration in young poplar plantations as well as native vegetation, using direct measurements and modeling and linking those predictions with groundwater models developed by collaborators (Eberts et al. 1999). The linkage suggests that over a 12-year period, trees planted for phytoremediation have the potential to reduce groundwater pollution by 50–90 percent. However, the model also predicted an actual decrease of only 20–30 percent because of an increase in groundwater inflow and the release of water from storage in the aquifer (Vose et al. 2000). The rate of uptake of water (transpiration) in poplar stands was quantified to evaluate the use of trees to clean up shallow groundwater pollutants. Results indicated that a substantial amount of groundwater was transpired by poplar in the first few years of establishment (Vose et al. 2000). Transpiration estimates for stands in the future suggest that phytoremediation is a potentially useful tool. Phytoremediation success will depend, however, on the hydrologic characteristics of the site. Where phytoremediation is applicable, a significant cost savings will be realized relative to conventional cleanup methods.

In recent years hydrologic investigations have included syntheses of long-term watershed studies; development and application of a hillslope hydrology model (Yeakley, Meyer, and Swank 1994; Yeakley et al. 1998); development/application of evapotranspiration runoff models (Vose and Swank 1992; Jakeman and Hornberger 1993; Chen et al. 1995; Post, Grant, and Jones 1998; Vose and Maass 1998; Worrall, Swank, and Burt 2003); and evaluation of the cumulative impacts of land use on water quality in a southern Appalachian watershed (Swank and Bolstad 1994; Bolstad and Swank 1997). Long-term hydrologic studies will continue to be a core element of the research program at Coweeta. Watershed behavior at the time scale of forest stand development provides new information and insights that are important to natural resource managers and the development of more rigid hypotheses. Although much has been learned, experience at Coweeta has shown unexpected long-term response to both natural and managed disturbances. Hydrologic investigations and databases also form a template that is essential to understanding broader and more complex environmental issues such as climate change, carbon cycling, and atmospheric deposition as they relate to effects on water resources and the productivity and health of forests. Thus, experimental watersheds provide a framework for detecting integrated effects of disturbance on water resources, developing hypotheses on cause-and-effect relationships, and testing such hypotheses.

Fernow Experimental Forest, West Virginia

In 1933 the Fernow Experimental Forest was established on Elk Lick watershed in the mountains of West Virginia because of the emerging need to address the connection between timber and watershed management. The original tree cover on the 3,640-acre Elk Lick watershed, part of the Monongahela National Forest, had been logged off between 1903 and 1911. By 1931 that watershed was accessible with a road network; free of major fire effects; and deemed to have soils, tree species, and topography representative of much of West Virginia. Trimble (1977) and Adams et al. (1995) provide a history of the Fernow Experimental Forest, the Parsons Timber and Watershed Laboratory, and documentation of the research program.

The guiding mission for Fernow's first half-century of watershed research was "to determine effects of forest resource management on quality, yield, and timing of streamflow; and to develop methods for improving water yield and timing of forest streams without detriment to water quality." Between 1950 and 1954 stream-gaging stations suitable for research on small watersheds (Reinhart and Pierce 1964) were installed on five experimental basins (watersheds 1 through 5), ranging in area from 38 acres to 96 acres. One of that original set (watershed 4) remains a permanently untreated control. The others were logged after a six-year period of calibration. First-year streamflow gains following logging ranged from 0.3 to 5.1 area inches, and gains were clearly linked to increasingly heavy timber cut (Reinhart and Eschner 1962). Regrettably, logs were skidded, with minimal concern for the effect on the watershed. Thus, where timber was most heavily cut, skidding impacts were greatest. Where timber was less heavily cut, skidding impacts were smallest. Although only minor stormflow responses were observed, major stream turbidity responses were measured, and these were mistakenly attributed to tree cutting rather than logs being dragged along overly steep skid trails and within stream channels. Regardless of tree-cutting severity, the forest floor remained largely intact, and infiltration remained high on all four watersheds except the portions of the watershed with roads and skid-trails (Reinhart and Eschner 1962). There was no evidence of soil loss where the forest floor was undisrupted — a hydrologic performance key later adopted for BMPs. Turbidity caused by log skidding practices (Table 3-2) returned to pre-timber harvest levels on all four of the treated watersheds within two years after skid trail use and logging/yarding disturbances in the channel were discontinued.

The formerly commercial clearcut watershed (watershed 1) was left untreated from 1956 to 1971, when 500 pounds per acre of urea were applied — about 18 percent of which was lost in streamflow during the first year after application (Aubertin, Smith, and Patric 1973). Virtually undetectable hydrologic effects of repeated extensive selection cutting on watershed 5 eventually warranted discontinuing these hydrologic studies. A repeat diameter-limit cut in 1972 (watershed 2) again caused minor

streamflow increases, with water quality unaffected (Patric and Aubertin 1977). Follow-up intensive selection cutting (watershed 2) also caused minor streamflow increase with minimal effects on water quality. Watershed 3 was clearcut in 1969, with careful logging on properly located and managed roads and with a shade strip retained along the stream. First-year streamflow increased about 10 in., with negligible effects on water quality (Patric 1980). This finding represented a significant contrast to the first studies, in which water quality was dramatically impacted. Ammonium sulfate was applied to simulate acid rain on watershed 9 in 1987 and to watershed 3 in 1989 (Adams, Edwards, and Kochenderfer 1993), the latter having regained complete tree cover. Both of those watersheds remain sites of continuing observation about acidifying effects on forest vegetation, soil, and streams (Adams, Angradi, and Kochenderfer 1997). Interim effects on soil and herbaceous plants have been negligible (Gilliam et al. 1994).

Table 3-2. Frequency Distribution^a of Turbidity^b Samples during Logging^c on Watersheds Roaded under Increasingly Stringent Erosion Control Measures

Erosion Control Measures ^d on Experimental Watersheds	Number of Stream Samples per Turbidity (JTU) Class				Maximum Turbidity (JTU)
	0-10	11-99	100-999	>1,000	
Channel skidding OK; unrestricted road location; grades up to 40%; no water bars; 7.3% of watershed in roads or skid trails	126	40	24	13	56,000
Channel skidding OK; unrestricted road location; grades up to 30%; water barred at about 35 ft intervals. 6.2% of watershed in roads or skid trails	171	17	8	7	5,200
No channel skidding; unrestricted road location; grades up to 20%; water bars as needed; 5.8% of watershed in roads or skid trails	195	8	0	0	210
No channel skidding or wet weather logging; roads about 40 ft from stream; water barred and seeded after logging; road grades up to 20%; 1.9% of watershed in roads and skid trails	201	2	0	0	25
Undisturbed forest, i.e., experimental control watershed	202	1	0	0	15

^a From Reinhart and Eschner (1962).

^b Reported as Jackson turbidity units (JTU) — roughly equivalent to parts per million of sediment in samples of streamwater.

^c Turbidity in streams draining all logged watersheds returned to levels in undisturbed forest within 2 years after logging ceased.

^d Forest floor minimally disturbed wherever there were no logging roads or skid trails, infiltration remained high, and overland flow was minimal.

After a two-year period of calibration, watersheds 6 and 7 were clearcut during 1964 and 1965. Both were maintained barren until 1970 by applying more than a ton of herbicides mixed with several hundred gallons of diesel fuel. Considerable air and soil surface heating resulted from changed albedo and upward thermal radiation (Hornbeck 1970). Annual streamflow increased about 11 in. — probably the maximum achievable on Fernow watersheds. Infiltration remained far above rainfall intensity; so, given careful road location, overland flow and sediment rarely reached either stream channel. Turbidities at low flow never exceeded 5 ppm (Patric and Reinhart 1971), with the range during stormflow (about 30 ppm to 130 ppm) differing little from turbidity on the control. The Public Health Service's laboratory at Wheeling, West Virginia, tested occasional low-flow samples, always finding them within that agency's standards for drinking water. By 1973 watersheds 6 and 7 supported dense stands of brush and herbaceous vegetation, with increased abundance and diversity of small mammal populations (Kirkland 1977). Planted Norway spruce (watershed 6) and natural hardwood reproduction (watershed 7) thrive, growing at rates commensurate with tree regrowth on conventionally logged land (Kochenderfer and Wendel 1983). Thirty years of subsequent observation (Patric 1995) show minimal effects of induced barrenness on soil, water, wildlife, and closed forest stands that are continuing to develop rapidly.

Watersheds 8 and 9, which were farmed at about the end of the 19th century (Lima, Patric, and Holowaychuk 1978), were the last basins on the Fernow to be treated. Partially reforested by 1983, watershed 8 was accessed and logged from minimum standard roads during 1983 and 1984, then mechanically prepared for planting to Japanese larch. Even with a 3.5 acre untreated buffer strip along the stream, sediment loading averaged about six times greater than on the permanently forested control (watershed 4) — an effect attributed to its history of farming and to a single record-setting rainstorm during site preparation (Kochenderfer and Helvey 1989). No forest management studies have been undertaken on the newly established watershed 10 (211 acres).

In keeping with the original mission statement, a half-century of hydrology research on the Fernow Experimental Forest has evolved substantially to deal with roads as an important sediment source in managed forests. The desirability of lower road densities led to tests of skyline harvesting, with road density only 25 percent of that required by conventionally used skidders (Kochenderfer and Wendel 1978). Only 3 percent of the skyline-logged land was severely disturbed, leaving more than 90 percent hydrologically unaffected (Patric and Gorman 1978). Measurement of road erosion and development of BMPs to minimize soil loss has led to widespread use of the minimum standard road (Kochenderfer, Wendel, and Smith 1984), greatly reducing stream turbidity during road construction and logging (Kochenderfer and Hornbeck 1999) (Figure 3-3). Table 3-3 summarizes average watershed soil loss from harvest activities and road runoff for several treatments applied at Fernow.



Figure 3-3. Rolling dip road on Fernow Experimental Forest minimizes concentration of flow on road surface.

Table 3-3. Watershed Average Soil Loss for Several Watershed Treatments Applied at Fernow

Observation Site	Soil Loss (t ac ⁻¹ yr ⁻¹)
Fernow watershed 4, permanently forested (Kochenderfer and Helvey 1989)	0.02
Well-managed logging with BMPs (Kochenderfer and Hornbeck 1999)	0.05
Probable average for typical forested land in eastern United States (Patric 1976)	0.10
Elk Lick watershed roads frequently close to creek (Kochenderfer and Helvey 1987)	0.23
Careless logging on watershed 1, skidding in stream channels (Kochenderfer and Hornbeck 1999)	1.44

Watershed Research in the Hills and Piedmont of the Southeast

Between the wetlands, flatwoods, and mountains of the South is the important hilly topography typical of the upper Coastal Plain and Piedmont regions. Much of this region had been managed for agriculture in the past but has reverted to forest. Two key projects in this domain include research of the Oxford Hydrologic Laboratory in Mississippi and the B.F. Grant Memorial Forest in Georgia.

Oxford Hydrologic Laboratory, Mississippi

The USDA Forest Service's Forest Hydrology Laboratory in Oxford, Mississippi, began operation as the Tallahatchie Research Center in 1945. Early research at the laboratory was coordinated with the Yazoo-Little Tallahatchie Flood Control Project to identify tree species, planting techniques, and other erosion control measures that would best ensure stabilization of millions of acres of severely eroded and abandoned agricultural land in northern Mississippi and western Tennessee. In 1956 there were four major objectives: develop techniques for improving the effectiveness of remedial land treatments; design and plan minor engineering structures and improvement works for erosion control; evaluate the

effectiveness of land treatment programs; and provide basic information needs (Ursic 1967; Williston 1988).

Loblolly pine proved to be the most effective erosion control species identified, for a variety of reasons: adequate source of seedlings, simplicity of planting, good survival, fast early growth, excellent needle cast, and abundant lateral roots. Research showed that, in general, by the time a pine plantation reached age five years — normally the age by which crown closure is achieved — a litter layer was produced that was sufficient to promote infiltration and reduce soil erosion (McClurkin 1967; Ursic and Duffy 1972; Williston 1988).

In 1962 the research mission of the Oxford Research Center was divided into two projects: Coastal Plain Hydrology, under project leader Stan Ursic (Figure 3-4); and Rehabilitation and Management of Severely Eroded Watersheds, under project leader Doug McClurkin. Much of the reported research during the late 1960s pertained to the utility of containerized seedlings, the effects of silvicultural regimes on forest litter depth and weight, and the effects of converting low-quality hardwood stands to loblolly pine on soil moisture, storm flow volumes, and sediment losses (Ursic 1963, 1970; Ursic and Dendy 1965; Dickerson 1972).



Figure 3-4. Dr. Stan Ursic of USDA Forest Service explains the operation of 3 ft H-flume, 2 ft coshoxton wheel, and splitter used to collect runoff samples from a forested watershed as part of the Oxford Hydrologic Laboratory in Mississippi.

During the 1950s and 1960s experimental watersheds and runoff plots were established and instrumented at several locations across northern Mississippi to address the following issues:

- Effects of converting old fields to loblolly pine on water yield and sediment losses (Ursic and Dendy 1965; Ursic 1969; Ursic and Douglass 1979)
- Effects of thinning and harvesting operations on the forest floor, water yield, and sediment losses (Ursic and Dendy 1965; Ursic 1970; Dickerson 1975; McClurkin, Duffy, and Nelson 1987)

These studies showed that planting pines on old fields decreased soil moisture during the growing season and decreased annual average streamflows and summer base flows. Conversely, thinning and harvesting operations increased annual water yields roughly proportional to the percentage

of the forest cover removed and caused short-term increases in sediment losses. Some of the experimental watersheds established during the 1950s and 1960s remained undisturbed until the 1970s to establish reliable calibrations for differentiating treatment effects on storm flows and sediment losses (Ursic and Dendy 1965; Ursic and Duffy 1972; Ursic 1970, 1976, 1986).

In the 1970s research was initiated to evaluate the effects of forest management practices on natural groundwater recharge (Ursic 1975). Related projects included basic research on water movement in undisturbed forests, including subsurface flow and deep percolation (Beasley 1976). Other studies measured the effects of upland hardwood conversion, forest thinning, and clearcutting on soil moisture (Ursic 1982). Gradual conversion of hardwoods to pines by killing the hardwoods and underplanting loblolly pines increased soil moisture and mean annual water yields for about five years, at which time the pines were large enough to transpire as much soil moisture as the hardwoods had prior to conversion. Afterward, mean annual water yields from the converted watersheds were less than those from upland hardwood watersheds. However, relating the effects of forest manipulations on deep groundwater recharge proved to be an unresearchable task. As a result, the project's work unit description was revised mid-1975, and subsequent research concentrated on the effects of intensive forest management on streamflow and water quality (Ursic 1974, 1975, 1986; Beasley 1979).

In the late 1970s the Uplands Hardwood Research Unit at Fayetteville, Arkansas, was combined administratively with the Forest Hydrology Laboratory (Lawson 1985). Studies were initiated to evaluate the loss of nutrients in storm runoff from forested and harvested watersheds (Schreiber, Duffy, and McClurkin 1976; Duffy et al. 1978; McClurkin et al. 1985; McClurkin, Duffy, and Nelson 1987). Results showed that watershed disturbances increased levels of phosphorus (both ortho and total), nitrogen (total Kjeldahl, nitrate, and ammonium), calcium, magnesium, and potassium in streamflow. Much of the phosphorus (P) loss was through adsorption to sediments (Duffy et al. 1978). However, nutrient losses from disturbed forests were small relative to those from agricultural land.

In the 1980s the scope of the Hydrology Laboratory's research was expanded to include the effects of clearcutting and mechanical site preparation on water yield and quality in the Ouachita Mountains of Arkansas (Miller, Beasley, and Lawson 1988a, 1988b). Clearcutting and site preparation increased both sediment losses and mean annual water yields, but the increases were relatively small and short lived. Clearcutting did not increase peak streamflows in the late fall, winter, and spring when soils were saturated.

In the 1990s the Ouachita Mountain research was expanded into a major regional project to address the issue of cumulative effects of forest management. Small experimental catchments were nested within larger gaged watersheds to better determine the sources of stream-borne

constituents and to track their movements. Budget cuts by the USDA Forest Service during the 1990s led to a major reduction in the research mission of the Oxford Forest Hydrology Laboratory.

B.F. Grant Memorial Forest, Georgia

In 1973 staff members from the University of Georgia began a study to determine "the effects of forest harvesting and regeneration on the quality, quantity and timing of water flows from Piedmont land. The intent was to find out the extent to which hydrological and mineral cycles are altered by 'normal' forest practices, and to predict the effect in a manner useful to forest land managers and to planners of 'best' management practices..." (Hewlett 1979). Two Piedmont watersheds (an 80-acre treatment watershed and a 105-acre control watershed) in the B.F. Grant Memorial Forest in Georgia were monitored and calibrated for a year. These watersheds were typical of many Piedmont forests, with a legacy of severely eroded soils resulting from cotton farming between 1880 and 1920. One of the legacies of the farming was a gully network. Commercial harvesting was conducted in 1974, and the harvesting was followed by typical mechanical site preparation and machine planting. Monitoring included continuous discharge recording (using an H-flume and stage recorder); sediment sampling (using a coarse sediment trap and Coshocton wheel with slow splitters); temperature (using recording thermographs); and dissolved minerals (using weekly grab samples and self-operating vacuum samplers for storm events).

Water yields increased significantly following harvesting and regeneration treatments (increase of 10 in. annual water yield over the watershed). Stormflow volumes increased by 27 percent for 1 in. storms and about 10 percent for 2 in. storms. Peak discharge, measured in units of cubic feet per second per square mile (csm), increased by 100 percent for small events following treatments but declined with higher peaks. Sediment increased substantially following treatments. Hewlett (1979) concluded that 90 percent of the increased sediment from these silvicultural activities (over the 30-year rotation) came from roads and channel damage from site preparation and planting operations. "Good roading and streamside management, plus hand-planting of the lower 25 percent of the basin, would probably have held average mass export to about 100 lbs/ac/year." Forest management activities did not significantly affect baseflow nutrient concentrations, although nutrient export loads were increased because of increased runoff. Water temperatures were appreciably increased after forest management activities; summer maximum temperatures increased by 11°F. The thin buffer was assessed to be inadequate to provide sufficient shade.

The B.F. Grant Memorial Forest project was especially important because it extended our understanding of watershed response to Piedmont conditions, investigated how "normal" forest management affected water quality, extrapolated effects over a full rotation, and provided practical guidelines to significantly reduced impacts — especially increases in sediment.

Hydrology Research in Wetland and Other Poorly Drained Sites

Moving along a continuum of watershed relief, we come to research in poorly drained forest sites, especially those classified as flatlands and wetlands. The effects of timber harvest on wetland hydroperiods and water chemistry has been a major area of research in the South. The Southeast has about 35 million acres of forested wetland, or 65 percent of total forested wetlands in the conterminous United States. Dominated by riverine wetlands (alluvial floodplains), southern forested wetlands also include organic soil flats (pocosins), mineral soil flats (wet pine flatwoods), and depressions (Carolina bays, cypress swamps, mountain fens). Overbank flooding is the major source of water and nutrients for riverine wetlands, and precipitation is the primary source of hydrologic and chemical input to other types of wetlands.

Evapotranspiration often is the second largest hydrologic component in the water budgets of wetlands. Wetland hydrology is represented by extremely dynamic fluctuations of the water table, varying periods of saturation (hydroperiod), and complex interactions of precipitation, evapotranspiration, and surface water and groundwater flows. Compared to upland hydrology studies, wetland hydrology research in the southern United States is relatively new (Sun et al. 2001); most of the hydrologic studies on forested wetlands have occurred in the past two decades.

One of the driving forces of early wetland hydrology studies in the 1970s was using forested wetlands as a low-energy alternative to recycle secondary treated wastewater (Ewel and Odum 1984). For this purpose, Heimburg (1976) conducted probably the earliest and most complete forested wetland hydrology study in the South. Notable long-term, paired-watershed studies on coastal plain wetland settings include the IMPAC studies at the Bradford Forest in Florida (Riekerk 1989a) and the Santee Experimental Forest in eastern South Carolina (Richter, Ralston, and Harms 1983). Those watersheds were established in the late 1970s to address the emerging environmental issues of intensive forest management on wetland landscapes.

Large-scale, multiple-site comparison studies on wetland hydrology started in the early 1990s to examine how timber management affects wetland ecosystem functions and values (Shepard, Lucier, and Haines 1993). Across 13 southern states, more than 70 research sites are currently conducting forest wetland research at different scales. Research results have been summarized in review papers by Riekerk, Neary, and Swank (1989); Shepard (1994); Walbridge and Lockaby (1994); Lockaby, Trettin, and Schoenholtz (1999); NCASI (1999b); and most recently Fulton and West (2002). Here we describe the research findings by wetland types and then follow with focused discussions of key watershed research at the IMPAC study in Florida, Santee Watershed in South Carolina, Belle Baruch Hydrologic Institute in South Carolina, North Carolina State wetland research, and Mobile-Tensaw River Delta Study in Alabama.

Wetland Types

Riverine Wetlands

There are more than 12 million ha of bottomland hardwoods forest in the southern United States. A series of harvesting experiments have been conducted to examine their ecological responses to timber harvesting (Aust, Lea, and Gregory 1991; Crawford et al. 1993; Lockaby et al. 1994, 1997; Aust et al. 1997; Messina et al. 1997).

Harvesting bottomland forests usually has little long-term effect on hydroperiod if BMPs are followed (Lockaby, Stanturf, and Messina 1997) or alternative harvesting methods (e.g., helicopters) are used (Perison 1997; Rapp, Shear, and Robison 2001). The most common hydrologic change following harvesting of bottomlands is a rise in the water table (Aust and Lea 1992; Wang 1996; Lockaby et al. 1997; Perison 1997). This "watering-up" is attributed to several causes: reduction of canopy interception and plant transpiration; reduction of soil saturated hydraulic conductivity and increase of bulk density if harvesting sites are severely disturbed; and increase of surface water storage and blockage of surface and subsurface drainage. One exception to this pattern is reported for dark-colored organic soils, where the water table dropped 20–40 cm during the postharvest period (Lockaby et al. 1994). The cause of this unique response is not well understood. The water table effects of forest harvesting on floodplains are most pronounced during the first two growing seasons (Wang 1996; Lockaby et al. 1997).

On-site water quality effects of harvesting floodplain forests are minor because of the low intensity of site disturbance (Wang 1996), unique hydrologic processes (slow-moving water), and increase in surface roughness for sediment and nutrient retention (Aust, Lea, and Gregory 1991; Rapp, Shear, and Robison 2001). Treatment effects often are overwhelmed by seasonal flooding events (Perison 1997).

Depressional Wetlands (Cypress Domes and Carolina Bays)

The southeastern United States, especially areas in Florida and the Atlantic Coastal Plain, contains many depressional wetlands that are seasonally dry and isolated from streams or rivers (Tiner et al. 2002). Examples are cypress domes (ponds), Carolina bays, and pocosin wetlands. These depressional wetlands can be important habitat for reptiles and amphibians (Russell, Gynn, and Hanlin 2002). Many of these small, isolated wetlands are imbedded in wet pine flats that are intensively managed for timber production.

Heimburg (1976) found that surface water in cypress domes was closely coupled with groundwater in surrounding pine flatwoods. Depending on the specific location of the cypress dome on the overall landscape, three groundwater flow patterns were postulated: flow-in, flow-out, and flow-through domes. These three flow scenarios subsequently have been confirmed (Crownover, Comerford, and Neary 1995; Sun, Reikirk, and

Korhnak 2000; Bliss and Comerford 2002). Carolina bays have similar hydrologic behaviors to cypress domes (Lide et al. 1995).

Echoing the responses to forest management demonstrated in bottomlands, reports from a hydrologic impact study conducted at the 42 ha cypress ponds/pine flatwoods mosaic site in north-central Florida (Crownover, Comerford, and Neary 1995; Sun, Reikirk, and Korhnak 2000; Bliss and Comerford 2002) suggested that tree removals from isolated wetlands and surrounding uplands resulted in water table rise and runoff increase. Compared to the nonharvested plot, water tables were significantly raised (as high as 100 cm) for two treatments: wetland and surrounding upland harvesting, and wetland harvesting only. This water table effect was greatest during the first dry growing season. Water tables were somewhat lower than the control in the subsequent relatively wet years. The hydrologic regime at this site appeared to have recovered within five years. A retrospective 25-year study on a similar landscape in the coastal plain of Georgia describes the development of a dense herbaceous understory in cypress wetlands following adjacent timber harvest, but the results suggest that solar radiation and increases in nutrient availability were the drivers of the vegetative change, not hydrology (Batzer, Jackson, and Mosner 2000).

Few data are available on the water quality effects of harvesting isolated wetlands. Ewel (1985) found that total nitrogen and organic N were increased substantially in cypress swamps immediately after thinning but were lower than baselines three months later. Forest harvesting did not have an important effect in surface water or pore water phosphorus concentrations in the flatwood/cypress pond transects at the aforementioned 42 ha study site in Florida (Comerford and Freitas 1997).

Wet Flats and Pocosins

Wet flats and pocosins lie in broad interstream divides on poorly drained soils. On higher elevations wet flats are better drained than pocosins that develop thick organic layers. Many of the wet pine flats and pocosins have been used for intensively managed timber production. Forest harvesting practices generally result in short-term water table rise and an increase in runoff. A long-term watershed-scale study at the Bradford Forest on a cypress-pine flatwoods landscape in northern Florida reported that maximum disturbance in a 48 ha watershed caused a 15 cm (150 percent) increase in water yield; the minimum disturbance in a 64 ha watershed resulted in an insignificant increase of 3 cm in water yield (see IMPAC discussion later in this chapter). Water tables rose significantly for both treatments, especially during drought months (Riekerk 1989a, 1989c). In the sixth year post-treatment, runoff from the maximum disturbance watershed was still significantly higher, but the increase was reduced from 150 percent of predicted runoff to 65 percent of predicted runoff (based on a regression using the control watershed runoff). The groundwater tables in both disturbance sites remained higher than for the control site. Hydrologic changes in water table and runoff were most pronounced in dry years.

Harvesting under wetland conditions such as on wet pine flats may cause alteration of soil hydrologic properties (e.g., hydraulic conductivity, macropores) from soil compaction, rutting, and puddling (Greacen and Sands 1980). The physical property changes affect subsurface flow and water table depth. Soil compaction, rutting, and puddling impacts generally become greater with increased soil wetness, clay content, and traffic (Green, Stuart, and Perumpral 1983). However, Aust et al. (1995) found that the hydrology of poorly and very poorly drained soils was less altered by skidding than that of moderately well drained or somewhat poorly drained soils.

An ongoing long-term intensive field-scale study on wet pine flats in South Carolina examined the hydrologic and site productivity effects of two harvesting schemes: wet-weather harvesting and dry harvesting (Preston 1996; Xu et al. 2002). Two site preparation levels (nonbed and bed) were randomly assigned to both dry weather and wet weather harvested plots; an additional level (bed and mole plow) was applied only to the wet weather harvested plots. Tree removals alone resulted in a raised water table of 14 cm and 21 cm on the dry and wet weather harvesting plots, respectively, with the maximum difference (>10 cm) occurring during the growing seasons (May through October). Churning and deep rutting resulted in a significant effect on the water table for wet harvest areas but not for dry harvest areas. Bedding lowered water tables initially for both harvesting regimes, but the dry harvesting site recovered rapidly within two years after replanting. Further analysis of soil physical properties concluded that bulk density, macroporosity, and hydraulic conductivity were significantly affected by all levels of wet harvesting disturbance. Dry weather harvesting also altered soil physical properties. From a spatial perspective, wet weather harvest created a much higher degree and extent of impact than did dry harvest (Xu et al. 2002). Overall, the study suggests that water table depth change was caused by change in vegetation, not by the altered soil properties from harvest traffic. Changes of soil physical properties resulting from harvesting and regeneration practices also were reported for a wet pine flat site in North Carolina, where soil macroporosity was reduced by half within a 200 cm profile (Blanton et al. 1998).

Forest harvesting followed by site preparation activities in wetlands has the potential to disturb surface soils, alter surface and subsurface flow paths, increase water yield, and accelerate nutrient cycling rates. These effects, in turn, can affect on-site and off-site water quality. Riekerk (1985) found that clearcutting of a pine-cypress flatwoods resulted in a significant increase in pH, suspended sediment, total nitrogen, potassium, and calcium during the first year after harvest. Fisher (1981) described the effects of clearcut timber harvesting and site preparation on the hydrology and water quality of a pine flatwoods site in western Florida. Runoff volume was increased during the first year, but by the second year most water quality parameters had returned to near-background levels. The impacts of

silvicultural operations for these level, sandy sites were less than in areas having more relief and shallow soils (Fisher 1981).

Prescribed burning as a forest management tool was developed largely in the Atlantic and Gulf Coastal Plains (Richter, Ralston, and Harms 1982). 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. One exception was a three-year paired watershed study at the Santee Experimental Forest in eastern South Carolina, which is described in more detail later (Richter, Ralston, and Harms 1982, 1983).

Intensive Management Practices Assessment Center (IMPAC), Florida

The Intensive Management Practices Assessment Center (IMPAC) in Florida represents a spatially small but intense and significant extension of watershed research in the South. Whereas Coweeta and Fernow provide watershed research for hilly and mountainous terrain, the IMPAC study provides information about water quantity and quality response on sandy flatwood sites.

IMPAC was initiated with support from the University of Florida, the USDA Forest Service, and the forest products industry. IMPAC was established in 1976 to study the effects of intensive forest management practices on water resources, soils, and wildlife. Three small watersheds in a managed industrial forest near Starke, Florida, covering a total of about 700 acres, were isolated by construction of roads and ditches. Because of the flat nature of the site, these watersheds were actually created by the road and ditch system (augmenting natural terrain features). In addition, because of the low channel gradients, special long-throated flumes were used to measure runoff (Figure 3-5). Water samples were automatically collected with pumping samplers and were stored in gaging stations with refrigerated collectors to help preserve samples in the intense Florida heat. Bedload traps were installed above the long-throated weirs to capture sandy bedload.

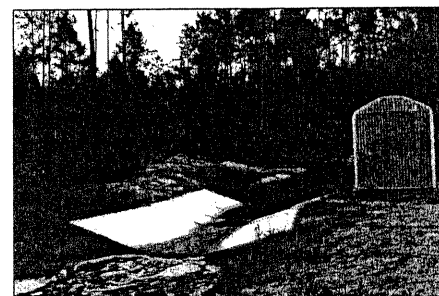


Figure 3-5. IMPAC site near Starke, Florida, with a long-throated flume serving as the control structure to measure discharge. A pumping sampler collected samples and stored them in the gaging station house.

The three watersheds were largely covered by slash pine (*Pinus elliottii*) on sandy soils (with a restrictive clay layer present in some, placed below the sandy soils). Some ponds also were interspersed in the forest stands.

After a 12-month calibration period, one watershed was machine harvested, slash burned, windrowed, bedded, and machine planted — a series of treatments characterized as causing high disturbance. The second watershed was manually harvested, slash was chopped, and the site was bedded and machine planted — a series of practices that resulted in a lower level of disturbance. The third watershed was left as a control.

Riekerk (1989c) found that water tables were higher after harvesting as a result of reduced evapotranspiration. He reported that daily runoff the first year increased in proportion to the fraction of the watershed clearcut but recovered over time. Water yield increased to 250 percent of expected (150 percent increase) from the high-disturbance treatment watershed and 117 percent from the low-disturbance treatment watershed (Riekerk 1983). A drought during the study may have delayed revegetation of the sites and slowed hydrologic recovery. Recovery was unexpectedly rapid for the low-impact site, but this outcome might have been a result of seepage through the artificial watershed boundaries. Riekerk (1989c) also found that bedding can accelerate or retard drainage from these flat sites. In the high-disturbance watershed, intense site preparation (reduced infiltration) and bedding orientation were found to facilitate storm flow. Although large but short-lived increases in runoff for a small fraction of a larger watershed are probably undetectable, Riekerk (1989c) cautioned about the possibility of localized impacts from accelerated runoff.

The water quality for these flatwood sites was distinctively different from that coming from well-drained, upland watersheds. Particularly noticeable was the low pH in these intermittent flatwood streams. The pH of runoff was found to correlate well with soil solutions in the watersheds (Riekerk, Morris, and Lassiter 1979). The chemical oxygen demand (COD) prior to treatment at these sites also was noticeably high compared to upland sites, and concentrations of organic nitrogen were an order of magnitude greater than concentrations of inorganic forms (Riekerk, Morris, and Lassiter 1979). Following treatment, water quality was reduced on both disturbed watersheds compared to the control (Riekerk 1983). The largest impact occurred immediately after the high-disturbance treatment, but absolute water quality impacts were low. For example, a comparison of water quality response to forest harvesting and site preparation by Riekerk, Neary, and Swank (1989) found that these sites had a relatively low response in sediment concentration and sediment export compared to other sites in the South. However, nutrients — particularly nitrogen — did show a response, but it was short lived (Riekerk, Neary, and Swank 1989).

This study has corroborated other experimental and modeling studies (Sun et al. 2000) in the region. Williams and Lipscomb (1981) found a water table rise of 15–35 cm after a partial cut of a coastal pine forest on sandy soils. At an even wetter study site, Rodriguez (1981) concluded that clearcutting a wet savanna watershed did not significantly alter the hydrology.

A second large watershed study was initiated in 1983 near Gainesville to investigate the effects of fertilizer and herbicide applications on water quality (Riekerk 1989b). Six plots of approximately 6 ha each were established by harvesting a mature slash pine forest and preparing the site using chopping, burning, and bedding, followed by planting slash pine. Artificial watersheds were created by using berms and ditching. Three plots were used as controls; three received annual applications of fertilizer and herbicide for four years. Fertilizer included nitrogen, phosphorus, potassium, calcium, magnesium, manganese, copper, zinc, boron, sulfur, and molybdenum and was applied by ground-based equipment with 3 m untreated zones around streams and wetlands. These treatments resulted in elevated NH_4 in the first and fourth year of application. Elevated levels of potassium and phosphorus were not observed until the fourth year of the study, which was a year of unusually high precipitation.

IMPAC remains an important center for the study of flatwoods hydrologic response and is adapting geographic information system (GIS) technology to support forest management decisions.

USDA Forest Service Santee Watershed, South Carolina

Located on the lower Atlantic Coastal Plain in eastern South Carolina as part of the Francis Marion National Forest, the 2,500 ha^{*} Santee Experimental Forest was established for experimental and demonstration purposes in 1937. Two paired watersheds — a control watershed (206 ha) and a treatment watershed (151 ha) — were gaged beginning in 1976 to evaluate the effects of prescribed burning on water quality. The area has low topographic relief (<4 percent), with surface elevation ranging from 4 m to 10 m above mean sea level. Dominant tree species include loblolly pine, longleaf pine, cypress, and sweet gum. Soils are primarily strongly acid, infertile Aquults sandy loams, characterized by seasonal high groundwater tables and argillic horizons with low base saturation that developed on marine terraces of the Pleistocene epoch. The climate of the research area is classified as humid subtropical, with long, hot summers and short, mild winters (Richter, Ralston, and Harms 1983). Mean annual precipitation is about 1,350 mm; July and August are the wettest months (together accounting for 28 percent of the total), and April and November are the driest months (together accounting for 10 percent of the total).

The most notable hydrologic research on the study site involved prescribed burning and its effects on nutrient cycling and water quality. Using a paired watershed approach, Richter, Ralston, and Harms (1982, 1983) studied the effects of prescribed fire on nutrient loading to streams. A total of 15 compartments in the treatment watershed were burned in the winters and summers of 1976 through 1979. The study concluded that periodic prescribed fires in southeastern Coastal Plain pine forests are not likely to have appreciable effects on the quality of groundwater and streamwater. After a period of no monitoring on these watersheds, monitoring was resumed following Hurricane Hugo to measure the effects of a

severe natural disturbance. Hugo caused significant forest blowdown throughout the Francis Marion National Forest.

Belle Baruch Hydrologic Institute, South Carolina

Hydrologic research at the Belle Baruch Institute has focused on the hydrology of natural forested watersheds of the lower Coastal Plain. Coastal forested watersheds are characterized by flat topography, poorly defined watershed boundaries, and high water tables (Young and Klaiwitt 1968). The majority of hydrologic research at the Baruch Institute has been done on Hobcaw Forest in eastern Georgetown County, South Carolina, bordered by Winyah Bay to the west and south and the North Inlet Salt Marsh to the east. Elevations range from 9 m on relict dunes along the western edge of the forest to 80 cm along the edge of the salt marsh. Approximately one-third of the forest drains westward in channels showing some signs of fluvial process. Soils are primarily Entisols on old dunes and Ultisols on gentle slopes (<2 percent). Topography on the eastern two-thirds shows no fluvial influence. Watersheds are formed by relict dune lines approximately parallel to the coast at about 650 m horizontal spacing. Average land slope to the east is 0.2 percent, and total elevation change within a watershed is less than 2 m.

Forest hydrology in the Coastal Plain has some similarities to the hydrology of steeper regions in that infiltration always exceeds rainfall as long as the forest floor is undisturbed and unsaturated (Bonnel 1993). However, there is insufficient slope to move water laterally in the unsaturated profile as interflow. Preferential flow paths lead to the water table rather than laterally. Over much of the Coastal Plain the water table is less than 1.5 m below the surface (Gilliam et al. 1974), and rainfall causes rapid rise of the water table (Williams 1978b; Gilham 1984). With sufficient rainfall, the water table can reach the surface on portions of the watershed — thereby producing direct runoff by saturated overland flow (Dunne and Black 1970). Further rain on these sites accumulates on the surface or becomes runoff.

Seasonal and Annual Water Table Dynamics at Belle Baruch

Water table dynamics were studied for a period of 14 years on a grid of 45 wells throughout the Hobcaw Forest (Williams 1978b; Williams and Lipscomb 1981). Water table dynamics over long periods tend to reflect the average moisture balance. Given 14 years of data, the monthly average water table positions can be predicted with relatively small errors (standard error from 2.8 cm to 5.9 cm). However, the data points show a very large distribution of values at any date (standard deviation from 20.8 cm to 43.9 cm). The water table at this site may be anywhere within the top 1 m of soil in the winter and the top 1.8 m in the summer and late fall. These relatively strange statistics are explained by the time series of weekly observations (Figure 3-6). Except when the water table is more than 1 m deep, the water table rises 9.7 cm per cm of rain (Williams 1978a). Daily potential evapotranspiration (PET) varies from 3.3 mm in March to 4.8 mm in July.

Assuming no hysteresis in the value of drainable porosity, these values would translate to water table drops of 3.2 cm day⁻¹ and 4.7 cm day⁻¹ during March and July, respectively. As Figure 3-6 shows, water table drops of greater than 20 cm/week were common in each summer. Most summer rainfall here occurs as convective storms in subtropical marine air masses (Muller and Grymes 1998). Sea breeze-induced instability also produces widely variable rainfall near the coast (Tainter and Cody 1983). Convection summer storms may be frequent, as in 1976 and 1982, or precipitation may occur as large, tropical cyclones in late summer and fall, as with Hurricane David (270 mm, September 1979) and Tropical Storm Dennis (159 mm, August 1981). If neither event occurs — as in 1978, 1981, and 1986 — the water table drops to nearly 2 m deep.

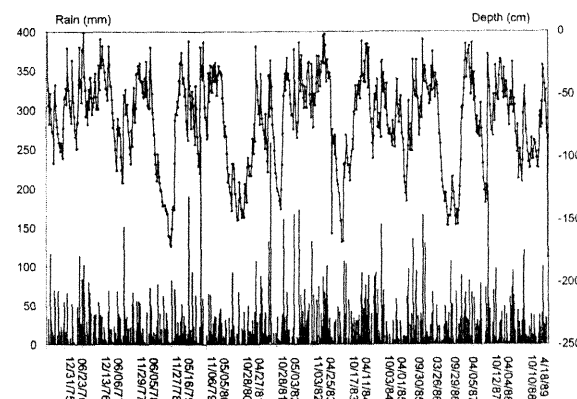


Figure 3-6. Time series of weekly water table depth observations and rainfall sums associated with the period prior to each observation. Observations generally were weekly, but individual periods were 4–14 days long.

With the exception of water table elevations, accurate hydrologic measurements are not easily taken on the lower Coastal Plain (Williams 1978a). Some problems can be overcome with specifically designed structures (Replogle, Riekerk, and Swindel 1978) and artificially bounded watersheds (Riekerk and Korhnack 1985). On Hobcaw Forest, seven watersheds were instrumented to examine flow into North Inlet in 1977 (Dame et al. 1991). Of these seven, only numbers 5 and 7 were sufficiently bounded (with 19th-century berms and ditches) to warrant long-term data collection. These watersheds were monitored until Hurricane Hugo, in September 1989, destroyed the flow control structures. In 1992 the flow control structure on watershed 5 was rebuilt slightly upstream of the original structure, reducing the watershed from 49 ha to 37 ha (Wahl 1996). Monitoring continued until 1995.

Results of this work indicate that streamflow is highly dependent on antecedent water table conditions. Flow can be separated into three separate regimes (Williams 1979). Without areas of saturated soil in the watershed, rainfall will infiltrate and there will be no streamflow. For this

watershed, the water table elevation corresponding to that condition is 1.1 m. In 1986 very low rainfall in late spring caused a drop to this point, and repeated rains of 30–40 mm produced no streamflow for the rest of the year. Coastal watersheds are quite level, and one might expect that considerably larger areas will become saturated as the water table rises above some threshold value. On this watershed that threshold is a water table elevation of approximately 1.5 m. The difference of 40 cm is similar to the height of the stream banks, suggesting that areas outside the stream saturate at that time. Above this threshold, small changes in the water table will produce large differences in streamflow. For example, similar rain events (24.8 mm and 25.1 mm) produced peaks of 6 mm and 18 mm, respectively. On day 37 the water table was 1.53 m; it was 1.62 m on day 41. Runoff tripled with only a 9 cm difference in the water table. Similarly, on days 109 and 115 in 1982 it rained 60.9 mm and 68.5 mm, respectively. Peak runoff was 6.2 mm on day 109 and 53 mm on day 115. Water tables were 1.32 m and 1.58 m, respectively. A difference of only 16 cm resulted in a nearly ninefold increase in peak flow.

Temporal variability is dominated by the high rates of both evapotranspiration (ET) and rainfall during the growing season and immediate interaction of both with water tables near the surface of the ground. As long as water table depth is less than approximately 1 m, response of the water table to the balance of rain and ET occurs in a matter of hours. There is a predictable annual cycle of surplus rainfall in fall and winter and deficit in April through June, resulting in a average water table depth at a minimum in March and a maximum in November. However, the water table at any time varies with summer thunderstorms and tropical cyclones. Streamflow is further varied by the interrelationship of antecedent water table position and rainfall amount. Similar rainfalls, often only days apart, may produce several-fold differences in the rate of streamflow.

Spatial Differences in Water Table at Belle Baruch

The well data at Belle Baruch reveal that Coastal Plain water table positions have high spatial correlation. Wells several kilometers apart show nearly identical water table behavior. Except for sea breeze effects, rainfall and ET are similar over distances less than 100 km. Spatial variability in water table position is a result of vegetation differences and lateral groundwater flows.

Within a watershed, the behavior of the water table in relation to daily ET loads can be used to determine lateral flow relations. Daily fluctuation of water table position in high-water table soils is one of the most widely recognized behaviors. On the coast, transpiration usually occurs for a period of eight hours, from 10:00 am to 6:00 pm. During that period the water table will show a drop of 3–8 cm. During the other 16 hours of the day the water table will either drop slightly, remain static, or rise to nearly the same level as the previous day. Each of these reactions can be associated with a landscape position. Near ridges the water table drops during the night, on

side slopes the water table remains constant, and in convex landscape positions the water table rises at night. These differences are equally apparent on very small slopes (<0.1 percent).

The success of relatively simple piezometer designs (Williams and McCarthy 1991; Mas-Pla et al. 1992) has allowed examination of both horizontal and vertical distribution of hydrostatic pressure. Tracer experiments also showed that most of the flow was carried in a relatively small layer within an aquifer (Mas-Pla et al. 1992; Yeh et al. 1995). Lateral flow generally is carried in a relatively thin layer of substrate with higher hydraulic conductivity. At any point within the watershed, flow is predominantly vertical (Williams 1996; Williams et al. 1996). Vertical gradients are toward the conductive layer, where nightly water tables decrease, and from the conductive layer, where nightly water tables increase.

Hurricane Hugo presented a unique opportunity to examine spatial distribution groundwater flow paths. The hurricane tidal surge covered about 400 ha of Hobcaw Forest with roughly 1 m of seawater, followed by 200 mm of rain in the succeeding two weeks. Soil that was unsaturated prior to the hurricane was filled with seawater (Gardner et al. 1991). At the watershed ridges the water table was 50–80 cm below the surface, yet it was near the surface at the stream margins. This disparity produced a salinity pattern in groundwater that was highest (2000 mg Na L⁻¹) near the ridges and lowest (<100 mg Na L⁻¹) near the stream channels. This pattern allowed the use of chloride from the saltwater as an uncontrolled tracer experiment. By April 1992 this water had moved to the bottom of the 5 m thick water table aquifer and showed chloride concentrations greater than 100 mg Cl L⁻¹. The salinity varied with rainfall, and ET showed considerable vertical exchange on a monthly basis (Williams 1993). There was a long-term flow pattern that moved saline water from the bottom of the aquifer to the surface along the western edge of the stream. Tree mortality patterns were much more closely aligned with these salinity patterns than with those measured immediately after the hurricane (Williams 1996).

Saturated overland flow is revealed in changes in stream chemistry at different stages of the hydrograph. Wolaver and Williams (1986) showed low flows with higher concentrations of calcium, silicon, and alkalinity and storm hydrographs high in organic carbon, organic nitrogen, and SO₄. High concentrations of nitrate or ammonium also are found in the first streamflow following prolonged dry periods (Riekerk 1982; Williams and Askew 1990; Wahl, McKeller, and Williams 1997). The frequency and concentrations increase when soils are drained for pine plantations (Williams and Askew 1988) or suburban development (Wahl, McKeller, and Williams 1997). Wahl (1996) examined stream concentrations during a storm event simultaneously with piezometric pressure and groundwater concentrations. These measures confirmed earlier proposed mechanisms. Base flow between storms was higher in calcium and alkalinity and had low

concentrations (10 mg C L^{-1}) of uncolored dissolved organic carbon (DOC). Soon after rainfall began, vertical gradients increased and near-stream groundwater (hyporheic water) was expelled into the stream. This water was higher in the inorganic nitrogen form, ammonium, where near-stream soils had limited aeration or the nitrate form where soils were initially aerobic. DOC concentrations increased later near the peak of the hydrograph. When rains resulted in a multi-peaked hydrograph, DOC concentration increased for each succeeding hydrograph peak. Highly colored DOC concentrations of 35 mg C L^{-1} were found during the third peak of one such hydrograph. This concentration is similar to soil-water concentrations found near the soil surface within the forest.

Mobile-Tensaw River Delta Study

The Mobile-Tensaw River Delta study is a long-term research project that was established in 1986 to examine impacts of forest operations on hydrology, water quality, and forest stand composition in a tupelo-bald cypress (*Nyssa aquatica-Taxodium distichum*) swamp (Aust 1989; Mader, Aust, and Lea 1989; Mader 1990) (Figure 3-7). The site is located in Baldwin County, Alabama, in the Mobile-Tensaw River Delta — a large deltaic plain below the confluence of the Alabama and Tombigbee Rivers. The 70-year-old pretreatment stands were located on very poorly drained muck swamps and consisted of approximately 85 percent water tupelo (*Nyssa aquatica*), 10 percent bald cypress (*Taxodium distichum*), and 5 percent Carolina ash (*Fraxinus caroliniana*). The site had been previously harvested by float logging during the late 1700s and mid-1800s and pull-boat logging during 1920. The hydric soil is Levy series (gray silty clay loam surface over a thick gray clay), superactive, acid thermic, and hydraquent, and the site typically experiences extensive overbank flooding (Aust et al. 1990, 1997).

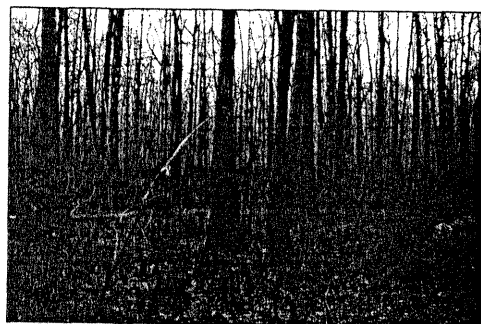


Figure 3-7. Mobile-Tensaw River Delta — site of long-term research on timber harvesting and water quality impacts.

Three disturbance treatments were installed in 1986. The helicopter (HELI) treatment consisted of clearcutting with chainsaws followed by helicopter removal of all merchantable stems. This treatment was installed to provide minimum levels of trafficking during harvests. The second

treatment, ground-based skidding (SKID), consisted of the same treatment as HELI followed by simulated skidder traffic with a cable skidder intended to severely disturb the site. Within the SKID treatment 52 percent of the treatment plots were trafficked (disturbed) to an average depth of 30 cm. The third treatment, removal of all regrowing vegetation following HELI with glyphosate herbicide (GLYPH), was intended to allow examination of the importance of regrowing vegetation to site recovery. The study was installed as three replications in a 3 by 3 Latin square (9 replications total). This experimental design also allowed gradients of distance from the river and along the river to be examined. In addition, 9 pseudoreplications (REF) of the nonharvested area were installed immediately adjacent to the disturbance treatments. True replications of the control were precluded within the Latin square design because of helicopter flight safety issues, but the pretreatment evaluations indicated that these areas were very similar to the pretreatment conditions of the disturbed areas. Values for these areas were compared to the disturbance treatments using t-tests.

The sites were intensively monitored during the first two years following disturbance and again at ages 7 years (Szabo 1998; Zaebst 1997; Zaebst et al. 1995), 10 years, 12 years (Warren 2001), and 16 years (Gellerstedt and Aust 2003) after treatment. Mader, Aust, and Lea (1989) found that the HELI and SKID treatments were fully stocked with desirable species during ages 1 and 2 years, but that the SKID treatment favored certain postdisturbance species, such as black willow (*Salix nigra*). Aust and Lea (1992) found that the rutting and churning of the skidder treatment reduced soil oxygen, soil reduction-oxidation (redox) potentials, and hydraulic conductivity, which indicated that the SKID treatment had made the site wetter relative to the other disturbance treatments (Table 3-4). Furthermore, all treatment sites were found to have less aeration and wetter conditions than the reference stands, probably because of the disturbance associated with tree felling on the very soft soils as well as reduced ET rates.

Table 3-4. Average Soil Oxygen, Soil Reduction-Oxidation (Redox), and Saturated Hydraulic Conductivity Values, by Treatment, for Upper 50 Cm Soil Depth during 1988 (Year 2 following Disturbance)

Treatment	Soil Oxygen (%)	Soil Redox (mV)	Saturated Hydraulic Conductivity (cm hr ⁻¹)
REF	5.4 a ¹	400 a	17.9 a
HELI	2.2 b	270 b	8.5 b
SKID	1.4 c	185 c	3.3 c
GLYPH	1.8 b	285 b	7.4 b

¹Values followed by different alphabetical characters are significantly different at alpha = 0.05. Values followed by same characters are not significantly different.

Sediment inputs were evaluated two years after treatment (Aust, Lea, and Gregory 1991). The completely denuded GLYPH plots trapped the least sediment (0.7 mm), followed by the REF (1.1 mm), SKID (1.2 mm), and HELI (2.2 mm) treatments. The REF and GLYPH treatments trapped the least sediment because they contained less herbaceous material than was developed on the SKID and HELI treatment sites. The SKID treatment apparently trapped less sediment than the HELI treatment because of the collapse of skid ruts during this period. During the initial two years, the investigators concluded that:

- The initial disturbance reduced soil aeration and water movement, particularly in the SKID treatment, and all disturbance treatments were wetter than the control area.
- Treatments such as HELI and SKID favored development of a dense herbaceous layer that resulted in increased sediment deposition during overbank flood events.
- Both the HELI and SKID treatments resulted in fully stocked stands, but the SKID treatment had fewer stems and a greater percentage of black willow.

Table 3-5. Average Annual Sediment Accumulation by Treatment and Measurement Period (mm yr⁻¹)

Treatment	1987–1988	1988–1993	1993–1996	1996–1998	1998–2002
REF	1.1 a ¹	7.6 a	15.2 a	5.1 a	5.1 a
HELI	2.2 b	15.2 b	25.4 b	7.6 b	7.6 ab
SKID	1.2 ab	12.7 b	22.9 b	7.6 b	5.1 a
GLYPH	0.7 a	20.3 c	33.0 c	15.2 c	10.1 b

¹ Values followed by different alphabetical characters are significantly different at alpha = 0.05. Values followed by same characters are not significantly different.

The treatments were reexamined during the seventh and eighth growing seasons (Aust et al. 1997; Zaebst 1997; Szabo 1998). Several important trends were found to have changed. The GLYPH treatment had changed from the bare soil conditions of years 1 and 2 to a lush, freshwater marsh. The HELI and SKID treatments had almost reached closed canopy conditions, and both were growing well. The regrowing vegetation in the GLYPH plots now allowed more sediment to be trapped than occurred with the other treatments, but the HELI and SKID treatments still trapped more than did the REF treatment (Table 3-5). During this remeasurement, the stand compositions of the HELI and SKID treatments were found to diverge somewhat. The HELI treatment areas had stands composed of a mixture of water tupelo, Carolina ash, bald cypress, and black willow; the SKID treatment had a greater tupelo component. Soil redox potentials and water tables were no different between these two treatments. Also during this period, the disturbance treatments were found to have a lower water table than the reference plot, indicating recovery of ET by age 7

years. Similar measurements and trends also were found at ages 10 years, 12 years, and 16 years (Aust et al. 1998; Gellerstedt and Aust 2003). Annual differences in sediment trapping were primarily a result of the total number of days that the sites were flooded. During the lowest sediment accumulation period (1987 through 1988), the site was flooded for less than 50 days. The highest values of sediment accumulation occurred during 1993 through 1996, when the site averaged more than 150 days of flooding per year.

By age 16 years both the HELI and SKID treatments produced stands that were similar in composition to the original, and both treatments were growing well (Table 3-6). The SKID treatment favored the growth of the flood-tolerant tupelo (Table 3-6). The original skidding disturbance reduced soil aeration and water movement and acted as a site preparation treatment that favored flood-tolerant species. The HELI treatment favored a wider variety of species, which allowed additional interspecific competition. Furthermore, the site has recovered from the traffic disturbance in several important ways. Annual sediment input has remained high, although it is becoming lower as the HELI and SKID canopy shade reduces ground flora. The sediment inputs filled the skidder ruts and brought nutrient-rich sediments in. In addition, the montmorillonitic clays on the site have repeatedly undergone shrinking and swelling during the wetting and drying cycles. This “self-plowing” has reduced the original compaction and porosity problems.

Table 3-6. Average Overstory Species Density by Treatment, Age 16 Years (count ha⁻¹)

Treatment	<i>Nyssa aquatica</i>	<i>Taxodium distichum</i>	<i>Fraxinus caroliniana</i>	<i>Salix nigra</i>	Other	Total
REF ¹	336 a ²	89 b	279 b	0	0	704 a
HELI	1,341 b	222 c	2,510 d	427 a	54 a	4,554 b
SKID	1,690 c	230 c	1,860 c	551 b	188 a	4,519 b
GLYPH	222 a	40 a	170 a	410 a	148 a	990 a

¹ Age 86 years.

² Values followed by different alphabetical characters are significantly different at alpha = 0.05. Values followed by same characters are not significantly different.

This study illustrates several important concepts regarding site impact studies:

- The original alterations in site hydrology and aeration have had long-lasting effects on species within the HELI and SKID treatments. Fortuitously, the severe disturbance of the skidding actually has resulted in the greatest biomass at age 16 years because the SKID disturbance favored a flood-tolerant species (water tupelo) — a species that also has a rapid growth rate. The HELI treatment also produces acceptable stocking and growth but lags behind the SKID treatment in terms of tupelo biomass.

- Although forested wetlands often are believed to be "sensitive" sites, some are incredibly resilient by virtue of the shrink-swell nature of the soil, sediment from flooding, and abundant stump sprouts. Sites lacking these factors may be more prone to harvest disturbances.
- Regeneration of these stands resulted principally from stump sprouts. Few trees, other than black willow, regenerated from seed in the HELI and SKID treatments, and the black willow is deteriorating. Recovery within the GLYPH treatment, which had no stump sprouts, was clearly delayed. Only stump sprouts compete well with the lush herbaceous growth.
- Sediment trapping was favored by disturbances that allow herbaceous vegetation to become established. This sediment trapping is important to the enhancement of stream water quality and to amelioration of skidding impacts.
- Evapotranspiration recovered faster than predicted. Apparently, herbaceous vegetation plays a greater role than was originally assumed.
- The GLYPH treatment brought the site to a bare soil state. This treatment has progressed from a freshwater marsh condition to shrub-scrub and is now slowly accumulating enough tree regeneration so that it eventually will become a forested wetland. The removal of the stump sprout regeneration source has clearly slowed the recovery of this area, but species similar to those found in the other treatment sites are becoming reestablished.

Coastal Plain Water Management Research, North Carolina

In the lower coastal plains of the Southeast, an area known as the Flatwoods, water tables lie near the ground surface for much of the year. Although the productivity of these lands is high, establishment of pine seedlings under saturated soil conditions is difficult. For this reason, ditching and drainage have been major hydrologic issues for forests in this area. Much of this vast area of forest lands is being intensively managed with pine forests for maximum timber production. Intensive forestry management practices include both silvicultural and water management treatments installed to maximize timber production. The silvicultural treatments include bedding of soils, fertilization, thinning, pruning, prescribed burning, and pesticide application. Water management involves artificial ditching to improve drainage, sometimes with control structures to retain water in the dry season. Forest management practices of the southeastern Coastal Plain can lead to significant changes in the water regime of forested lands (Riekerk 1989). Impacts of drainage and water management on the hydrology and water quality of wetland forests in eastern North Carolina had been reported from the 1960s (Terry and Hughes 1978; Campbell and Hughes 1980; Skaggs et al. 1980; Hughes 1982; Gregory 1988). This section focuses mostly on the studies from late 1980s that deal with impacts of intensive forestry practices, especially

drainage and water management, on the hydrology and water quality of plantations of fast-growing pines.

Hydrologic effects of ditching vary, depending on soil characteristics and the stages of vegetation development. Campbell and Hughes (1991) report that free drainage to ditches in pine plantations resulted in a water table drop of 30–60 cm compared to undrained pocosins during wet seasons. Standing water was minimized, as were water table fluctuations, but soil saturation was maintained. Drainage did not change the basic hydrologic cycle or convert wetlands to uplands. A retrospective study on wet flats in Virginia found that ditching significantly lowered the water table in 0- to 3-year-old pine plantations during wet seasons when the water table was close to soil surface (Andrews 1993). At age 23 years, however, the ditching effect was dramatically reduced during the growing season. A study of the ditching effect on water table level in Pomona sand in Florida suggested that ditching affected water table levels up to 45 m from the ditch (2 m deep and 3 m wide) when the water table was within 80 cm of the surface (Segal et al. 1986). Hughes et al. (1990) report no apparent difference in flow volume and seasonal hydrographs among a 16-year-old plantation, unditched natural timber, full stocked pine plantations, mixed plantation/natural watershed, and a ditched natural stand.

Using a paired watershed approach, Amatya and others (Amatya, Skaggs, and Gregory 1996; Amatya et al. 1998; Amatya, Gregory, and Skaggs 2000) studied the effects of controlled drainage on the hydrology, water quality, and storm events of 15-year-old unthinned pine plantations. Controlled drainage involves the use of a gated weir to hold water in the drainage ditches during the dry season. These researchers found that outflow from the watershed under outlet control with a raised weir during the summer through fall period was reduced to 21 percent of gross rainfall, compared with 31 percent for the watershed under free drainage. The controlled drainage reduced both drainage volumes and peak drainage rates. As a result, ET as a residual in water balance was 10 percent higher on average in watersheds with controlled drainage. Controlled drainage treatment did not affect water tables deeper than 1.3 m (Amatya, Gregory, and Skaggs 2000). This treatment, however, significantly ($\alpha = 0.05$) reduced storm outflows for all events and peak outflow rates for most events. Water table depth at the start of the event influenced the effect of controlled drainage on storm event hydrology. In terms of water quality (Amatya et al. 1998), annual average total phosphorus (TP) and ammonium-nitrogen (NH_4N) exports from the watersheds under treatment were reduced by 7–72 percent compared to the watershed under conventional free drainage. Taking into account the characteristic differences that existed when all three watersheds were under free drainage, the reductions in annual average export of total suspended solids (TSS), nitrate-nitrite-nitrogen (NO_3N), and total Kjeldahl nitrogen (TKN) were as high as 47 percent, 16 percent, and 45 percent, respectively. The authors conclude that controlled

drainage treatment can be used to reduce TSS and nutrient exports in surface drainage from pine plantations, primarily through reduced drainage outflows.

At the same site, Amatya, Skaggs et al. (2003) also evaluated controlled drainage with a raised weir and an orifice at the bottom to allow some discharge during storm events to quantify the impacts of such treatment on outflow water characteristics. They reported that the peak drainage rates from watershed with the orifice were substantially dampened, resulting in a 17 percent reduction, on average, of annual drainage outflow compared to a conventionally drained watershed. Measured annual concentrations of nutrients in the watershed with orifice control were reported to be somewhat higher than on the conventionally drained watershed. As a result, despite reduction of flow in all five years (1995–1999), the effects of orifice-weir on NO_3N , TKN, and total nitrogen (TN) were not statistically significant, except for sediment and TP. Using the paired watershed approach at the same site, Blanton et al. (1998) studied the effects of harvesting of 21-year-old pine plantation in one of the watersheds. The authors report that harvesting operations reduced drainable porosity by approximately 50 percent, indicating that these changes may have effects on storm outflow hydrographs.

Lebo and Herrmann (1998) found increased outflow and small increases in nutrient concentrations following tree harvest in coastal watersheds. For a three-year period beginning at harvest, annual outflow, N export, and P export increased 111–164 mm, 2.1–2.2 kg N $\text{ha}^{-1} \text{yr}^{-1}$, and 0.12–0.36 kg P $\text{ha}^{-1} \text{yr}^{-1}$, respectively. Outflow and nutrient concentrations returned to baseline levels within two to three years. On a landscape scale, these relatively small increases in annual nutrient exports associated with harvest and site preparation are further reduced from 4 to 7 percent above baseline levels when placed in the context of a 30- to 35-year growth cycle for loblolly pine in coastal North Carolina.

As part of a watershed-scale study of cumulative impacts of management practices on hydrology and water quality of coastal watersheds, Amatya et al. (2002a) and Amatya et al. (2000, 2001) describe the hydrology and water quality of a 2,950 ha drained managed pine forest over five years (1996–2000). This size is typical of large forest tracts found in the coastal plains of North Carolina. The forested watershed generally yielded no outflows in the summer, except for periods when large tropical storms brought the water table to the surface. Annual ET estimated as the difference of rainfall and runoff was 970 mm on average for five years. The ranges of measured N concentrations at the field edges were 0.5–15 mg L^{-1} for organic soils and 0.3–5.0 mg L^{-1} for mineral soils. The annual total N loading from this watershed varied from approximately 4.8 kg ha^{-1} (1997) to as much as 26.6 kg ha^{-1} (1996), with an average of 14 kg ha^{-1} . Organic N dominated the total nitrogen contents.

Appelboom et al. (2003) evaluated forest road management practices for reducing sediment production and transport from forested watersheds. Their study, using data from the same forested watershed described above, indicates that access roads within these flat, forested watersheds have little impact on the sediment concentration of the drainage waters at the watershed outlet. This result is contrary to the typical findings from upland watersheds. The Appelboom et al. (2003) research indicates that most of the sediment originating from the road surface settles in the slow-moving waters of the ditch network prior to reaching the outlet. In another companion study, Appelboom et al. (2002) showed that a continuous berm maintained along the edge of a forest road can reduce total sediment loss by an average of 99 percent compared to the same type road without a berm. Similarly, a gravel road reduced the total sediment loss by an average of 61 percent compared to the nongraveled road, followed by 56 percent reduction for a 90 cm wide grassed strip compared to nongrass.

Hydrologic Modeling in the Coastal Plain

Most of the results reported above were based on two to four years of continuous monitoring. Although continuous monitoring can provide data for quantifying hydrologic and nutrient balances and on a more spatial and temporal basis, it is rarely possible on a long-term basis. To quantify long-term water and nutrient budgets and the interactions and cumulative impacts of many processes and parameters affecting hydrology and water quality, researchers have developed hydrologic simulation models. When such models are successfully developed and tested, they can be used to identify combinations of practices that will enhance productivity and reduce environmental impact (Skaggs 1980; Hammer and Kadlec 1986; Thomas and Beasley 1986; Guertin, Barter, and Brooks 1987; Heatwole, Bottsher, and Campbell 1987; Heatwole, Campbell, and Bottsher 1987; Parsons, Skaggs, and Doty 1987; Konyha, Robbins, and Skaggs 1988; Konyha, Skaggs, and Gilliam 1988; Beasley and Thomas 1989; Chescheir, Skaggs, and Gilliam 1990; McCarthy 1990). Another important application of hydrologic models for regulatory and legal purposes is the prediction of water table depths and the effects of water management practices on those depths. Models can be used to evaluate whether drainage or other water management and cultural practices cause lands to satisfy or not satisfy legal criteria for wetlands. The ability to simulate the performance of a system over long periods (e.g., 20–40 years) allows examination of water management practices under the wide variability in climatic conditions that occurs in the South.

A model (DRAINMOD) for predicting the effects of drainage practices on outflow from field-scale areas was developed by Skaggs (1978, 1980) for poorly drained agricultural lands. Using approximation analytical methods, DRAINMOD predicts daily infiltration, drainage rate, surface runoff, ET, and soil water storage, based on an hourly water balance calculated for a soil profile at the midpoint between two parallel ditches. DRAINMOD

simulates water table response and soil moisture between ditches for different combinations of surface and subsurface water management practices. Reliability of model predictions has been verified in extensive field experiments (Skaggs and Chescheir 1999). In a study of hydrology of pocosins, Broadhead and Skaggs (1989) compared predicted water table depth, monthly drainage volumes, and runoff hydrographs with experimental data collected for a 25-month period on both natural and drained pocosin sites south of Lake Phelps in Washington County, North Carolina. Predicted water table depths were within 0.1 m and drainage volumes were within 14 percent of observed values. Konyha, Robbins, and Skaggs (1988) used DRAINMOD to evaluate the hydrologic effects of peat mining on an eastern North Carolina pocosin. A computer simulation study of pocosin hydrology using a 33-year period of weather data in DRAINMOD was conducted by Skaggs, Gilliam, and Evans (1991). The pocosins are lands situated on broad, flat basins with poorly drained organic surface soils and shallow water tables. In the model, forest vegetation is simulated by changing the effective rooting depth, which varied from 0.15 m to 0.25 m for natural pocosins to 0.40 m for bedded pine forest. The study showed that average annual runoff predicted for a natural pocosin on a Portsmouth soil increased from 277 mm to 384 mm as the depressional storage was decreased from 300 mm to 5 mm. Conversion from natural pocosin vegetation to a managed pine forest with a deeper rooting zone decreased predicted annual outflow by about 9 percent. DRAINMOD simulation shows that drainage ditch spacing greater than 400 m has no measurable effect on average annual runoff, but year-to-year variation in annual runoff was much greater than the effects of all other factors considered.

DRAINMOD was modified for application to wetlands classification by adding a counter that accumulates the number of times the water table rises above a specified depth and remains there for a given duration. Skaggs et al. (1991) used DRAINMOD with long-term weather data to simulate hydrology of two wetland soils. The authors report that the wetland status of the soils is affected primarily by depth of surface storage and drainage intensity. They also found that the reliability of model predictions could be maximized by calibrating input parameters on the basis of short-term water table monitoring.

McCarthy (1990) modified the subsurface drainage, rainfall interception, and evapotranspiration components of DRAINMOD (Skaggs 1978) and developed a new model, DRAINLOB, to describe hydrologic processes in a drained loblolly pine plantation. McCarthy (1990) and McCarthy and Skaggs (1991) had pointed out possible errors in predictions of drainage outflow rates using DRAINMOD under water table drawdown and fluctuating high-water tables for a hypothetical watershed. Therefore, DRAINLOB uses a nonlinear Boussinesq equation to predict effects of lag time, bank storage, and water table shape on drainage flux that are characteristic of forestry drainage ditches.

Because evaporative loss of intercepted rainfall also may significantly alter the water balance of a forested watershed, an interception component was added to DRAINLOB. The volume of forest canopy interception loss was calculated by the method of Rutter et al. (1972) cited in McCarthy, Flewelling, and Skaggs (1992) and Amatya, Skaggs, and Gregory (1996). Evaporative losses from rainfall interception are first allowed to occur, based on the potential wet canopy evaporation rate calculated by the Penman-Monteith method with zero canopy resistance. When the canopy storage becomes dry, dry canopy transpiration can occur. Evapotranspiration is defined as the sum of dry canopy transpiration and soil evaporation. The hourly potential transpiration is calculated by the Penman-Monteith method, using a stomatal conductance function in the model along with measured leaf area index (LAI) and weather variables (McCarthy, Flewelling, and Skaggs 1992; Amatya, Skaggs, and Gregory 1996). Soil evaporation was calculated as a decreasing exponent of LAI times PET (Thornthwaite method), as suggested by Nutter and McKenna (1983), cited in McCarthy, Flewelling, and Skaggs (1992).

DRAINLOB was tested for predicting daily outflows and water table depths from three experimental watersheds under both conventional free drainage (McCarthy, Flewelling, and Skaggs 1992) and controlled drainage (Amatya, Skaggs, and Gregory 1994). The authors found that a 15-year-old unthinned loblolly pine stand would intercept as much as 1.9 mm of rainfall in a single storm. Cumulative interception may represent 10–30 percent of the annual rainfall, depending on rainfall distribution and canopy density. Test results using a two- to four-year period of data showed that the model can be used with reasonable accuracy for evaluating conventional and controlled drainage treatments on poorly drained soils.

The new algorithms from DRAINLOB (McCarthy 1990) for pine forests were later added to FLD&STRM (Konyha and Skaggs 1992) — a watershed-scale model with a ditch and stream routing component for drained agricultural lands — to develop a watershed-scale forest hydrologic model, DRAINWAT (Amatya 1993). The performance of DRAINWAT was tested with a limited 11-month dataset from a 3,200 ha managed pine forest on poorly drained soils in eastern North Carolina (Amatya et al. 1998). The average absolute difference between predicted and measured daily drainage rates was 0.45 mm day⁻¹. Total cumulative outflow was underpredicted by only 5 percent. The effects of variability of rainfall and potential ET on predicted drainage outflows also were evaluated. Simulations also showed that the effects of clearcutting less than 10 percent of the area on a Cape Fear sandy loam (mineral) soil resulted in a 5 percent increase in annual drainage outflow but only a 2.5 percent increase when the same area was clearcut in Belhaven muck (organic) soil.

Amatya et al. (2002b) performed multiyear and multisite testing of this DRAINMOD-based watershed-scale model (DRAINWAT). One of the sites was a 2,950 ha watershed on a previously studied managed pine forest

(Amatya et al. 1998). The predictions of daily drainage rates and total outflow were in very good agreement ($R^2 = 0.85$; $E = 0.79$) using measured data for a five-year period (1996 through 2000), except for peak flow rates from large tropical storm events, during which measurements may have been in error because of gage overtopping. The watershed-scale model was used in conjunction with a simple in-stream transport and transformation model of first-order kinetics to estimate annual nitrogen loads from this watershed for the same period (Amatya, Chescheir, Fernandez et al. 2003). The method assumes that the decrease in N loads as drainage water moves from the field edge to the watershed outlet is exponentially dependent on transit time and can be described with a single attenuation coefficient. This coefficient, defined as a nutrient delivery ratio, is a function of travel time and the nutrient decay rate — which depends on the season, location in the watershed, and type of nutrients. Travel time is essentially dependent on the velocity of flow, which in turn depends on location and season. The velocity in the ditch-canal network predicted by the model was used to estimate travel time for N movement from the field edge to the watershed outlet via a ditch-canal network. A nitrogen decay rate coefficient based on literature data was used in the first-order kinetics equation. Nitrogen concentrations based on measured and/or extrapolated data were used with predicted daily outflows to compute daily N loadings at each field edge. The results of the annual N loads were predicted within 22 percent of the measured data. The results were compared with a spreadsheet version of the model built upon @RISK (Palisade Corporation 1997) that was further used to conduct uncertainty analysis of model input parameters, such as decay rate, average velocity, and concentrations on estimated nitrogen loads (Amatya, Chescheir, Skaggs et al. 2003).

Synthesis of Silvicultural Water Quality Findings for the Southeast

The dominant water quality issues in southeastern forest management are sediment, roads (as sources of sediment), nutrients, fires (as sources of sediment and nutrients), pesticides, and water temperature. Over the past 50 years, numerous studies have been conducted to evaluate how different types of forest management influence water quality in the South. The following subsections summarize major findings of research into these silvicultural water quality issues.

Sediment

The impacts of forest harvesting on sediment yield are directly related to harvesting methods and road building. When forest harvesting is conducted in a manner designed to preserve water quality, it does not cause significant stream sedimentation (Hewlett 1979). Conversely, abusive logging practices and conversion of mountain forests to agriculture results in significant erosion and stream sedimentation. Long-term effects of forest road construction and harvesting on watershed sediment loading were studied at Coweeta (Swank, Vose, and Elliott 2001). Prior to forest access road construction (~3 km) and cutting, sediment yield averaged 0.23 metric

tons $\text{ha}^{-1} \text{yr}^{-1}$, whereas that from its control watershed was 0.1 $\text{t ha}^{-1} \text{yr}^{-1}$. Most of the logging was completed with a cable yarding system; tractor skidding was restricted to a 9 ha area where slopes were under 20 percent. This treatment resulted in significant increases in water yield and soil loss. The first year following treatment, annual soil loss increased above predicted levels. Accelerated rates of soil loss continued for three years. At that point, the cumulative soil loss was approximately 3.3 times greater than expected (without treatment). The average sediment yield was about 0.34 $\text{t ha}^{-1} \text{yr}^{-1}$, or 50 percent above the pretreatment level at the end of this 15-year experiment (Figure 3-8). The majority of the measured sediment was sourced from road erosion. (All tonnage references in this section are metric tons.)

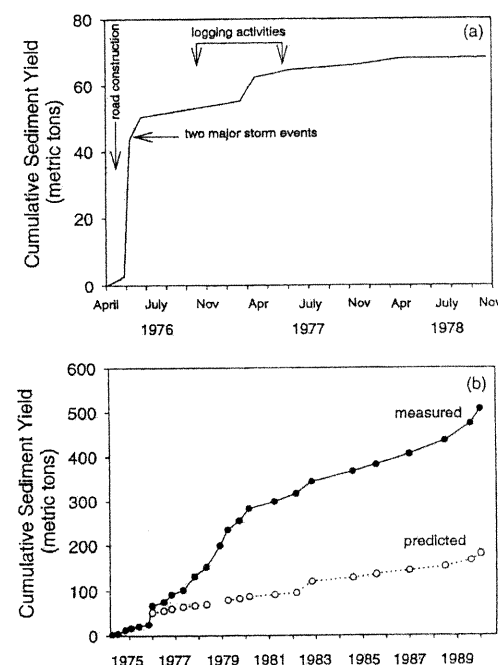


Figure 3-8. Impacts of forest access roads on streamflow sedimentation (from Swank, Vose, and Elliott 2001).

Harvesting trees in the South without soil disturbances generally does not increase sediment levels in runoff, but mechanical site preparation with shearing and windrowing of debris does generate significant sediment pollution (Hewlett 1979; Ursic 1986). However, there are unusual circumstances where this is not the case. Ursic (1991a) compared the hydrologic responses to clearcutting with skidders and logging with a cable yard at a hilly upland site in the southern Coastal Plain in north Mississippi. This study found that skidder harvesting increased sediment only slightly ($0.12 \text{ t ha}^{-1} \text{yr}^{-1}$), whereas cable harvesting increased sediment sixfold

(3.3 t ha⁻¹ yr⁻¹) for the first five years on average. Subsurface flow played a critical role in elevated channel erosion and deposition in this forested landscape (Ursic 1991a). Another study assessing 16 small, mature loblolly pine plantation watersheds on the upper Coastal Plain in Tennessee indicated the importance of channel erosion in affecting sediment loading (Ursic 1991b). This study suggested that harvesting trees growing on previously degraded lands had limited effects (<0.093 t ha⁻¹ yr⁻¹ increase) on sediment loading, usually within four years of treatment.

Mechanical disturbance of the forest floor during harvesting and site preparation is a major concern for future soil productivity and potential soil erosion increases (e.g., Beasley 1979; Hewlett 1979; Beasley and Granillo 1988). Common knowledge suggests that soil structure and site hydrology can be affected by increased disturbance intensity. A study at a Piedmont site in Alabama found, however, that bedding as a site preparation practice for tree planting after clearcutting actually reduced surface runoff compared to a nonbedding site (Grace and Carter 2001), as a result of higher surface roughness and storage created by the former option. Although this was a small-scale study, it demonstrated the uncertainty of hydrologic responses to current silvicultural practices.

Scoles et al. (1994) described 15 years of hydrologic and water quality research from gaged watersheds in the Ouachita Mountains of Arkansas and Oklahoma. They note that soil loss increased 3- to 20-fold following selection and clearcut harvesting. The amount was still low, however — about one-thirtieth that from cropland — and recovery to baseline conditions occurred in the first five years of the 35-year rotation. Most erosion occurred during a few large storms each year, and 90 percent of annual stream sediment came from roads. Projected sediment delivery to streams as a result of harvesting, site preparation, and erosion from roads in the Ouachita Mountains was about 0.16 t ha⁻¹ yr⁻¹. Lawson (1985) reports that undisturbed pine forests in the Ouachita Mountains, Ozark Plateaus, and Boston Mountains averaged less than 0.02 t ha⁻¹ yr⁻¹ of sediment losses. Maximum amounts of sediment losses of 0.13 t ha⁻¹ yr⁻¹ were observed during the first year following clearcut timber harvesting. Recovery to preharvest levels of sediment production had occurred within three years.

A summary of studies on 291 forested basins in eastern United States (Patric, Evans, and Helvey 1984) reports sediment losses ranging from 0.004 t ha⁻¹ yr⁻¹ to 0.8 t ha⁻¹ yr⁻¹, with an average loss of 0.056 t ha⁻¹ yr⁻¹. In an earlier study, Patric (1976) found that sediment losses from undisturbed as well as carefully managed forest land usually range from 0.02 t ha⁻¹ yr⁻¹ to 0.04 t ha⁻¹ yr⁻¹. At the opposite end of the scale, completely forested watersheds in Virginia's mountains lost almost 1.5 in. of soil (more than 80 t ha⁻¹ yr⁻¹) when about 28 in. of rain fell during a single night (Williams and Guy 1973). Given the wide range of human-caused and natural variation, almost any amount of sediment is possible. Accurate separation of naturally produced sediment from human-caused sediment is difficult.

Nevertheless, applicable research leaves little doubt that, given prudent management, routine forest activities cause only minor and transitory increases in sediment production.

Sediment issues in southeastern Piedmont forest lands are complicated by legacy sediments deposited in stream and river valleys by historical row-crop agricultural practices. The history of agricultural practices in this area of the piedmont is well documented (Trimble 1974; Richter and Markewitz 2001). Poor farming practices during the cotton-farming era — approximately 1810 to 1930 — depleted the topsoils and caused deep and large-scale erosion. The early settlers reportedly would lay their rows for crops parallel to the slopes of the hills to obtain better drainage for their crops (Whitney 1919). Many of the gullies in this area formed as a result of these early drainage rows, and at the time of the first soil survey reports many had developed into ravines. The following excerpt, from a speech by H. H. Bennett (1933), Chief of the Soil Conservation Service, on January 31, 1933, describes some of the landscape around the Georgia and South Carolina Piedmont during a soil survey conducted in 1911:

46 thousand acres of stream-bottom, once the most productive soil of the entire state, were classed as Meadow, or land covered with sand and mud washed out of the cultivated hills, and thus made subject to increased overflows due to the choking of channel ways with the debris of erosion... I found on this second trip that the gullies had not stopped with their chiseling away of the fine agricultural lands. They had grown longer, deeper, and wider; they had branched out, forming new canyons. A roadway which I had traveled previously had been moved; it must be moved again. But it can be moved but once more, since yawning ravines are approaching from the opposite direction.

Once a gully was created by poor management practices and extended into the saprolite, large amounts of material moved from the hillslopes and into the stream valley. Glenn (1911) reported that many of these gullies were forming in the Piedmont region and that erosional processes and downcutting through the soil mantle was largely left unchecked.

Trimble (1974) estimated that 10–30 cm of native topsoil were lost during the late 1800s and early 1900s as a result of poor agricultural practices. Trimble (1975) calculated that within the Savannah River watershed, only 4 percent of the soil eroded from the Piedmont uplands since the 1700s has been carried past Augusta, Georgia. This erosion resulted in the transport of much sediment into Georgia's Piedmont streams. Much of this sediment is still mobile in Piedmont streams, and it complicates efforts to quantify current sediment inputs from silvicultural and other activities.

Roads

Forest access roads can be considered long, linear ribbons of compacted earth that can create and route overland flow and sediment to stream systems. Sediment budgets in commercial forest lands often are dominated by road contributions. Traditional methods of forest road construction

and maintenance have resulted in large increases of forest soil erosion and stream sedimentation. Numerous road construction practices that minimize erosion and sedimentation have been identified. Examples of these practices are coarser paving gravels, grassing of road beds, construction of broad-based dips, brush sediment barriers along road margins, and road buffer strips (Douglass and Swift 1977). A great deal of research has been conducted in the Southeast to investigate how to reduce sedimentation from forest access roads. Many of these studies were conducted at Coweeta and Fernow (Table 3-7). Swift (1988) provides a comprehensive summary of Coweeta's road experiments and the results.

Table 3-7. Summary of Road-Related Sediment Studies Conducted at Coweeta and Fernow

Research Subject	Coweeta Results	Fernow Results
Soil loss from ineptly located and managed logging roads	6,850 yd ³ of soil eroded from 2.3 mi. of road (Hoover 1952)	Road surfaces lowered 0.9–1.2 in. during 1 year (Trimble and Weitzman 1953)
Soil loss from well-located forest roads	2–115 t ac ⁻¹ yr ⁻¹ (Swift 1984a)	2–80 t ac ⁻¹ yr ⁻¹ (Kochenderfer and Helvey 1987)
Flood frequencies and culvert sizes needed to convey flow beneath roads	Results applicable to most of southern Appalachian Region (Douglass 1974)	Higher peak flows in central Appalachian region require larger culverts (Helvey 1981)
Distances soil eroded from roads, then was carried across the forest floor	Average distance ranged from 32–112 ft, with BMPs (Swift 1986)	Distance less than 200 ft at 33 sites, farther at 7 sites, no BMPs (Patric and Kidd 1982)
Principles of road design to minimize soil erosion	Wide-ranging treatment in rather technical terms (Swift 1984b)	Basic principles in nontechnical terms (Kochenderfer 1970)
Layman's guide to forest road building	Somewhat technical (Swift 1985)	Slide/tape program (Kochenderfer, Wendel, and Kidd Undated)
Soil loss from adequately located and managed logging roads	General discussion of erosion control and soil losses (Swift 1985)	Soil losses from minimum standard logging road (Kochenderfer, Wendel, and Smith 1984)
Unused roads stabilize soon after logging discontinued	Easily reopened by clearing revegetation (Douglass and Swank 1976)	Reforestation reduces road prism width (Kochenderfer, Edwards, and Wood 1997)

Road experiments at Coweeta began in 1934 with the establishment of Coweeta Hydrologic Laboratory. The first studies were conducted by C.R. Hursh in a successful attempt to reduce erosion and required maintenance. Hursh demonstrated that significant reductions in soil loss from forest roads could be made by mulching or vegetating the adjacent cut and fill slopes (Hursh 1935, 1939, 1942; Swift 1988). Hursh conducted numerous studies that identified the best construction methods for forest roads and employed bioengineering to stabilize slopes (Swift 1988). Although facilitating the construction of roads was a major motivation for this

research, streams benefited from significant reductions in sedimentation following road construction. Hursh's work laid the foundation for subsequent research that specifically addressed the impacts of roads on stream water quality.

Forest road impacts on stream sedimentation were investigated in the exploitive logging research on watershed 10 (see section on Coweeta experiment station), in which loggers were allowed to construct roads and timber access in a manner typical of that time. This activity included construction of skid trails directly upslope, adjacent to, and within streams (Swift 1985). These practices resulted in the loss of 408 m³ of soil per km of road constructed (Lieberman and Hoover 1948a). Sediment delivery to streams was high and turbidity peaked at 5,700 ppm (Lieberman and Hoover 1948b), significantly reducing downstream aquatic fauna (Tebo 1955). Road erosion became such a problem that the roads had to be closed and stabilized. It was concluded that the sedimentation observed in the stream resulted almost exclusively from road erosion rather than from other forest harvesting activities (Swift 1988).

A subsequent series of experiments was conducted to determine how sound watershed management practices would affect timber harvesting operations. Two watersheds (numbers 40 and 41) were selected for this study. Although both watersheds were slated for harvesting, watershed 40 was to be managed for water production and watershed 41 was to be managed to maximize timber production (Swift 1988). Road construction practices on watershed 40 were tightly controlled. This control included restrictions on road placement, road width, vehicle operations, skidding and yarding, and stream crossings, as well as the use of outward sloping roads and employment of vegetative runoff and erosion control measures. The techniques employed on watershed 40 were successful in protecting water quality. Construction techniques, maintenance requirements, and relatively high initial cost requirements were deemed impractical by timber managers and loggers (Swift 1988). This led to the Stamp Creek demonstration project in 1956. Over a four-year period, local foresters and loggers conducted harvesting operations while receiving consultation on road design from Coweeta Hydrologic Laboratory. The road maintenance and construction techniques employed in this study proved to be economically more feasible than those in the watershed 40 experiment. No significant impacts to water quality, as determined through turbidity monitoring, occurred as a result of the forest harvesting or road network (Swift 1988).

In a further effort to improve existing forest road erosion and runoff control measures, scientists at Coweeta began a multiple resource management experiment in 1962. This experiment resulted in development of the broad-based dip for forest road construction. Previously engineers had relied on water bars and ditches to collect and drain runoff from road surfaces. In this study, roads were sloped outward and inside ditches were eliminated. This arrangement allowed runoff to flow as sheet flow rather

than concentrating and forming channels. On steeper road segments, water bars were replaced with broad-based dips in the road surface that directed runoff off the road surface and onto the forest floor (Cook and Hewlett 1979). This technique prevented concentration of surface runoff and allowed for infiltration of runoff water on the forest floor rather than allowing it to channelize and flow to the nearest stream. The broad-based dips were constructed by creating a 6 m wide, 3 percent upslope grade on the roads. The dips were also sloped outward at 3 percent to direct flow off of the road surface. The elimination of ditches, outslipping of roads, and use of broad-based ditches greatly reduced runoff and erosion from the roads in this study. Consequently, these methods were adapted as standards for forest road construction by the national forests in Region 8 of the USDA Forest Service (Swift 1988).

Despite advances made in reducing the erosion and transport of sediment away from forest roads, scientists at Coweeta felt that forest roads were still generating too much sediment and runoff. Consequently, efforts were undertaken to improve the durability of active forest roads and reduce the erodibility of roads that received light traffic. In 1976 Swift began a series of experiments to determine how various road surface treatments affected erosion rates. The treatments were installed on forest roads composed of two soil types and included bare soil, grassed roadway, and a variety of aggregate road beds. Runoff and sediment from the treatment roads were monitored over a three-year period. Soil losses from all treatments were greatest immediately following construction. Subsequent pulses of soil loss were triggered by intense rainfall events. Road surface type was significant in reducing loss rates. Soil losses from bare roadbeds were eight times those from graveled roadways. The erosion rates declined in the ensuing six months, but losses from the bare soil were still six times greater than those observed from the gravel treatments. The largest losses came from roads that experienced logging traffic. Roads protected by thinner layers of rock experienced losses similar to those observed with bare soil when logging trucks were present. Large crushed stone (20 cm) afforded the most protection against erosion; however, it was deemed too coarse for many vehicles. Medium crushed rock (15 cm) provided roadbed protection similar to that observed with the 20 cm stone but at a significantly reduced cost. Erosion rates from fine crushed rock (5 cm) roadbeds were similar to those from bare soil. On lightly traveled roads, seeding of roadbeds and cut and fill slopes reduced erosion rates by 50 percent from that observed under bare soil conditions (Swift 1984a).

The specific sources of sediment from road erosion also are important because they influence where erosion control efforts should be concentrated. Swift (1984b) monitored erosion rates from roadbeds, cut slopes, and fill slopes along the series of road treatments described in the preceding paragraph and in Swift (1984a). Although soil losses from all surfaces were high during heavy rains, erosion rates on bare cut and fill slopes

accounted for 70–80 percent of total soil losses from the sites. In a test of integrated sediment control options, graveling of the roadbed reduced soil losses to less than 20 percent of the bare soil condition; the combined treatments of vegetating the cut and fill slopes along with graveling the roadbeds reduced total erosion rates to less than 10 percent of the pretreatment condition (Swift 1984b). Despite these improvements, Swift reported that the net loss of soil from the entire roadway was 20 times greater than that estimated for undisturbed forest.

The combination of road construction practices and treatments outlined above significantly reduces the erosion and transport of soil away from forest roads (Swift and Burns 1999). Through proper design, filtering of runoff from forest roads can be induced by directing flow onto the natural litter layer of the forest floor (Swift 1985). In extremely steep terrain, this filtering may not be sufficient to arrest sediment-laden flows. Forest roads still generate significant amounts of sediment that frequently end up in streams and impairs water quality. The proximity of a road to a stream or drainage way is one of the leading factors in determining whether eroded sediments will impair streams. Thus, proper design and placement of roads adjacent to streams, as well as stream crossings, are very important. Consequently, guidelines for proper design and sizing of stream crossings have been developed for the southern Appalachians (Douglass 1974; Swift 1985).

Employment of filter strips along roads also mitigates the propagation of road sediment through a drainage network and into streams. Although filter strips normally include natural vegetation, their performance may be augmented by using trees and woody slash material to form brush barriers. Such materials are readily available from trees cut during road construction and residual forest harvesting materials. Studying forest roads in the mountains of southwestern North Carolina, Swift (1986) quantified the benefits of filter strips in arresting the propagation of sediment-laden flows off road surfaces. Whereas the average transport distance for all sites ($n = 88$) was 22 m, the average distance from bare fill sites was 34 m. Grass cover reduced this distance by approximately 40 percent. The use of brush barriers below road fills reduced the mean and maximum distances by half. In addition, Swift found that natural forest litter was instrumental in inhibiting transport. Sites that had forest litter removed by fire treatments had transport distances 50 percent greater than those with natural forest floors. Sites that had fill slopes protected by grass cover and diverted runoff through forest litter and brush barriers provided the most resistance to flow (Swift 1986). Based on transport distances, Swift established standard widths for forest road buffers as a function of slope and brush barrier construction.

Researchers at Coweeta are continuing their investigations into the dynamics of forest road erosion, sediment transport, and stream sedimentation. Clinton and Vose (2002) investigated the effectiveness of road

paving in reducing the delivery and transport of sediment from forested mountain roads in the southern Appalachians on four road surface types: two-year-old pavement, improved gravel, improved gravel with sediment control, and unimproved gravel. The paved road system generated the least sediment; the unimproved road generated the most. The distances of sediment transport away from the roadbed were (in order of decreasing distance) paved, improved gravel, improved gravel with sediment control, and unimproved. Riedel and Vose (2002a) subsequently reported that not only do roads increase stream sedimentation, roads and road usage levels change the nature of stream sediments. The stream sediments in their southern Appalachian study watersheds shifted from a predominantly organic composition (80 percent organic during baseline conditions) in forested benchmark streams to a predominantly mineral composition (20 percent organic during baseline conditions) in watersheds impacted by forest roads and residential development.

In an effort to quantify and predict the effects of road sedimentation and forest road BMPs, Riedel and Vose (2002b) conducted a validation study of GIS-based cumulative effects sedimentation models. They found that the resolution of input data is as important as model mechanics; increasing input data resolution from 90 m to 30 m to 10 m increased model predictive strength (predicted versus observed correlation coefficients) fourfold. These results were used to identify optimal locations of implementation of forest road BMPs. Following an initial pulse of sediment from site disturbance, the BMPs reduced sediment yield by 50 percent (Riedel and Vose 2003).

Timber Harvest Effects on Stormflows

Results of southeastern studies on storm flow effects of timber harvest have been consistent with studies elsewhere in North America. As a result of reduced summer evapotranspiration in clearcuts and young plantations, canopy removal increases flow volumes and peaks for storms occurring during the growing season and for early fall storms (Patric and Reinhart 1971; Hewlett and Doss 1984). In forests, early fall storms produce little or no runoff because soils dried out by a summer of evapotranspiration absorb and store most precipitation. In comparison, soils on clearcut sites are wetter and thus become more responsive earlier in the fall. Fall flow events usually are small, however, compared with winter events and events driven by intense summer thunderstorms. During winter, when most large runoff events occur, there is little difference between soil moisture levels in clearcuts and forests, and studies have revealed little difference in flow peaks for large and infrequent flow events (Hewlett and Helvey 1970; Hewlett and Doss 1984; Helvey and Kochenderfer 1988; Kochenderfer, Edwards, and Wood 1997).

The effects of timber harvest and site preparation on storm flows vary with the amount of bare soil exposed, the amount and locations of road surfaces, the connectivity of road runoff to streams, time since harvest,

season, size of watershed, and size of storm. Therefore, peak flow effects from timber harvest show significant variation between studies and vary between undetectable (Kochenderfer, Edwards, and Wood 1997) and as much as a 35 percent increase in peaks on a highly impacted 80-acre piedmont watershed (Hewlett and Doss 1984). Working at Fernow, Kochenderfer, Edwards, and Wood (1997) studied the effects of selective harvest to 35.6 cm stump diameter with skidroads on contour and 10 percent road coverage on a 39 ha watershed. They found no statistical or apparent difference in annual peakflows following harvest. They did find some increase in growing season peaks and in stormflow volumes (magnitude not reported). Similarly, Helvey and Kochendorfer (1988) found that "a commercial clearcut that removed 74 percent of basal area from a 74-acre watershed and a harvest that removed 91 percent basal area from an 85-acre watershed had no effect on annual peak flows."

Nutrients

Nutrient concentrations in forested basins may be affected by fertilization, nutrient release after clearcutting, insect outbreaks, and fire. Change of streamwater chemistry is one important signature of ecosystem response to watershed disturbance. The impacts of forest harvesting on water chemistry and nutrient export were reported in several papers developed at Coweeta (Johnson and Swank 1973; Douglass and Swank 1975; Swank and Swank 1981; Swank and Vose 1994; Swank, Vose, and Elliott 2001). Research into forest harvesting impacts on water chemistry has shown that relatively minor increases in nutrient export occur immediately after harvesting. Johnson and Swank (1973) analyzed long-term water chemistry responses (Ca, Mg, K, and Na). They found that over the duration of experimental record, clearcutting treatments have not caused substantial losses of Ca, Mg, K, and Na. Increases following harvesting decline rapidly with time as streamwater chemistry returns to near-baseline conditions. Continued increases in $\text{NO}_3\text{-N}$ have been observed following harvesting of deciduous trees and may result from a combination of species composition shifts, mineralization in response to forest floor decomposition, and altered soil nutrient cycling. Conversely, reductions in nutrient export occur following conversion of grasses to forest and mixed deciduous forest to eastern white pine. As with anthropogenically driven changes in forest composition, reductions in forest standing crop resulting from insect outbreaks at Coweeta increased nutrient export. The duration and magnitude of these impacts are directly related to the life cycles and population density of infesting insect species.

Converting hardwoods to white pines at Coweeta not only reduced water yield, it also altered streamwater quality (Swank and Vose 1994). During the 20 years following initial treatment, streamwater solutes generally were similar between the pine-covered watersheds and the mixed hardwood control watersheds, except for $\text{NO}_3\text{-N}$ and SO_4^{2-} . Flow-weighted mean $\text{NO}_3\text{-N}$ concentrations increased slightly (0.1 mg L^{-1}); SO_4^{2-} concentrations

increased nearly threefold. Like Johnson and Swank (1973), Swank and Vose (1994) report reductions in average losses of calcium, magnesium, potassium, and sodium of 2.3, 1.7, 4.4, and 1.2 kg ha⁻¹ yr⁻¹, respectively.

Swank, Vose, and Elliott (2001) contrasted the long-term water chemistry records of a grazing and clearcut watershed with its associated control watershed. Increases in nutrient export occurred following harvesting; the largest — though still relatively small — losses occurred during the third year following treatment. Export increases frequently were lower than background rates of atmospheric deposition (watersheds are a sink for nutrients). Similarly to previous results, the nutrient losses returned to baseline levels within a few years after treatment. Unlike in previous studies, a second phase of increased NO₃-N losses was found beginning 14 years after treatment. The authors hypothesize that there were several potential factors contributing to the elevated NO₃-N export, including mortality and shifts in species composition, nutrient releases from decomposition, elevated soil nitrogen transformation, and reductions in the soil C to N ratio.

Qualls, Haines, and Swank (1991) and Qualls et al. (2000, 2002) have conducted extensive research on the dynamics of soluble organic nutrients in undisturbed and harvested forest ecosystems at Coweeta. The forest ecosystems retained more than 99 percent of water soluble organic C, N, and P produced in litterfall, throughfall, and root exudates. Although cutting increases organic fluxes in these ecosystem compartments, soil retention mechanisms efficiently buffer against leaching of organic nutrients to streams after clearcutting.

Fertilization with N and P to increase tree growth potential is common in the South. A study on the North Carolina Coastal Plain suggests that fertilization resulted in elevated concentrations of NH₄ up to 3.8 mg L⁻¹, urea up to 1.2 mg L⁻¹, total N up to 9.3 mg L⁻¹, total P up to 0.18 mg L⁻¹, and orthophosphate up to 0.1 mg L⁻¹, measured in the soil at the field (27 ha) edges. Three weeks after treatment, concentrations of all ions returned to pretreatment levels. Concentration of nitrate-N ranged from zero to 1.2 mg L⁻¹ during the 60-day monitoring period (Campbell 1989). Similar findings in the Coastal Plain are reported in Segal et al. (1986) and Riekerk (1989b). More information about fertilization impacts on water quality for other physiographic regions can be found in NCASI (1999a). In general, fertilization on forest lands rarely caused nitrate-N concentration in streams exceeding the Environmental Protection Agency's (EPA) drinking water standard of 10 mg L⁻¹, especially if care was taken to avoid direct application to streams.

The long-term streamwater chemistry monitoring efforts at Coweeta Hydrologic Laboratory have established baseline conditions for control watersheds. Unanticipated deviations from normally observed concentrations cause researchers to take notice. Such was the case when Swank et al. (1981) investigated increased nitrate levels on watershed 36 and found that they were the result of insect defoliation. In 1969 defoliation of the

mixed hardwood forest on watershed 27 by fall cankerworm was observed (Swank 1988). During the ensuing years of the infestation, average monthly nitrate concentrations, as NO₃-N, rose significantly. Peak nitrate levels occurred in conjunction with the period of maximum outbreak and defoliation in 1974. With the decline of the cankerworm population, nitrate concentrations approached those of the baseline conditions. Thus, when scientists observed a similar pattern of increasing nitrate concentrations on watershed 36, they suspected that the cankerworm infestation had spread. An inspection of the watershed in 1974 revealed an increase in cankerworm egg mass on surveyed trees. As with watershed 27, nitrate concentrations returned to baseline conditions as the cankerworm outbreak subsided (Swank 1988). A comprehensive discussion of the mechanisms responsible for this phenomenon has been published (Swank et al. 1981).

A similar response of stream nitrate levels to insect infestations occurred on Coweeta watershed 6. Following the forest-to-grass conversion treatment in 1965–1967, watershed 6 was allowed to undergo natural succession. During this period, “mean annual NO₃-N concentrations in streamwater gradually declined from about 0.75 mg L⁻¹ in 1972 to 0.50 mg L⁻¹ in 1978...” (Swank 1988). Nitrate concentrations then suddenly rose back to 0.75 mg L⁻¹. This rapid increase in nitrate export occurred in conjunction with a widespread outbreak of the locust stem borer in a pioneer species, the black locust. As the outbreak continued, mean annual NO₃-N concentrations continued to rise. As infestations peak and black locust mortality sets in, creating gaps favorable for early successional species, Boring and Swank (1984) hypothesize that NO₃-N concentrations would tend toward baseline levels.

A synthesis of the long-term dynamics of inorganic N for Coweeta watersheds (Swank and Vose 1997) finds the following: (1) Control watersheds are highly conservative of N, with atmospheric deposition <9.0 kg ha⁻¹ yr⁻¹ and stream exports below 0.25 kg ha⁻¹ yr⁻¹; (2) streams draining control watersheds show significant time trend increases in annual NO₃ concentrations and increases in seasonal amplitude and duration of NO₃ concentrations during the period 1972–1994; (3) streamwater chemistry trends are partially attributed to significant increases in inorganic N concentrations in bulk precipitation and/or reduced biological demand resulting from forest maturation; and (4) for disturbed watersheds, stream inorganic N data provides evidence for stages 1, 2, and 3 of watershed N saturation.

Clinton et al. (2002) summarize the research results from four experiments examining stream nitrate (NO₃-N) responses to forest fires in the Nantahala National Forest in western North Carolina. A fell and burn fire (Jacob's Branch) and two stand replacement fires (Winespring Creek and Hickory Branch) were implemented as prescriptions to improve degraded xeric oak-pine forests. The fourth (Joyce Kilmer) fire was an arson-related wildfire, burning the understory in an old-growth mesic-xeric forest. The Jacob's Branch and Joyce Kilmer fires occurred in the fall; the fires on

Winespring Creek and Hickory Branch were spring burns. Stream nitrate was elevated following the burns on Jacob's Branch and Joyce Kilmer, whereas no stream nitrate response occurred with the two spring burn sites (Table 3-8). Clinton et al. (2002) surmise that N released during the spring burns was immobilized by vegetation uptake, whereas N released during the fall burns was not.

Table 3-8. Increases in Streamwater $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ following Fire

Study	Burn Type	Season	Mean (mg L ⁻¹)		Max (mg L ⁻¹)		Impact duration	Citation
			$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N}$	$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N}$		
Jacob's Branch	Fell and burn	Fall	0.030	0.00	0.075	0.00	8 mos	Knoepp and Swank (1993)
Joyce Kilmer	Arson wildfire	Fall		0.00	0.12	0.00	6 wks	Clinton et al. (2002)
Winespring Creek	Stand replacement	Spring	0.00	0.00	0.00	0.00	0 mos	Vose et al. (1999)
Hickory Branch ^a	Stand replacement	Spring	0.00	0.00	0.00	0.00	0 mos	Clinton et al. (2002)

^aSlightly elevated levels of $\text{NO}_3\text{-N}$ were detected for two weeks following the burn in an upper reach of Hickory Branch creek, immediately adjacent to the burn site. However, no changes in streamwater $\text{NO}_3\text{-N}$ were detectable at the monitoring site located at the outlet of the watershed encompassing the burn area.

Table 3-9. Mean Increases in Stream Water Constituents following Fire and Fertilization, in mg L⁻¹ (adapted from Neary and Currier 1982)

Subwatershed	Treatment and Comments	$\text{NO}_3\text{-N}$	$\text{PO}_4\text{-P}$	Na	K	Ca	Mg
Crane Creek	Undisturbed	0.004 a ¹	0.012a	0.989 a	0.501 a	0.571 a	0.327 a
Wash Branch	Partial burn	0.012 b	0.013	1.245 c	0.617 c	0.863 c	0.440 c
Jumping Branch	Partial burn plus fertilizer	0.051 c	0.021	1.154 b	0.606 bc	1.040 d	0.478 d
Crossland Creek	Total burn plus fertilizer	0.049 c	0.013	1.359 d	0.695 d	0.967 d	0.441 c
Townes Creek	Confluence of Crane, Crossland, and Wash Branch	0.012 b	0.011	1.210 bc	0.566 b	0.709 b	0.386 b

¹Values followed by different alphabetical characters are significantly different at $\alpha = 0.05$. Values followed by same characters are not significantly different.

The Jumping Branch Fire, an unrelated wildfire, burned 1,093 ha of the Blue Ridge Mountains of South Carolina in 1978. For one year after this fire, Neary and Currier (1982) monitored stream chemistry ($\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$, Na, K, Ca, and Mg) and total suspended solids from five streams. Of these streams, Crane Creek was undisturbed, Wash Branch was partially burned, Jumping Branch was partially burned and fertilized, and Crossland Creek was completely burned and fertilized. Townes Creek was

downstream of the confluence of Crane, Crossland, and Wash Branch (Neary and Currier 1982). Increases in streamwater nitrate, $\text{NO}_3\text{-N}$, were attributed to the fertilizer applications. Elevated concentrations of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ in streamwater were largely confined to storm flow events; mean concentrations were not statistically higher than those observed on the undisturbed Crane Creek (Table 3-9). The anions, Na, K, Ca, and Mg ranged from 12 percent to 82 percent above background levels during the monitoring period (Neary and Currier 1982).

Water Temperature

Forest harvesting along streams usually results in increased stream temperatures (Swift 1973; Wooldridge and Stern 1979; Swift 1982). Swift and Messer (1971) monitored stream temperatures in nine watersheds that included both treatment and control watersheds. On the watersheds that experienced complete harvests, summer stream temperatures increased from an average of 19°C to more than 23°C. The most intensive treatments raised temperatures by more than 7°C. Conversely, water temperatures in streams with uncut streamside or riparian vegetation showed no increases in stream temperature. In addition, temperatures in the impacted streams returned to pretreatment levels with subsequent regeneration and shading provided by riparian vegetation. The observed temperature increases significantly altered streamwater quality as water temperatures were raised above levels that were unsuitable for the native trout populations (Swift and Messer 1971).

In a subsequent study, Swift (1973) investigated the effectiveness of preserving a 12 m buffer of streamside vegetation in mitigating potential streamwater temperature impacts resulting from forest harvesting on a small, mountain watershed. The stream flowed through alternating patches of cut and uncut riparian zones. Water temperature rapidly increased by 6°C as the stream flowed through a 900 m cut area. Then the temperature decreased by approximately 1°C as the stream flowed through a 800 m downstream, uncut riparian area, and it subsequently increased again somewhat as the stream flowed through a 200 m cut area. The stream temperature eventually stabilized to normal (12.8°C) after passing two forested sections (2,100 m). The alternating network of cut and uncut riparian areas limited maximum water temperatures to less than 20°C — a temperature given as an indicator of trout habitat impairment.

Swift (1982) reported long-term impacts of cable logging on streamwater temperatures. The first two years following cable logging, average summer stream (38 percent shaded) water temperatures had increased 3.3°C. Regeneration of streamside trees by stump and root sprouts increased streamside leaf biomass to 78 percent of the pretreatment condition within three years following treatment. Subsequent temperature increases averaged 1.2°C. Minimum temperatures were elevated only in the first year of treatment; the daily temperature range (minimum-maximum) was elevated during the five years of the study. Streamwater temperature increases were

predicted to decrease at a rate of 0.3°C per year, ultimately returning to pretreatment levels.

Pesticides

Pesticides have been increasingly used in the South to control insects and weeds. Potential pollution by these materials can result from direct aerial application, aerial drift or volatilization, leaching and transport by subsurface flow, and transport adsorbed to suspended particles. Because these chemicals can be important tools to accelerate forest growth and combat pest outbreaks, a substantial amount of research has been conducted in the South to understand the fate of applied forestry pesticides (Neary 1983; Neary et al. 1985; Michael and Neary 1990; Neary, Bush, and Michael 1993; USDAFS 1994; Neary and Michael 1996). The literature suggests that the risk of long-term contamination from pesticide application is low when care is taken. Although each chemical or biological agent (e.g., *Bacillus thurengiensis*) has its own properties, residues generally are not persistent (especially for more recently adopted chemicals) and do not bioaccumulate. A review of herbicide data shows that when herbicides are not applied directly to streams and when buffer strips are used, peak residue concentrations generally are low (<500 ppb), and residue levels in surface runoff generally are less than 36 ppb for ground application or less than 130 ppb for aerial applications (Riekerk, Neary, and Swank 1989). A recent review of herbicide toxicity to wildlife found that most herbicides used in modern silviculture are of low toxicity to aquatic and terrestrial organisms (Tatum, Shepard, and Wigley 2002) and thus pose little hazard to wildlife.

This assessment in no way absolves forest chemical applicators of any concerns about their application of chemicals. Inappropriate application methods can result in direct entry or excessive drift of chemicals into streams. Although the toxicity of most commonly used forest chemicals is low for aquatic organisms, there is some toxicity. Models such as AgDRIFT provide an opportunity to test application equipment and operation variables to confirm that planned applications will minimize any water quality impacts (Teske and Ice 2002). Through mechanisms described herein (e.g., leaching and lateral subsurface transport to the stream or transport attached to suspended particles), even well-placed chemicals may reach streams — although usually at very low concentrations. Preferential flow-paths in forest soils can result in some bypassing and delivery of chemicals to streams. Nevertheless, forest sites tend to have less pesticide loss than nearby agricultural sites because applications are infrequent over the rotation of a stand and do not accumulate over time, and forest soils have generally higher organic matter, which provides for pesticide sorption and decomposition.

BMP Effectiveness Studies

Forestry best management practices (BMP) to minimize nonpoint pollution from forestry activities have evolved over time and have been developed largely on the basis of observations from long-term hydrologic

studies and the water quality research described in this chapter. Recognizing the high infiltration capacity of forest soils, BMPs are designed to minimize the amount and duration of bare soils and to reduce the hydraulic connectivity of runoff from bare soil areas to streams. Although specifics vary from state to state, all state forestry BMPs share the following basic recommendations:

- Minimize bare ground coverage and soil compaction.
- Separate bare ground from surface waters.
- Inhibit hydraulic connections between bare ground and surface waters.
- Avoid disturbance on steep convergent slopes.
- Separate fertilizer and pesticide application from surface waters.
- Provide a forested buffer around streams.
- Engineer stable road surfaces and stream crossings.

Specifics of these guidelines vary between states with respect to elements such as streamside management zone (SMZ) widths, allowance of thinning within SMZs, spacing recommendations for water diversions on logging roads, road surfacing recommendations, and so forth. Some of these differences are related to sociopolitical differences between states, some to differences in silvicultural techniques, and some to general physiographic differences between regions that make certain water quality issues more or less important in those regions. (See www.usabmp.net.)

Because the forest industry relies on BMPs to meet water quality protection requirements of the Clean Water Act, BMP effectiveness studies are an active area of research in the Southeast. Southeastern BMP effectiveness studies published since 1990 include Kochenderfer and Edwards (1990); Adams et al. (1995); Arthur, Coltharp, and Brown (1998); Keim and Schoenholtz (1999); Williams et al. (1999); Wynn et al. (2000); Vowell (2001); Williams, Hook, and Lipscomb (2001); Williams et al. (2002), and Carroll et al. (2004). These studies used a variety of study designs, including paired watershed experiments, cross-landscape comparisons, and upstream-downstream comparisons. Furthermore, most of these studies were interdisciplinary and considered a suite of water quality factors, including temperature, sediment, nutrients, in-stream habitat structure, and benthic macroinvertebrate communities. Taken together, these studies demonstrate that modern BMPs substantially mitigate nonpoint pollution from forestry activities at the site scale, although the BMPs are not 100 percent effective. These studies also demonstrate that the biotic and chemical noise in larger streams renders the water quality effects of forestry activities using BMPs undetectable. In other words, the water quality effects of modern forestry are very small in comparison to spatial and temporal variability in water quality in larger streams.

Williams et al. (1999) provide an intriguing comparison of management impacts with and without BMPs, using a retrospective comparison to the

earlier study by Hewlett (1979) at the B.F. Grant Memorial Forest in the piedmont. Recall that Hewlett indicated that most of the increased sediment observed at the time of harvesting and reforestation came from roads and channel disturbance. Hewlett estimated that with properly designed and maintained roads, effective SMZs, and careful site preparation and planting methods, 90 percent of the increase in sediment could be avoided. Williams et al. (1999) monitored sediment and other water quality impacts from timber harvesting operations on Piedmont watersheds where state BMPs were applied. They found that much of the sediment yield increases observed after timber harvesting resulted from increased channel flow (as a result of reduced evapotranspiration with removal of the vegetation). They found small but significant increases in sediment concentrations immediately after harvesting, even with BMPs. Nevertheless, the increases were small, especially compared with those measured by Hewlett (1979). Williams et al. (1999) estimated that the BMPs reduced sediment yield increases tenfold compared with the earlier study — just about what Hewlett had estimated.

Continuing and Emerging Issues and Final Thoughts

Forestry BMPs are voluntary throughout the Southeast, and only one state requires a permit for silvicultural activities. This nonregulated environment for water quality protection allows greater market flexibility for forest products industries. Decisions regarding harvest and site preparation can be made on the basis of market and cash flow considerations, without the expense of permitting delays. To maintain this flexibility, the forest products industry must be able to demonstrate to the public and to water quality management agencies that forestry BMPs are implemented and effective. Furthermore, the effectiveness of BMPs must be assessed cumulatively, at a watershed scale, to calculate the contributions of forest activities to a Total Maximum Daily Load Program (TMDL) for a basin. This effort will require development of process-based models of BMP performance linked with in-stream models of pollutant transformations and transport.

Modern forestry operations in the southeastern United States usually are superimposed on a landscape with a long history of intensive (sometimes referred to as abusive) agriculture that preceded forestry as the dominant land use of many areas of the South. For example, upland erosion in the southeastern Piedmont from approximately 1810 to 1930 totaled 16–30 cm (Trimble 1974). Most of this sediment is still in valley storage. Therefore, in-stream habitat and biotic conditions are still largely influenced by legacy impacts of historic land use. Additional work is needed to conceptually reconstruct presettlement conditions and to account for historic sediment in water quality evaluations.

Often we have idealized expectations about the quality of water coming off forest watersheds. The water quality coming off forest watersheds is uniformly better than the quality of runoff from watersheds in other land uses. Given the diversity of forest and watershed conditions shown here for

the South, from mountains to wetlands, however, it should not be surprising that the quality of water for even least-impaired watersheds in this region can vary widely and may not achieve idealized criteria. Ice and Binkley (2002) review EPA-proposed, ecoregion-based national water quality criteria for total nitrogen and total phosphorus. They found that many small forest streams would not achieve these proposed criteria, even where these streams arose from undisturbed research control watersheds. In the southern Coastal Plain, the control watershed for the Santee in South Carolina provides an excellent example of this problem: Runoff from this watershed couldn't meet either proposed total nitrogen or total phosphorus criteria. The Santee, like some other wetlands, was found to have especially high organic nitrogen loads. Another study by Ice and Sugden (2003) found that the majority of least-impaired streams monitored could not achieve the dissolved oxygen criteria for Louisiana in the summer. Criteria for judging water quality must be physically achievable and biologically relevant.

The South presents an enormous challenge to foresters, forest hydrologists, watershed managers, and aquatic biologists. The region comprises tremendous forest and watershed diversity (as presented in this chapter), high timber values, abundant and diverse aquatic species, and overabundant demands on water resources. The body of work reviewed in this chapter demonstrates that we have learned many important lessons about how to manage forest watersheds to achieve substantial protection of essential beneficial uses of runoff. We summarize some of these lessons below.

KEY LESSONS LEARNED IN THE SOUTHEAST

- Water yields increase following timber harvesting and site preparation, largely as a result of reduced evapotranspiration.
- Stormflow volume and maximum peak flows also tend to increase following harvesting, in response to changes in soil moisture storage available (as a result of evapotranspiration and interception changes) and other factors, such as modified soil characteristics after disturbance.
- Water yields and changes in storm runoff diminish with revegetation of sites.
- Erosion and sedimentation following harvesting, site preparation, and planting, although relatively small compared to that under other land uses, can be significant increased over rates measured for undisturbed forest watersheds.
- The greatest potential for increases in sediment from forest activities is associated with poorly designed or maintained roads and channel disturbance for hilly or mountainous sites. Practices that reduce these impacts can greatly reduce overall changes in sediment related to forest activities.

- Roads may not be an important source of sediment for flat sites.
- In some riverine forest sites, disturbance that increases herbaceous vegetation can increase sediment trapping.
- Any increases in nutrient concentrations and loads following harvesting and site preparation tend to be short-lived, usually disappearing within a few years.
- Natural disturbances such as insect outbreaks also can temporarily increase nutrient losses from forest watersheds.
- Stream temperatures can be protected by providing shade though the use of streamside management zones.
- Water quality and appropriate management practices can vary widely because of the diversity of conditions found in the Southeast.

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Chapter 4

Assessing the Impacts of Intensive Forest Management: Watershed Studies of the Mid-South

R. Scott Beasley, Edwin L. Miller, Wilbert H. Blackburn, and Edwin R. Lawson

ABSTRACT: During the 1970s several factors combined to lend impetus to research aimed at quantifying erosion and sedimentation resulting from intensive silviculture. A series of experimental watershed studies was initiated in Arkansas, Oklahoma, and Texas to address this issue. Standardized instrumentation and analyses were employed to enhance comparability of results among regions. These studies found that water yield increases from timber harvesting were roughly proportional to reductions in forest cover. Water yield response to management varied, in part, as a result of large differences in precipitation patterns between years. Sediment losses from undisturbed forests were minimal. Harvesting and site preparation increased sediment losses in runoff, but these losses were small compared to other land uses and moderated after a few years. Site-specific factors contributing to increased sediment losses in response to forest management included slope gradient, percentage of the basin with exposed mineral soil, and presence of rock fragments in the soil capable of forming an armored surface.

KEYWORDS: armored layer, Clean Water Act (PL 92-500), erosion, exposed soil, herbicides, mechanical site preparation, sediment, soil compaction, soil moisture

Introduction

During the 1970s several factors combined to lend impetus to research aimed at quantifying erosion and sedimentation on forestland. The increased use of clearcutting and mechanical site preparation in even-aged forest management caused concerns about potential declines in site productivity related to loss of topsoil and nutrients. Public perceptions regarding intensive forest management on public and private land prompted Congress to include silviculture in landmark legislation intended to protect water quality. The Federal Water Pollution Control Act Amendments enacted in 1972 (Public Law 92-500) required states, for the first time, to identify and control, to the extent feasible, all nonpoint sources of pollution, including silviculture. Limited research prior to that time indicated that generalizations about silvicultural effects on soil losses and water quality are limited by complex, dynamic interrelations among factors controlling erosion. Spatial and temporal variations in soil properties, climatic regimes, site factors, and specific forest practices limit