# Chapter 15: Ecoregion 8.5.3 Southern Coastal Plain: Santee Experimental Forest, South Carolina

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## Introduction

This chapter synthesizes environmental monitoring and studies performed at Santee Experimental Forest (SEF) that are relevant to water quality within the lower coastal plain (LCP) of the southeastern United States. The SEF lies within the Carolina Flatwoods section of the LCP (Griffith et al. 2002) where forested wetlands strongly influence water quality through hydrological and biogeochemical processes and provide important ecosystem services.

### Site Description

The SEF consists of 2469 ha of federal land dedicated to research, demonstration trials, and long-term monitoring. SEF (lat. 33° 08' 15" N, long. 79° 49' 0" W) is located within the Francis Marion National Forest near Huger, South Carolina, 50 km northwest of Charleston, South Carolina (fig. 15.1). Terrain consists of broad flats and bottomlands, with elevation ranging from 0 to 21 m above sea level. Forest vegetation is dominated by loblolly pine (*Pinus taeda* L.), oaks (*Quercus* spp.), and other hardwoods, and longleaf pine (*P. palustris* Mill.) typical of the flatwoods forest (Harms et al. 1998). About 70 percent of the SEF is within the habitat management area for the red-cockaded woodpecker (*Picoides borealis)*, which is listed as endangered under the Endangered Species Act (16 USC 1531 et seq.). The SEF research watersheds are nontidal headwaters of Huger Creek, a freshwater tidal creek, within the Cooper River Estuary that opens to the Atlantic Ocean.

The SEF has low-gradient, black-water streams that drain the flatwoods landscape. These streams have beds of unconsolidated sediments with textures ranging from clay to sand and broad floodplains. Most streams have considerable woody debris and leaf litter within the channel, derived primarily from riparian vegetation. Bottomland deciduous hardwood trees dominate the riparian zone, producing a closed canopy except during the leaf-off season from mid-November until mid-March.

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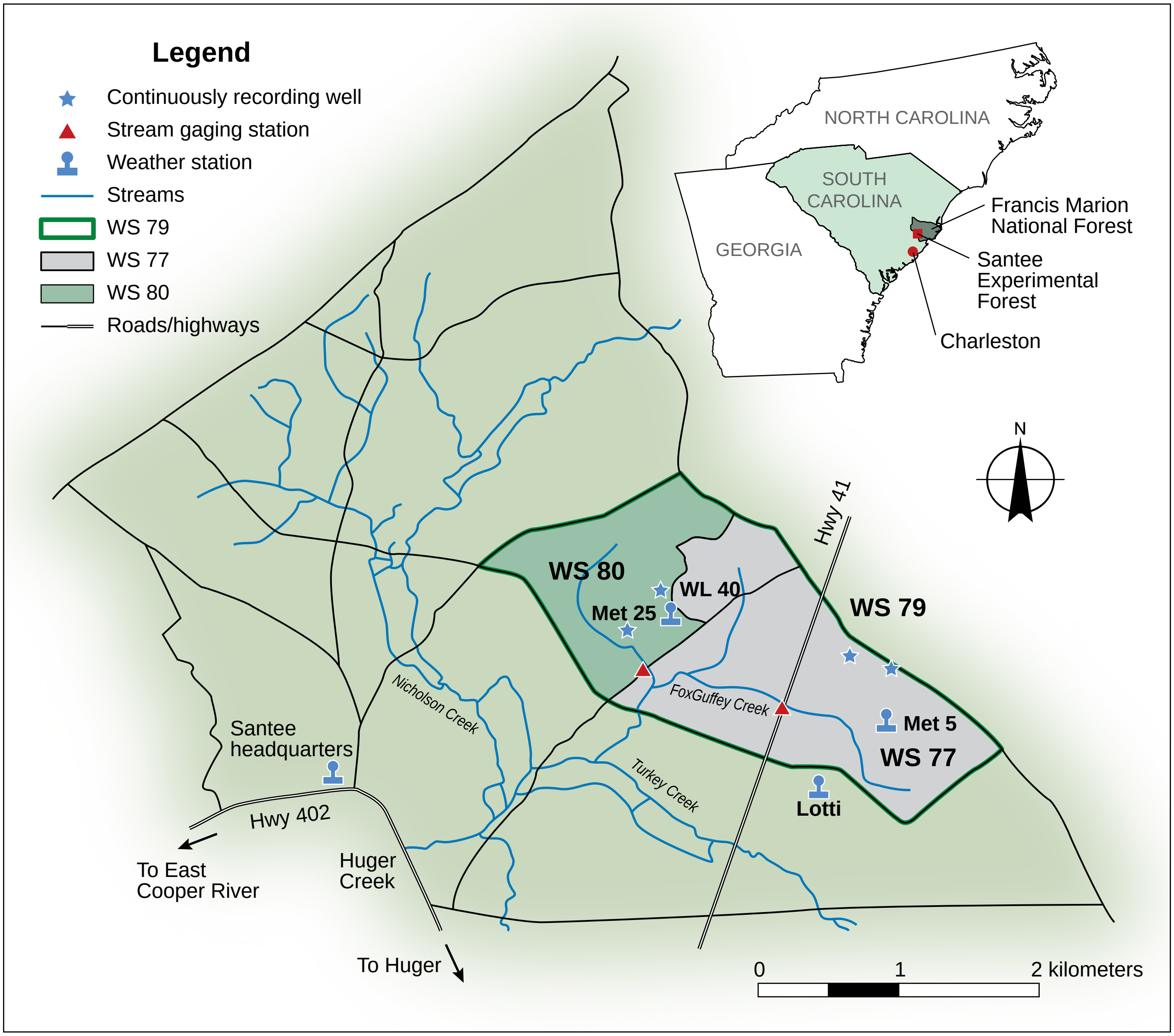


Figure 15.1—Santee Experimental Forest near Huger, South Carolina. Three gaged watersheds (WS 77 and WS 80 inside the larger WS 79) are indicated. Locations of streamflow monitoring stations (triangles) and meteorological stations (stars) are also shown (from Harder et al. 2007).

Climate is subtropical, with an average annual temperature of 18.3 °C and average annual precipitation of 1370 mm (Dai et al. 2013). The forest was heavily affected by Hurricane Hugo in 1989 (Hook et al. 1991), and its current vegetation consists of relatively young stands that are vigorously regrowing in the aftermath of this tropical storm.

Soils in SEF are predominantly Aquic Alfisols and Ultisols (USDA SCS 1980), primarily somewhat-poorly to poorly drained sandy loams with clayey subsoils. These soils have high surface-water retention capacity and low permeability, producing slow surface-water drainage (USDA SCS 1980).

## Research History

The land comprising the SEF has a long history of agricultural use and timber extraction (Smith 2012). The SEF was established in 1937 by the U.S. Forest Service (USFS) with a mission of silvicultural research, environmental monitoring, demonstration, and educational activities in support of sustainable forest management practices. Gaged watersheds were installed during the mid-1960s to study the effects of forest management practices on surface water hydrology and water quality. The two first-order watersheds, which average 28 percent wetlands, are characteristic of the LCP (Sun et al. 2000). The monitoring of watersheds began in November 1963 on nested first- and second-order streams, and an adjacent third-order stream was discontinued in May 1982 and resumed from November 1989 to the present. Watershed hydrology, weather, and water quality data are available at the SEF website (USDA FS 2017).

## Program of Research

The focus of research in SEF watersheds has been the effects of silvicultural practices and natural disturbances on ecosystem processes, hydrometeorological and biogeochemical processes, flooding patterns, water budgets, and wetland hydrological regimes (Amatya et al. 2006, 2007, 2015). An initial goal was to establish paired watersheds (reference and treatment) to assess the effects of silvicultural practices. Early research investigated water budgets and runoff dynamics (Young and Klaiwitter 1968). This was followed by research that assessed the effects of prescribed fire on soil and stream water chemistry (Richter et al. 1983).

Over the past 20 years, the greater Charleston metropolitan area, including land surrounding SEF, has experienced rapid growth in population and urban development. Datasets from SEF can represent reference conditions for the forested LCP that have experienced natural disturbances or disturbances associated with forest management treatments; accordingly, these watersheds provide a useful baseline for assessing impacts of development in other watersheds within the coastal landscape. Datasets for SEF watersheds include repeated vegetation surveys, extensive records of land use and detailed LiDAR data, all of which give context for interpreting results from experimental studies conducted in the watersheds.

**Monitoring and experimentation**—

The meteorological dataset for the overall SEF site included daily measurements of precipitation and air temperature that began in 1946. Two full meteorological stations are maintained on the forest. Monitoring of streamflow, precipitation, soil moisture, and water table elevation began in 1963 in WS 77, a first-order watershed. Watershed WS 79, associated with a second-order stream, and watershed WS 78, associated with a third-order stream, were subsequently established (Young and

Klaiwitter 1968). WS80 was established as a first-order reference watershed in 1968. WS 77 was salvage logged in 1989 following Hurricane Hugo. Post Hurricane Hugo, additional forest management treatments were implemented on WS 77, including mastication or mechanical mowing of understory vegetation, thinning, and periodic prescribed fire. Vegetation in WS 77 currently consists of loblolly pine, longleaf pine, and, bottomland hardwoods within the riparian zones.

#### Instream water quality monitoring—

Weekly instream water quality samples were collected by grab sampling at the watershed outlets for the periods 1976–1982, 1989–1994; and, continuously since 2003 on a flow-proportional basis at the outlets of WS 77, WS 79, and WS 80. Sampling and laboratory protocols are described by Amatya et al. (2007).

#### Atmospheric deposition and ambient air pollution monitoring—

Wet and dry atmospheric deposition rates and surface-level ambient ozone concentrations have been monitored at SEF since 2008, and status of data is shown in table 15.1. The atmospheric deposition protocols correspond with the National Atmospheric Deposition Program NADP (NADP 2019), although SEF is not a formal member of the NADP.

#### Availability of publications and data—

Hydrometeorological, instream water quality and atmospheric deposition data and associated metadata may be accessed from the SEF website (USDA FS 2017). Long-term daily climate and streamflow datasets, formatted for comparison with like datasets from numerous other experimental forest and range (EFR) and long-term ecological research (LTER) sites, can be downloaded from the ClimDB/HydroDB website (LTER Network 2013).

## Biological Responses to Stream Nutrients N and P

### Issues of Concern

In the southeastern United States, elevated nitrogen (N) and phosphorus (P) can cause undesirable growth of aquatic plants. Excessive inputs of these nutrients can impair beneficial uses of surface waters through eutrophication and reduced dissolved oxygen (DO). The predominant sources that result in N and P enrichment in waterbodies in this region are nonpoint source discharges of N and P, from agricultural and urban lands, and atmospheric deposition of N compounds. Nutrient loading from the LCP streams to coastal estuaries and near-shore waters is a threat to important fish and shellfish resources and has the potential to negatively affect commercial and recreational fisheries, as well as tourism, that depend on these resources (Lapointe and Bedford 2007).

**Table 15.1—Status of hydrologic (rain and streamflow), stream water chemistry, and air quality variables being measured on reference (WS 80) and treatment (WS 77) watersheds at Santee experimental watersheds before and after Hurricane Hugo in 1989**

| Variable | Years before Hurricane Hugo | Years after Hurricane Hugo | Management |
|---|---|---|---|
| Rain | 1969–1981 | 1989–94; 1996–1999; 2003–present | WS 77 for post-Hugo, mechanical mowing of understory, thinning, and periodic prescribed fire. Loblolly pine, longleaf pine, and, bottomland hardwoods in riparian zones dominate WS 77. Plants were left to naturally regenerate on WS 80 for post-Hugo. Loblolly pine and hardwoods dominate WS 80. |
| Flow | 1969–1981 | 1989-1994; 1996–1999; 2003–present | |
| $NH_4^+$-N, $NO_3^-$-N, TKN, and TN | 1976–1981 | 1989–1994; 2006–present No TKN on both watersheds | |
| $PO_4^{3-}$ and TP | 1976–1981 ($PO_4^{3-}$ only on WS 77 and WS 80) | 1989–1994; 2006–present (TP only on WS 77 and WS 80) | |
| DOC | | 2004–present | |
| $Ca^{2+}$, $Mg^{2+}$, K+, and $Na^+$ | 1977–1980 | 1990–1994; 2003–present (WS 77): 2004–present (WS 80) | |
| $Cl^-$ and $SO_4^{-2}$ | 1977–1980 | 1990–1994; 2003–present (WS 77) 2004–present (WS 80) No $SO_4$ on both watersheds (2003–2007) | |
| pH | 1976–1982 | 1989–1994; 2003–present | |
| Dissolved oxygen | | 2006–present | |
| Conductivity | | 2006–present | |
| Temperature | | 2006–present | |
| Salinity | | 2006–present | |
| Wet and dry atmospheric deposition of N and P | | 2008–present | |

Variables: $NH_4^+$-N = ammonium-nitrogen, $NO_3^-$-N = nitrate-nitrogen, TKN = total Kjeldahl nitrogen, TN = total nitrogen, $PO_4^{3-}$ phosphate, TP = total phosphorus, DOC = dissolved organic carbon, $Ca^{2+}$ = calcium , $Mg^{2+}$ = magnesium, $K^+$ = potassium, $Na^+$ = sodium, $Cl^-$ = chloride, $SO_4^{-2}$ = sulfate, N = nitrogen, and P = phosphorus.

## Findings From Studies

**Instream N and P—**

Stream water at the outlets of watersheds WS 77, WS 80, and WS 79 have been monitored for nitrate ($NO_3^-$)-N, ammonium ($NH_4^+$)-N, total N (TN), phosphate ($PO_4^{3-}$)-P, and total P (TP) for intermittent periods from 1976 to 1994 and continuously since 2003. Wet and dry atmospheric deposition of these same nutrients has been monitored at SEF since 2008.

Binkley (2001) reported that stream water $NO_3^-$-N concentrations on WS 80 were very low, averaging 0.017 mg $NO_3^-$-N/L, with highest values in winter and early spring. $NH_4^+$-N concentrations averaged 0.045 mg/L, more than double those of $NO_3^-$-N. Ammonium concentrations declined with increased streamflow, but $NO_3^-$ -N concentrations did not change as flow increased. Dissolved organic nitrogen (DON) averaged ~1 mg/L, which was tenfold higher than dissolved inorganic nitrogen (DIN). Phosphate-P ($PO_4^{3-}$-P) concentrations averaged 0.028 mg/L and declined slightly with increased flow. These nutrient concentrations were consistent with other black water streams draining southeastern forested watersheds dominated by conifers (Chescheir et al. 2003).

**Instream biological surveys—**

Biological monitoring in SEF streams has consisted primarily of fish surveys. Following Hurricane Hugo in 1989, Hansbarger and Dean (1994) surveyed fish in Fox Gully Creek draining the treatment watershed (WS 77), and it was resampled in 2002, 2003, 2004, and 2006 (Krause and Roghair 2010). The number of fish species captured has differed widely, with 10 species reported in 1993, 4 in 2003, and 3 in 2006. Except for the banded killifish (*Fundulus diaphanous* Lesueur), recorded fish species were native to the Santee-Cooper Drainage. The trophic composition of the fish assemblage in Fox Gully Creek remained unchanged from 1993 to 2006. Insectivores dominated the community, which indicated that invertebrate food sources were probably stable. One species of freshwater mussel, *Elliptio complanata,* was also reported in Fox Gully Creek (Krause and Roghair 2010). Concurrent with the fish surveys, DO, temperature, hardness, pH, and alkalinity were also measured (Krause and Rroghair 2010). Survey data are available from USFS Southern Research Station, Center for Aquatic Technology Transfer. Additional biological monitoring has been done in streams of the surrounding Francis Marion National Forest (Hansbarger and Dean 1994), and macroinvertebrates were sampled in SEF streams in 2013, collaboratively with South Carolina Department of Health and Environmental Control (SCDHEC), although results are not yet published. New work, begun in 2016, is studying the response of aquatic invertebrate communities to prescribed fire, comparing communities within WS 80 and WS 77 streams.

## Other Factors Relevant to Biological Responses to Stream Nutrients N and P

**Streamflow—**

The annual water budgets of the first-order watersheds were described by Young and Klaiwitter (1968) and Harder et al. (2007), and the effects of climate variability on hydrologic processes and conditions on the SEF were characterized by Dai et al. (2013). WS 77 and WS 80 are highly responsive to rainfall, and the ratio of runoff to precipitation is dependent on antecedent moisture conditions (Amatya et al. 2006, Jayakaran et al. 2014). This hydrologic response is similar to that of WS 78, an adjacent third-order watershed (Amatya et al. 2015, La Torre Torres et al. 2011). Annual stream outflow from WS 80, as a fraction of annual precipitation averaged 9 percent and ranged from 5 percent in 1981 to 43 percent in 1997. On WS 77, runoff as a fraction of precipitation averaged 25 percent, and ranged from 9 percent in 2004 to 44 percent in 1991. Such wide ranges resulted from shallow water table dynamics that are driven by evapotranspiration and precipitation. As a result, the contributions to streamflow from shallow surface runoff and subsurface drainage are highly variable (Epps et al. 2013) and influence stream export of dissolved and particulate nutrients.

Other stream water quality parameters that may influence biological responses, including pH, temperature, conductivity, and DO, have been measured intermittently in both the reference (WS 80) and treatment (WS 77) watersheds since the mid-1970s.

## Dose -Response Studies

Dose-response studies have not been conducted at SEF.

## Reference Watershed

WS 80 was established as a first-order reference watershed in 1968, and since then has been protected from onsite human disturbance. WS 80 is 160 ha (206 ha before 2001) and drained by a single stream. Surface elevations within this watershed range from 3.7 to 10 m with 0 to 3 percent slopes (Harder et al. 2007). Portions of the bottomlands were used for rice cultivation from the late 1700s to the mid-1800s, while the uplands were used for livestock and production of timber and forest products (Smith 2012). Following incorporation into the Francis Marion National Forest in 1933, vegetation on previously disturbed areas was not managed but was allowed to naturally regenerate. The mixed-conifer and hardwood stands that developed are considered typical for this landscape (Czwartacki and Trettin 2013).

Studies of WS 80 provide rare scientific evidence of the response to severe hurricane disturbance and subsequent ecological recovery of an LCP forest and stream without onsite human disturbance. Before Hurricane Hugo, the vegetation consisted of mixed stands of oak and loblolly pine. In 1989, Hurricane Hugo destroyed over 80 percent of the forest canopy (Hook et al. 1991). Post-Hugo, the watershed's forest was allowed to regenerate naturally; fallen and dead standing trees were left in place, and no timber was removed. In the decades following Hugo, the forest vegetation regenerated, with mixed hardwoods and pine predominating, and streams were allowed to respond without human intervention.

Results of stream water monitoring of N and P on this reference watershed since 1976 are reported under the heading "Findings From Studies: Stream Water N and P." The response of N and P in this stream to Hurricane Hugo are described below in the section "Response to Management Practices and Natural Disturbances." For more detailed descriptions of this reference watershed and associated studies, see Amatya et al. (2005), Harder et al. (2007), and Epps et al. (2013).

## Cross-Site and Regional Studies

**Stream water N and P—**

Amatya et al. (2009) studied the relationship between streamflow and water quality for the third-order Turkey Creek watershed (WS 78), a forested watershed extending beyond the SEF into the Francis Marion National Forest. Stream water quality data in this basin is available for 2006–2009, for the nutrients $NO_3^-$-N+ nitrite ($NO_2^-$)-N, $NH_4^+$-N, TN, and TP. Concentrations were within the ranges reported for the other SEF watersheds (Amatya et al. 2007) and other basins with similar land use within the LCP, except $NH_4^+$-N, which was slightly higher in Turkey Creek than in the SEF WS 77 and WS 80 streams. Muwamba et al. (2016) reported that, similar to WS 79 and WS 80, organic-N dominated N chemistry in Turkey Creek, with very low levels of inorganic N.

Watersheds on the SEF were part of the nationwide assessment of streams that examined patterns of temporal variation in stream water chemistry (Binkley 2001). SEF was among eight EFRs that were detailed in the assessment, which included over 300 streams. The low DIN and $PO_4^{3-}$ and high DON concentrations observed in SEF streams were consistent with other southeastern forested watersheds dominated by conifers. Data on wet and dry atmospheric deposition of $NO_3^-$-N, $NH_4^+$-N, TN, and $PO_4^{3-}$-P, collected at SEF, have not been used by NADP in regional or national deposition syntheses nor to map pollutant loading.

## Responses to Management Practices and Natural Disturbances

**Effects of prescribed burning and thinning—**

Prescribed fire is a common silvicultural practice in pine-dominated flatwood forests in the LCP. This treatment is used to reduce potential risk of severe wildland fire by lowering accumulation of biomass fuel on the forest floor, and for restoring critical habitat for longleaf pine and endangered red-cockaded woodpecker (*Leuconotopicus borealis* Vieillot). Understory hardwoods compete significantly for soil moisture in upland pine forests of the mid-south (Harrington and Edwards 1999); consequently, control of understory vegetation with prescribed fire or mastication can result in increased streamflow (Amatya et al. 2006).

A treatment of winter burning of understory and pine litter was implemented on 20 percent of WS 77 each year for 5 successive years from 1976 to 1981. No significant changes were found in water quality, water yield, or soil properties compared to the untreated reference watershed (Richter et al. 1983). Mean annual stream TN and TP loads showed no substantial response, compared to reference, from either the annual partial burning during the 1976–1981 period, nor from a thinning in 2006 followed by burning in 2007 and 2009. During the treatment years 2006–2011, TP exports from both the treatment and reference basins were almost equal at 0.02 ± 0.02 kg/ha/yr. A before-and-after comparison for the treatment watershed (WS 77), however, revealed decreases in total cumulative monthly TN loads of 0.58 kg/ha and decreases in total cumulative monthly TP loads of 0.02 kg/ha compared to the 2004 to 2006 pretreatment period, although only the result for TP was significant ($\alpha = 0.05$).

**Effects of Hurricane Hugo**—
Data from Wilson et al. (2006) indicated a significant increase in average stream water outflow from WS 80 for 3 years following Hurricane Hugo, the most severe natural disturbance since SEF was established. Annual exports of N and P from the unmanaged WS 80 were significantly higher in the post-Hugo period compared to the pre-Hugo period. The largest increase (39 percent) was for $NO_3^-$-N followed by 21 percent for total Kjeldahl N, organic N (ON), and TN and 6 percent for $PO_4^{3-}$ (Wilson et al. 2006). The managed watershed (WS 77) had post-Hugo increases in stream N and P that were similar to the reference. Wilson et al. (2006) concluded that forest disturbance by Hurricane Hugo increased nutrient exports from the SEF watersheds during the first 5 years after the hurricane primarily as a result of increases in streamflow, but the authors noted that the increased exports were above a very low prehurricane baseline. The likely mechanism explaining these findings was that hurricane damage to vegetation reduced both evapotranspiration and vegetative uptake of nutrients, which increased runoff (Jayakaran et al. 2014) and nutrient exports. Other studies have reported similar increased outflows of water and nutrients from other coastal forested watersheds damaged by Atlantic hurricanes.

**Comparisons of pre- and post-Hugo periods—**
Measured stream water concentrations of $NO_3^-$-N and $NH_4^+$-N were very low both before and after Hugo for both WS 77 and WS 80, with ON the dominant form of N in both watersheds (fig. 15.2). During the post-Hugo period, ON was significantly ($\alpha = 0.05$) lower (0.35 ± 0.08 mg/L) than in the pre-Hugo period (0.71 ± 0.42 mg/L) in study watershed WS 77, but not in reference watershed WS 80. On the other hand, $NH_4^+$-N and DIN were significantly higher ($\alpha = 0.05$) for the post-Hugo period compared to the pre-Hugo period, but only in watershed WS 80. Slightly higher ON values observed in the WS 77 watershed post-Hugo were not significantly different when compared to values from the pre-Hugo period. Stream water nutrient concentrations in WS 80 showed that export of TN and $PO_4^{3-}$ had returned to pre-Hugo mean levels 16 to 21 years after the hurricane disturbance (fig. 15.3). The TN and $PO_4^{3-}$ loads in both watersheds during the post-Hugo regeneration period were found to be substantially lower than those of the pre-Hugo period,

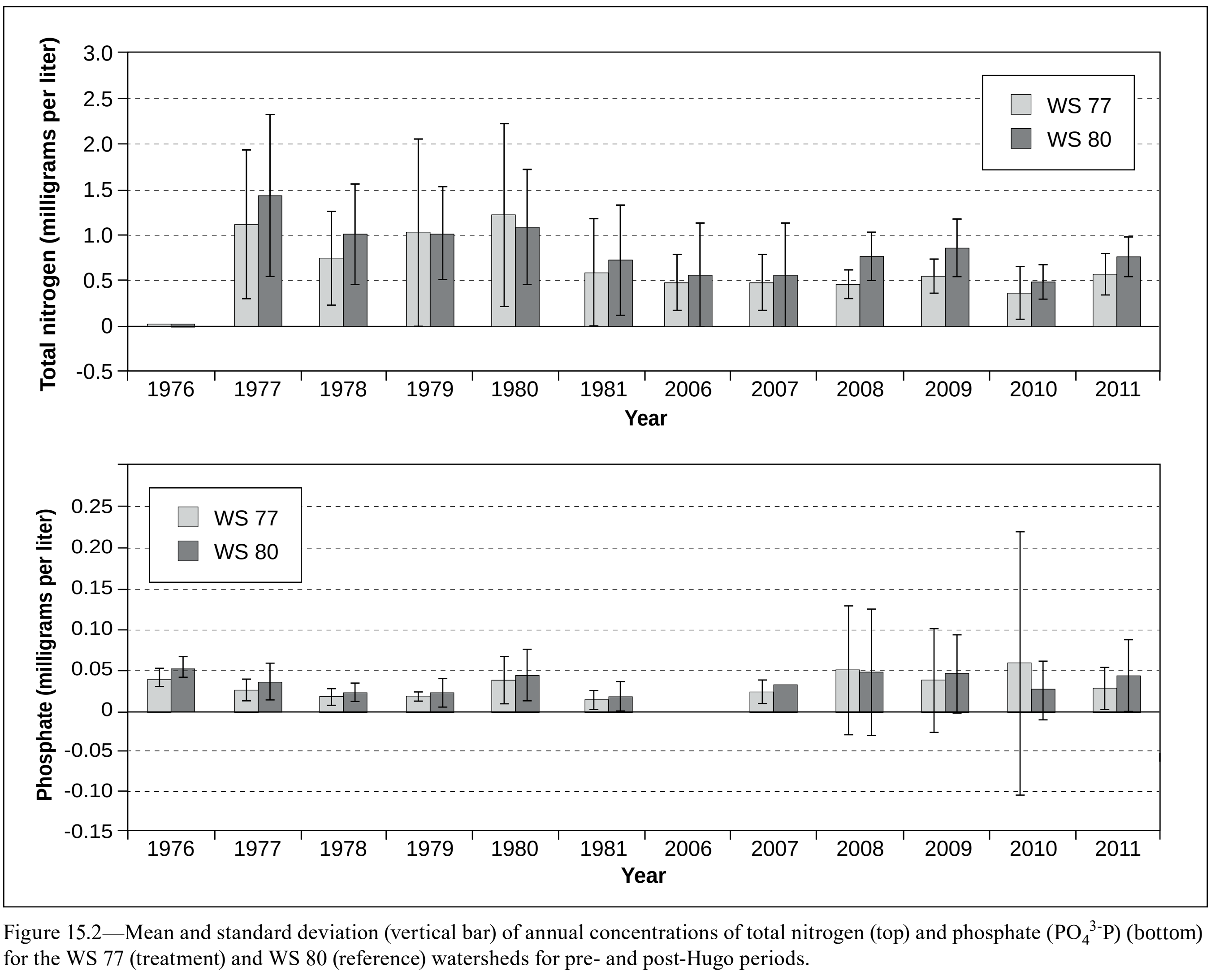


Figure 15.2—Mean and standard deviation (vertical bar) of annual concentrations of total nitrogen (top) and phosphate ($PO_4^{3-}$-P) (bottom) for the WS 77 (treatment) and WS 80 (reference) watersheds for pre- and post-Hugo periods.

although in WS 77, only TN was significantly different (α = 0.05). Decreased loads during the regeneration period were probably the result of reduced streamflow in both watersheds reported by Jayakaran et al. (2014), who cited the return to pre-Hugo streamflow levels as evidence that the hydrologic cycles, and possibly the cycles of N and P, in this coastal forest were resilient even after the severe disruption of Hurricane Hugo.

**Effects of dry and wet years on nutrient export—**
Droughts are recurring natural disturbances that affect nutrient export from SEF watersheds. During prolonged dry periods of low rainfall in the years 2007 and 2011 (Amatya et al. 2015), exports of TN and TP were much smaller than during the other years of the post-Hugo period (figs. 15.3 and 15.4). Both annual average flow and TN concentrations were lower in 2007, whereas only average annual flow was lower in 2011. During the relatively wet year of 2008, the opposite was true; TN export was significantly higher (α = 0.05) than during the other years of the

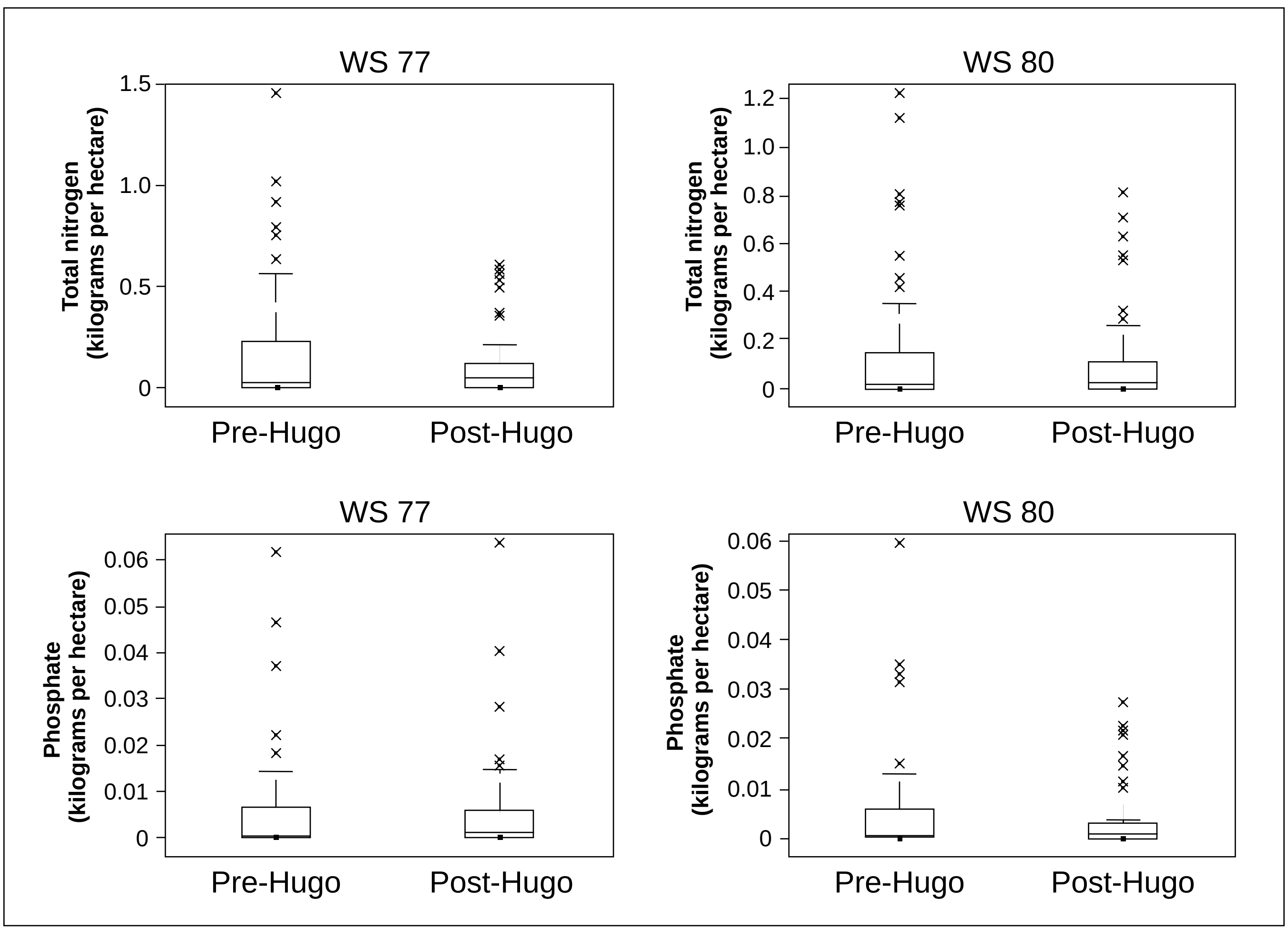


Figure 15.3—Distribution of calculated monthly loads of total nitrogen and phosphate-phosphorus for watershed (WS) 77 (treatment) and WS 80 (reference) watersheds for the pre- and post-Hugo periods.

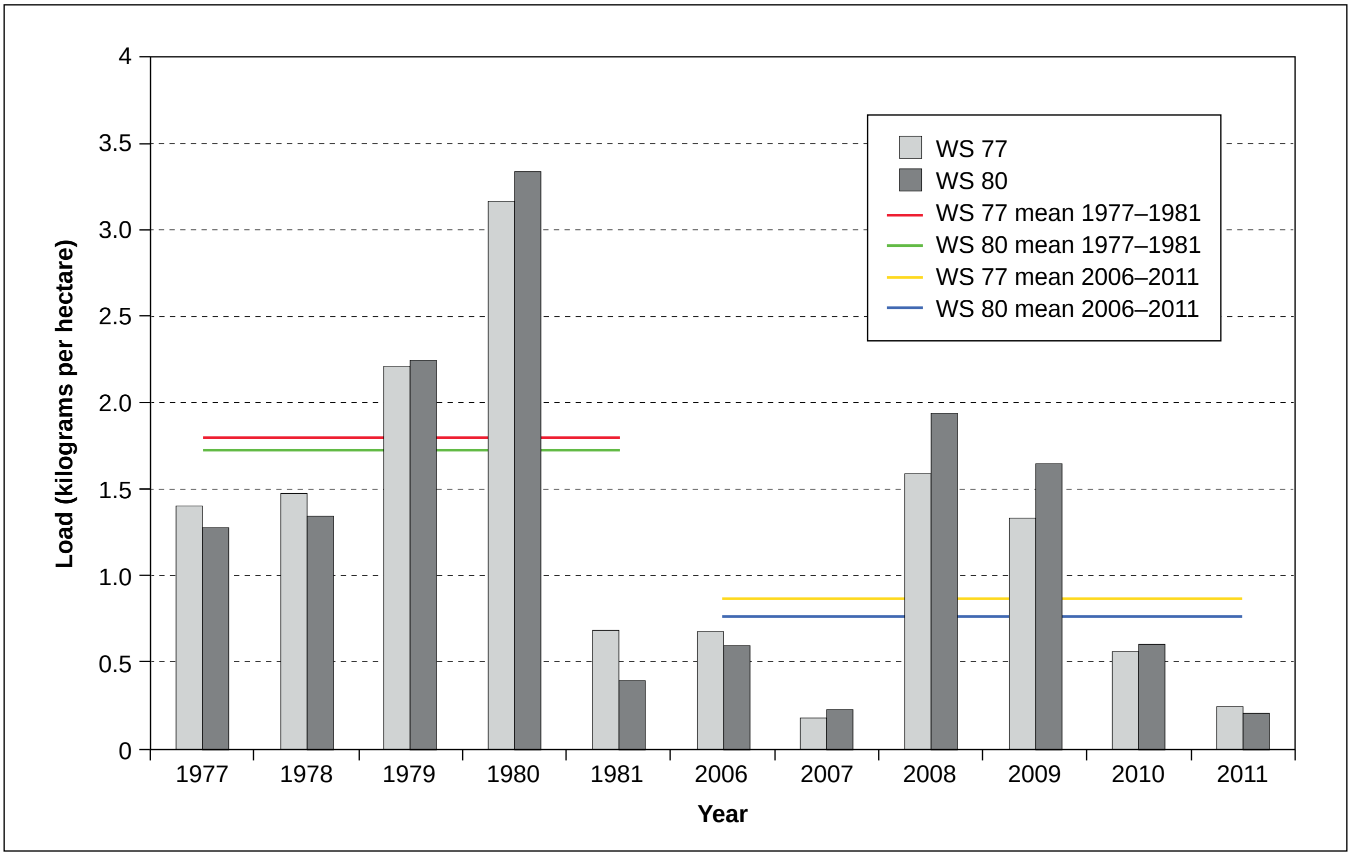


Figure 15.4—Calculated annual total nitrogen loads for WS 77 (treatment) and WS 80 (reference) watersheds for the post-Hugo (2006–2011) period. The horizontal lines are the mean annual values.

post-Hugo period. Similarly, TP loads were much lower in the dry years, 2007 and 2011, while higher TP loads occurred in the wetter year, 2008, in both watersheds, WS 77 and WS 80 (fig. 15.5). However, lower TP concentrations in dry year than the wet year were significantly different only in the treatment watershed and only in the dry year 2007, but not during 2011, nor in the reference watershed in either year. Thus on an annual basis, hydrology, largely driven by rainfall, seemed to have the largest influence on export of TN and TP from SEF forests to downstream ecosystems; although, in some dry years, decreased stream water concentrations of those nutrients also played a role.

## Reliability and Limitations of Findings

The SEF findings are representative of LCP forests on the southeastern Atlantic seaboard. When a high degree of accuracy is required or where land use differs from SEF, validation monitoring or studies might be considered to test how well data and results from SEF predict local conditions.

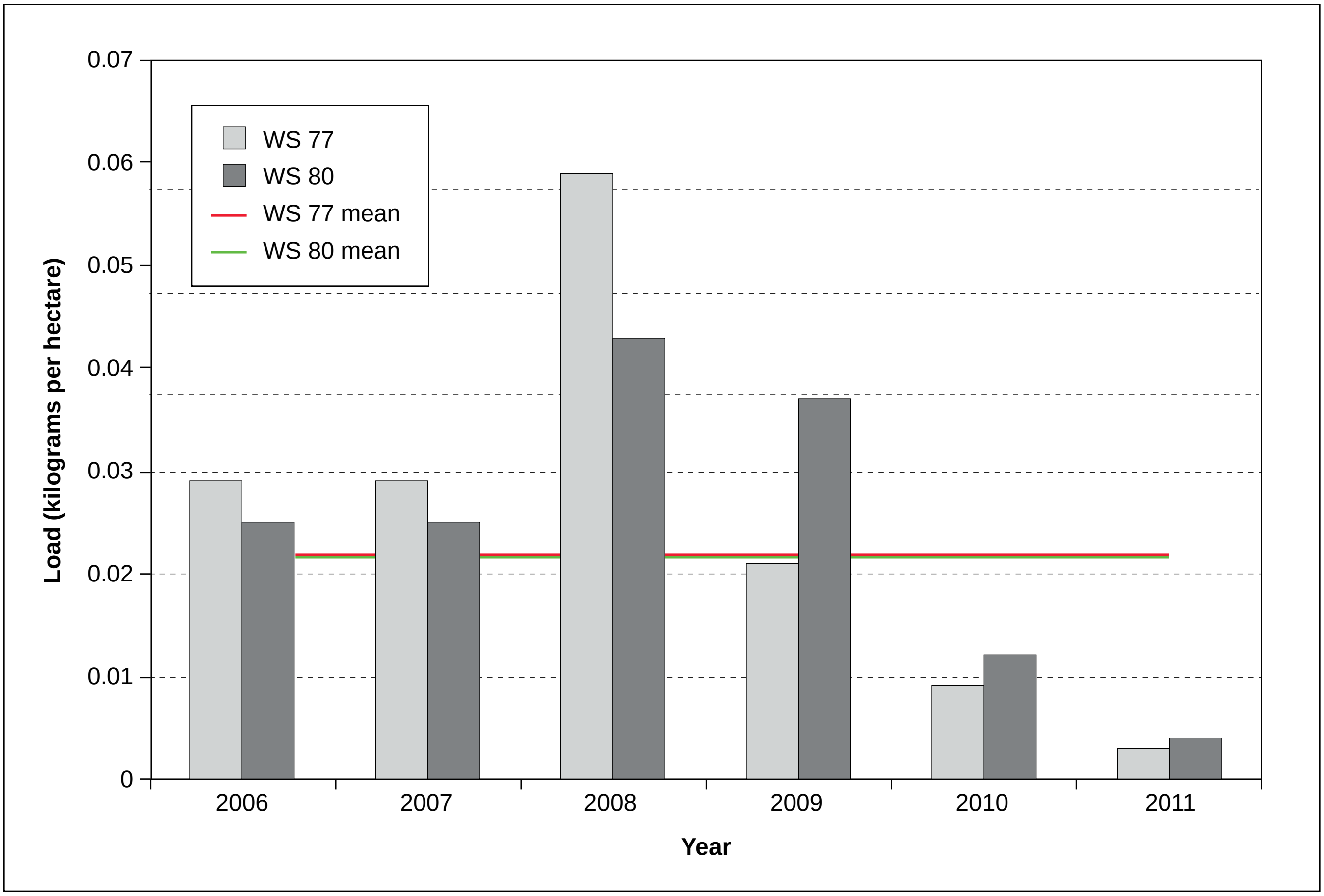


Figure 15.5—Calculated annual total phosphorus loads for watershed (WS) 77 (treatment) and WS 80 (reference) watersheds for the post-Hugo (2006–2011) period. The horizontal line is the mean annual value for the entire period.

## Research Needs

From the perspective of state water quality regulators, the highest priority research need related to N and P that might be addressed at SEF is, What salient features of the aquatic biology of LCP streams are useful indicators of reference condition, and could these indicators be used to detect, characterize, and quantify a biological response across a gradient of nutrient enrichment? Filling this research need would help regulatory agencies develop data-driven bioassessment tools for headwater streams in this region of the state. Filling this need at SEF would require initiating and regularly repeating stream biological surveys in the SEF reference watershed that would include algae, macrophytes, macroinvertebrates, and fish. Concurrently, monitoring of channel geomorphology, as well as other instream ecological processes, such as whole-stream metabolism, leaf litter breakdown, and nutrient spiraling would also need to be performed. In addition, biological response thresholds to stream nutrient enrichment would need to be investigated, either by comparing the biological assemblages in SEF reference streams with streams across a gradient of nutrient loading, or by conducting nutrient enrichment experiments. Such experiments would consist of monitoring biological responses to additions of varying concentrations of N and P, separately and in combination, to selected stream reaches or to artificial stream microcosms.

The following questions were formulated by state water quality regulators to identify useful, but lower priority, research needs that could be investigated at SEF:

- What are the relationships between multiple stressors in headwater streams, including nutrient loading, and other factors, such as temperature, and drought, and what are their combined effects on important instream ecological processes, such as whole-stream metabolism, leaf litter breakdown, and nutrient spiraling?
- How do seasonal variations in DO and organic matter influence a stream's biological assemblage; and how might a better understanding of seasonal effects be used to adjust biological monitoring and assessment protocols to produce more representative and meaningful results?
- What are the salient characteristics of streams in this region of the state (e.g., biological, geomorphological, and hydrological) that differ predictably across a gradient of hydrologic permanence ranging from ephemeral (consisting of surface storm water runoff only) to perennial flows (consisting of surface runoff and groundwater); and, might these be used to rapidly classify streams in the field?
- How do instream biological assemblages, and the physical features and processes that sustain them in freshwater tidal streams downstream of SEF, respond to variations in nutrient loading of N and P from headwater streams such as those in SEF?

## Potential Utility to Water Quality Regulatory Agencies

Existing long-term datasets from SEF, including streamflow and stream water nutrient concentrations and fluxes, on both reference and managed or treatment watersheds, along with data on nutrient inputs from atmospheric deposition have the potential to be very useful for SCDHEC's efforts to establish numeric nutrient criteria for estuaries, rivers, and streams. For example, long-term data from the SEF reference watershed were used in comprehensive analyses of flow and water quality in the Charleston Harbor (TetraTech 2008), providing valuable context for natural, background loading from headwaters to the estuary. The reference data were also used in revisions to total maximum daily loads (TMDLs) completed recently for the Charleston Harbor (Lu et al. 2005), and the Cooper and Ashley Rivers (Cantrell 2013), as required by the federal Clean Water Act (CWA) section 303(d). SEF stream data provide baselines that may be used by regulators when setting numeric nutrient criteria, and when developing protocols and practices for monitoring, assessing, and preventing excessive nutrient and other pollutant inputs that come from the urbanizing landscape.

There has been a long-standing and sustained recognition of the importance of headwater streams (US EPA 2014, Vannote et al. 1980), including those with only seasonal or ephemeral flow, to the overall health of watersheds and to large downstream receiving waters, including rivers and estuaries. The SEF site is well suited for research on the contributions of perennial, intermittent, and ephemeral headwater streams within the LCP to the chemical, physical, and biological integrity of downstream waters, especially freshwater tidal streams and estuary waters.

Overall, the SEF site has great potential to provide valuable scientific information to regulatory decisionmakers, natural resource managers, and others. Its strategic location, the public availability of its data, its existing long-term record of water quality and streamflow, and its connectivity to sensitive downstream estuaries enhance its potential usefulness for regulators. Regulators might draw upon SEF research results for developing science-based approaches to setting standards; conducting monitoring and assessment; evaluating permit applications, proposed impacts, and compensatory mitigation; and developing and implementing TMDLs throughout this region of South Carolina. For example, data on DO and carbon might be useful for developing allowable discharge limits that are protective of the estuary. Similarly, information on background nutrient loading could be used to provide the foundation for TMDLs for the LCP. Long-term environmental datasets, such as streamflow and meteorological records, might also provide a useful context for interpreting the extensive data SCDHEC has collected from conducting monitoring of benthic macroinvertebrate assemblages in streams in the vicinity of SEF (fig. 15.6).

Headwater streams have been monitored at SEF in a reference watershed reflecting minimal human disturbance over a long period. These datasets could be useful to SCDHEC in reviewing and approving compensatory mitigation plans for stream restoration activities under CWA Section 401 Water Quality Certifications. For example, long-term datasets from the SEF reference watershed might be used to develop an understanding of, and describe reference condition for, streams and wetlands in this region of the state. This would be helpful for setting appropriate expectations for results from stream restoration activities, including calculating credits appropriately, and setting appropriate ecological performance standards, both interim and final, and monitoring requirements.

In 2010, SCDHEC began developing extensive hydrology and water quality datasets to provide a basis for assessments and models. Data and published

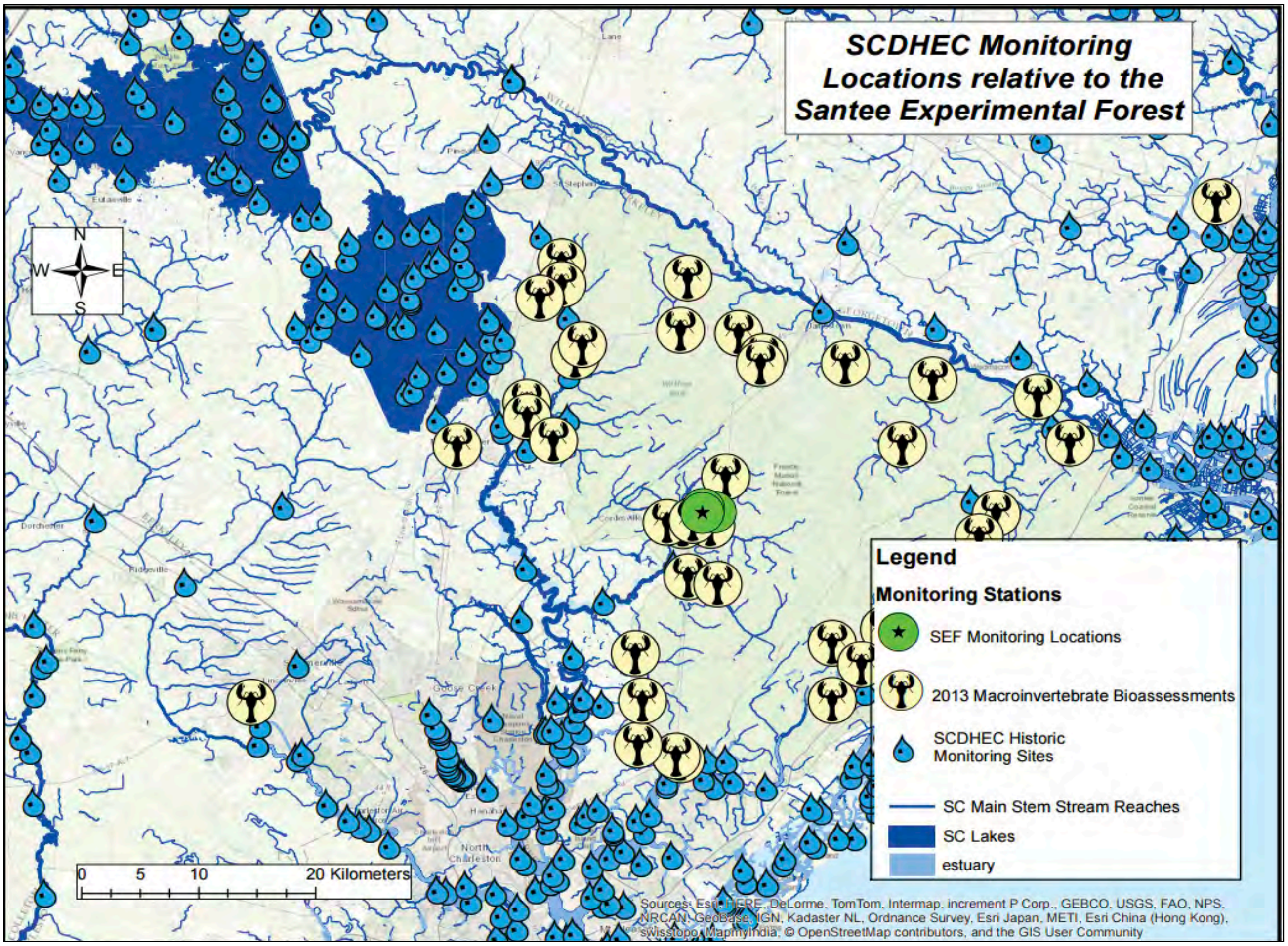


Figure 15.6—South Carolina Department of Health and Environmental Control (SCDHEC) biological monitoring stations for benthic macroinvertebrate communities in the vicinity of Santee Experimental Forest (SEF) in eastern South Carolina (SC).

research from SEF provide a scientific basis for regulators to use in developing models of water quality in LCP forests. Such data and models might be useful to regulators for accounting for outputs from managed and unmanaged forested lands when developing water quality standards and TMDLs for this region, and as part of developing numeric criteria for estuaries in South Carolina (Wilson 2010). Similarly, existing datasets from SEF that include repeated vegetation surveys, extensive records of land use, and detailed LiDAR data can augment water quality and streamflow data and might be useful to water quality regulators for assessing the effectiveness of riparian buffers in reducing nutrient loading, maintaining and improving downstream waters, and in developing recommendations for minimum buffer requirements.

## Biological Responses to Stream Nutrients Other Than N and P

### Issues of Concern

There are currently no pressing concerns in the region related to direct effects of nutrients other than N and P on water quality.

**Mercury—**

A potential issue related to the nutrient sulfur may be indicated by elevated methyl mercury (MeHg) levels that have been found in tissue samples from fish from LCP streams within the Francis Marion National Forest and from the East Fork of the Cooper River, downstream of SEF (Pelva and Hansen 2003). A neurotoxin that accumulates in aquatic food chains, MeHg reaches high tissue levels in apex predator food fish, posing a risk to human health (Bradley et al. 2012). Methyl mercury is the most biologically active and toxic form of Hg found in the environment and was found to be enhanced by increased ambient levels of $SO_4^{2-}$ in wetlands at the Marcell Experimental Forest (chapter 2) (Jeremiason et al. 2006). Prescribed fire in upland areas may also affect Hg cycling, perhaps by altering ambient $SO_4^{-2}$, and can potentially increase Hg mobilization and transport out of watersheds subject to this management practice (Woodruff and Cannon 2010).

### Findings From Studies

Stream water quality monitoring in WS 77, WS 79, and WS 80 has included calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^+$), sodium ($Na^+$), sulfate ($SO_4^{2-}$), chloride ($Cl^-$), and bromide ($Br^-$) for intermittent periods from 1976 to 1994, and continuously since 2003. Concentrations of these ions were similar to those in other LCP black water streams. These ions have also been monitored in wet and dry atmospheric deposition at SEF from 2008 to present.

### Other Factors Relevant to Biological Responses to Stream Nutrients Other Than N and P

Environmental factors studied at SEF that were identified earlier as affecting responses to N and P would also affect responses to nutrients other than N and P. These factors include parameters such as streamflow, pH, temperature, conductivity, and DO.

## Reference Watershed

Stream water quality at the outlet from reference WS 80 has been monitored for $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, $SO_4^{2}$, $Cl^{-}$, and $Br^{-}$ since 1976. The response of these nutrients to Hurricane Hugo in this reference stream are reported in the section "Response to Management and Natural Disturbances" below.

## Cross-Site and Regional Studies

SEF has not been included in cross-site studies related to nutrients other than N and P. Data on wet and dry atmospheric deposition of nutrients other than N and P, collected at SEF, have not been included in NADP regional studies, nor in national syntheses or mapping of deposition.

## Responses to Management and Natural Disturbances

Stream fluxes of basic cations, $Ca^{2+}$ and $Na^{+}$, did not respond to management practices, and Richter (1980) reported no water quality impacts to waters near burned pine forest. Comparing dissolved organic carbon (DOC) concentrations for the years 2012 and 2013, greater concentrations were recorded from reference WS 80 than from treatment WS 77, likely as a result of periodic burning in WS 77.

In the aftermath of Hurricane Hugo, annual mean concentrations of $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, and $SO_4^{2-}$ showed an increase for both WS 77 and WS 80 for the 1990 to 1994 period compared to the pre-Hugo period from 1977 to 1981 (table 15.2). Subsequently, stream water concentrations of these ions were lower during the 2008 to 2013 period, after forest vegetation had recovered from hurricane damage (Jayakaran et al. 2014), compared to the immediate post-hurricane period of 1990 to 1993. Maximum post-Hugo concentrations of these nutrients in WS 77 and WS 80 streams are compared to concentrations in the pre-Hugo period in table 15.2. Nutrient concentrations increased in both streams after Hugo during 1990–1994 (table 15.2), presumably as a result of decay of the large input of dead plant materials,

**Table 15.2—Maximum stream water concentrations of Ca2+, Mg2+, K+, Na+, and $SO_4^{2-}$ during pre- and post-Hurricane Hugo periods in WS 77 (treatment) and WS 80 (reference).**

| Period | Watershed | Calcium ($Ca^{2+}$) | Magnesium ($Mg^{2+}$) | Potassium ($K^{+}$) | Sodium ($Na^{+}$) | Sulfate ($SO_4^{2-}$) |
|---|---|---|---|---|---|---|
| | | | | mg/L | | |
| Pre-Hugo (1977–80) | WS 77 | 7.7 | 1.5 | 2.7 | 8.0 | 5.9 |
| Post-Hugo (1990–94) | WS 77 | 13.1 | 2.6 | 8.1 | 13.5 | 10.5 |
| Pre-Hugo (1977–80) | WS 80 | 21.6 | 3.9 | 3.5 | 8.2 | 8.7 |
| Post-Hugo (1990–94) | WS 80 | 40.7 | 3.0 | 5.2 | 14.3 | 17.4 |

WS = watershed.

and suppression of vegetative nutrient uptake. The sole exception was $Mg^{2+}$, which decreased after Hugo in the WS 80. The ratio of post-Hugo to pre-Hugo maximum concentrations in stream water for reference watershed WS 80 was 1.9 for $Ca^{2+}$, 0.77 for $Mg^{2+}$, 1.5 for $K^+$, 1.7 for $Na^+$, and 2.0 for $SO_4^{2-}$.

## Reliability and Limitations of Findings

Stream-related datasets and research results related to nutrients other than N and P from SEF apply to other LCP forested watersheds that have had land use histories similar to SEF. Where a high degree of accuracy is required or land use histories differ from SEF, validation monitoring or studies should be considered to test how well data or results from SEF represent local conditions.

## Research Needs

The highest priority research need for the regulatory community, that might be addressed at SEF, related to nutrients other than N or P, was identified as, Do $SO_4^{2-}$ enrichment scenarios or typical prescribed fire treatments lead to increased production of MeHg and increased bioaccumulation of MeHg within LCP wetland and stream food chains? Answering this question is critically important to regional regulatory agencies because fish consumption advisories related to MeHg are common in coastal waters. Science on the sources and pathways of Hg contamination will be useful for developing more effective regulations to protect the public from this health risk. Answering this question at SEF would require conducting studies that include prescribed fire treatments and measuring Hg and MeHg in stream water, in benthic sediments, and in food chains, including fish tissue samples from fish species most likely to be consumed by the public. Effects of $SO_4^{2-}$ enrichment on MeHg production in SEF wetlands would also need to be investigated experimentally in microcosms and field plots. Continued monitoring of $SO_4^{2-}$ levels in SEF streams and atmospheric deposition would provide status and trends of ambient $SO_4^{2-}$, which may be a factor in MeHg production in streams.

Other research needs of interest to the water quality regulatory community, but of lower priority, include how prescribed fire may affect production of organic compounds that may interfere with drinking water purification treatments (Chow et al. 2007), and how nutrients contained in suspended sediments might contribute to total nutrient fluxes from LCP headwater catchments.

## Potential Utility to Water Quality Regulatory Agencies

Water quality regulatory agencies might be able to use existing long-term datasets from monitoring of nutrients other than N and P in stream water and from atmospheric deposition at SEF for practical regulatory purposes such as developing TMDLs and better storm water regulation. Research results on effects of prescribed fire, and effects of tropical storms on stream nutrients other than N and P might also be of immediate use to regulatory agencies for practical applications. For example, they might use them for assessing the impacts of extreme precipitation events on loading, for planning and permitting allowable withdrawals and discharges, and for considering the potential effects of altered flow regimes on nutrient transport.

Because SEF is set aside to remain undeveloped, it might serve as a valuable reference system and study site to assess how forests serve to buffer effects of urban development on coastal streams and stream ecosystems services, such as providing clean drinking water, mitigating floods, and contributing to productive aquatic habitat.

Key points:

- Nutrients other than N and P have been monitored in stream water and from atmospheric deposition at SEF.
- Disturbance from Hurricane Hugo temporarily increased stream water concentrations and fluxes of most nutrients other than N and P, but disturbance from the management practice of prescribed burns had little effect on the concentrations of those nutrients in stream water.
- The research need of highest priority to the regulatory community related to nutrients other than N and P that might be filled at SEF is investigating the effects of sulfate enrichment and prescribed fire treatments on production of MeHg in LCP wetlands and its accumulation in aquatic food chains.
- Existing SEF datasets and research results on nutrients other than N and P might be used by regulators for practical purposes such as incorporating effects of forest management and severe hurricanes into development of water quality criteria and TMDL models.

## Overview and Synthesis

The location of SEF on the LCP, directly above the stream-to-estuary interface, enhances the value of this study site for water quality regulatory agencies. Research and monitoring from SEF may be useful for addressing regional water quality issues such as effects of prescribed fire, hurricane damage, and rapid urbanization on wetlands and streams in LCP forests that provide important inputs of freshwater and nutrients to coastal estuaries. SEF can provide science-based information about reference conditions in LCP streams that might be useful for developing standards or thresholds for both hydrology and nutrients. The body of scientific work at SEF has focused primarily on hydrology and water quality monitoring. Investigations of aquatic biology have mostly consisted of fish surveys. Future studies, including monitoring and assessing the biological response to water quality factors including nutrient levels and fluxes could build on that foundation.

Research needs that might be filled at SEF that are of highest priority to the regulatory community were identified as developing science-based biological indicators of reference stream conditions, thresholds of biological response to N and P enrichment, and the effects of sulfate enrichment and prescribed burns on wetland MeHg production and its accumulation in aquatic food chains. Future work to fill these needs will benefit regulatory agencies by providing a scientific basis for developing sensitive bioassessment tools for headwater streams in the LCP, and for developing water quality regulations that better protect public health against the environmental hazard of MeHg contamination in fish. Cooperation between water quality regulatory agencies and the USFS on research at SEF has the potential to produce results that will both serve regulatory purposes and advance scientific understanding of the structure and function of these ecosystems.

Key points:

- SEF is an important source of long-term datasets providing scientific findings for understanding conditions in headwater streams that drain forested wetlands in the LCP, and that provide direct inputs to coastal estuaries via the stream network.
- SEF's carefully protected reference watershed provides a good, reliable baseline for conditions of minimal human disturbance that may be useful in developing criteria, TMDL modeling, and permitting.
- While fish surveys have been conducted in SEF streams, less is known about other biological assemblages such as benthic macroinvertebrates and algae.
- Effects on stream conditions of management practices, such as thinning and prescribed burns, and effects of natural disturbances, such as hurricanes, have been extensively investigated in SEF watersheds.
- Research needs that might be filled at SEF of highest priority for the regulatory community were identified as developing biological indicators of reference stream condition, developing an understanding of biological thresholds of response to N and P enrichment, and developing an understanding of the effects of sulfate enrichment and prescribed burns on wetland MeHg production and its accumulation in aquatic food chains.

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