Spatial and Temporal Patterns of Sediment and Nutrient Flux in a Coastal Plain Agricultural Basin, Littlefield, North Carolina

Karen Cappiella
U.S. Bureau of the Census
and
Michael Slattery*
Department of Geology, Texas Christian University

This paper reports the results of a 6-month field study conducted in a small coastal plain watershed in eastern North Carolina. The objective was to identify spatial and temporal patterns of nitrogen, phosphorus, and sediment flux under a range of flow conditions in the basin. Although the pollutant concentrations and exports found in this study were, overall, relatively low, a number of problem areas were identified including: (i) cultivated fields, that contributed disproportionately large amounts of nitrate-plus-nitrate to the total basin export due to the leaching of unused nitrogen-based fertilizer, and (ii) devegetated ditch banks, where TSS concentrations were found to be almost three times greater than areas draining crop or pasture.

Introduction

The North Carolina Division of Environmental Management manages pollution in North Carolina waters through the use of a basinwide water quality plan. Every five years, new data are compiled for each basin, and the result is a report consisting of a general basin description, causes and sources of water pollution, water quality status, existing regulations, and management implications. According to the most recent report on the Neuse River basin, which encompasses both the piedmont and coastal plain regions of North Carolina, the major pollutants are nitrogen, phosphorus, and sediment (NCDEM, 1997).

Nutrient pollution is a potential problem in coastal plain waters because of the large percentage of land in agricultural use, which adds high levels of nitrogen and phosphorus to the fields in the form of fertilizers and animal wastes. In fact, the use of inorganic nitrogen fertilizer in North Carolina increased by 400% between 1945 and 1983 (Jacobs and Gilliam, 1983) and, in 1987, fertilizer accounted for 45% of the total nitrogen yield from the Lower Neuse (EPA, 1987 online report, see http://www.epa.gov/surf2/hucs/03020202/canindicators/canindex.html). Furthermore, the clearing and plowing of land for agriculture increases its susceptibility to erosion of sediment, which often contains nutrients in their particulate form, specifically sediment-bound phosphorus. Recent studies have also shown that the surface waters of the North Carolina coastal plain are highly susceptible to sediment pollution because a significant amount of erosion is occurring in this area (e.g., Phillips *et al.,* 1993; Phillips, 1997; Slattery *et al.,* 1998; Phillips *et al.,* 1999). The problem, however, is that little is actually known about erosion processes in the region or about the transport, storage, and ultimate fate of the eroded soil. There is also a dearth of information on nutrient export from headwater basins in the region, as evidenced by the recent addition of so-called "candidate indicators" in the EPA's Index of Watershed Indicators.

This paper reports the results of a field study conducted in a small coastal plain watershed in eastern North Carolina. Our objective was to identify spatial and temporal patterns of nitrogen, phosphorus, and sediment flux under a range of flow conditions in the basin, and to then interpret these patterns based on factors such as land use, seasonal hydrological conditions, and runoff mechanisms. Two specific research questions were addressed, as follows:

*Corresponding author

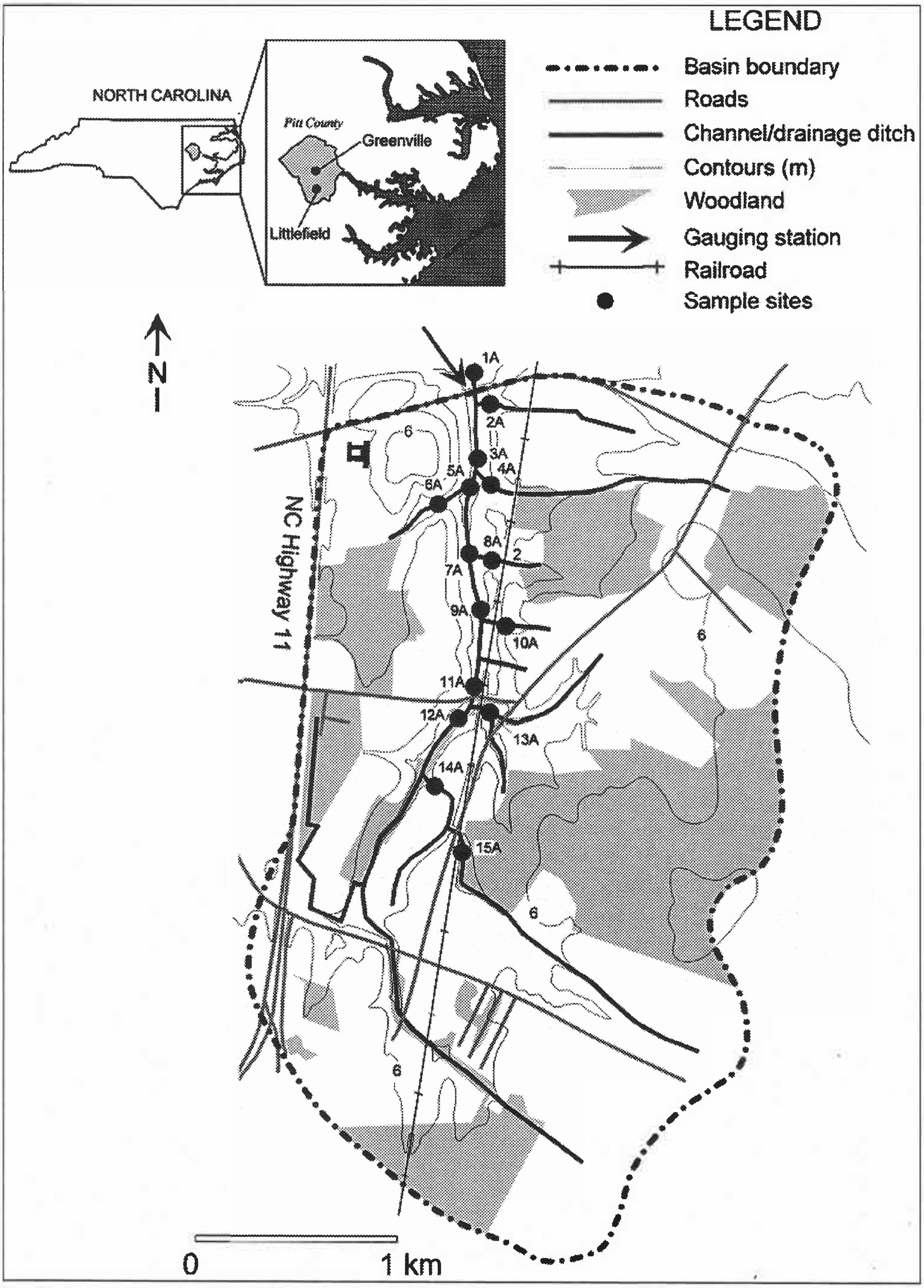

Figure 1. The study basin in Littlefield, North Carolina, showing the main channel and ditches with sampling locations. The ditch at 10A was almost always dry; 8A also dried out on occasion. The site at 14A became inaccessible after the 1st month of sampling.

1. What, if any, spatial patterns are apparent with regard to nitrogen, phosphorus, and sediment flux across the study basin, and what factors affect these patterns (for example, do certain portions of the basin contribute disproportionate amounts of sediment, nitrogen, or phosphorus to the total basin export)?

2. What, if any, temporal patterns are apparent with regard to nitrogen, phosphorus, and sediment flux throughout the study period, and what factors affect these patterns (for example, do pollutant levels fluctuate after fertilizer application, after crop harvest, or with seasonal hydrological changes)?

Study Site and Methods

The research site is a small coastal plain agricultural watershed located near the Pitt County, North Carolina community of Littlefield (Figure 1). The basin has an area of approximately 776 hectares, and includes the headwaters of Swift Creek, a major tributary of the Neuse River. Approximately half the site is mixed pine and hardwood forest, while the remainder is primarily agricultural land, planted in tobacco and cotton, with a significant portion under pasture. A network of subsurface tile drains and surface ditches artificially drains the fields. The main ditch experiences year-round base flow. The topography in the basin is gentle, as is characteristic of the Coastal Plain. Maximum relief is 7m with typical slope gradients on the order of 0.001 to 0.004. The climate is humid subtropical.

The basin is located on the Pleistocene-aged Wicomico marine terrace. The soils are Ultisols belonging to two general groups. One may be called the Norfolk group, after the Norfolk series, a Typic Kandiudult. In addition to the Norfolk series, soils at the site in this group include the Wagram series, an Arenic Kandiudult which differs from the Norfolk only in the thickness of the surficial horizons, and the Lynchburg and Goldsboro series, which are somewhat poorly and moderately well-drained members, respectively, of the same drainage catena as the well-drained Norfolk. The second group consists of finer-grained Ultisols mainly along stream terraces, of which the most common are the Pantego and Bayboro series (both Umbric Paleaquults).

A gauging station was established at the basin outlet in May 1997. Flow was monitored with a Sigma 900MAX portable water sampler fitted with an integral flow meter to measure water level and discharge. The sampler was programmed to take 500 ml water and sediment samples every 15 minutes during storm conditions. An external "tipping bucket" rain gauge fitted to the water sampler recorded the timing of each 0.1 inches of rain. An Endico/YSI 6000UPG Multiprobe also provided a continuous and detailed record of stream turbidity in relation to changing discharge at the outlet. Four storms were monitored in detail: September 12; September 24-25; November 7; and November 12-14. Runoff samples were collected from field slopes during a fifth storm on September 28. Manual water samples were also collected at 13 sites across the basin during both low flow and storm flow conditions from May to November of 1997. All samples (n = 402) were returned to the laboratory and analyzed for six forms of pollutant: dissolved kjeldahl nitrogen (DKN), total dissolved phosphorus (TDP), nitrate-plus-nitrite, particulate nitrogen (PN), particulate phosphorus (PP), and total suspended solids (TSS), all according to standard methods. Because base flow samples were almost always visually clear, TSS was only conducted on the storm samples.

Results and Discussion

Spatial patterning

The first of the two research questions was initially addressed by graphing the average pollutant concentrations at each sampling location during both storm flow and low flow conditions (Figure 2). Subsequent statistical tests were performed on the data based on the classification of each sampling location as either crop, pasture or forest, its primary land use. These included one-way analysis of variance and Kruskal-Wallis tests, to

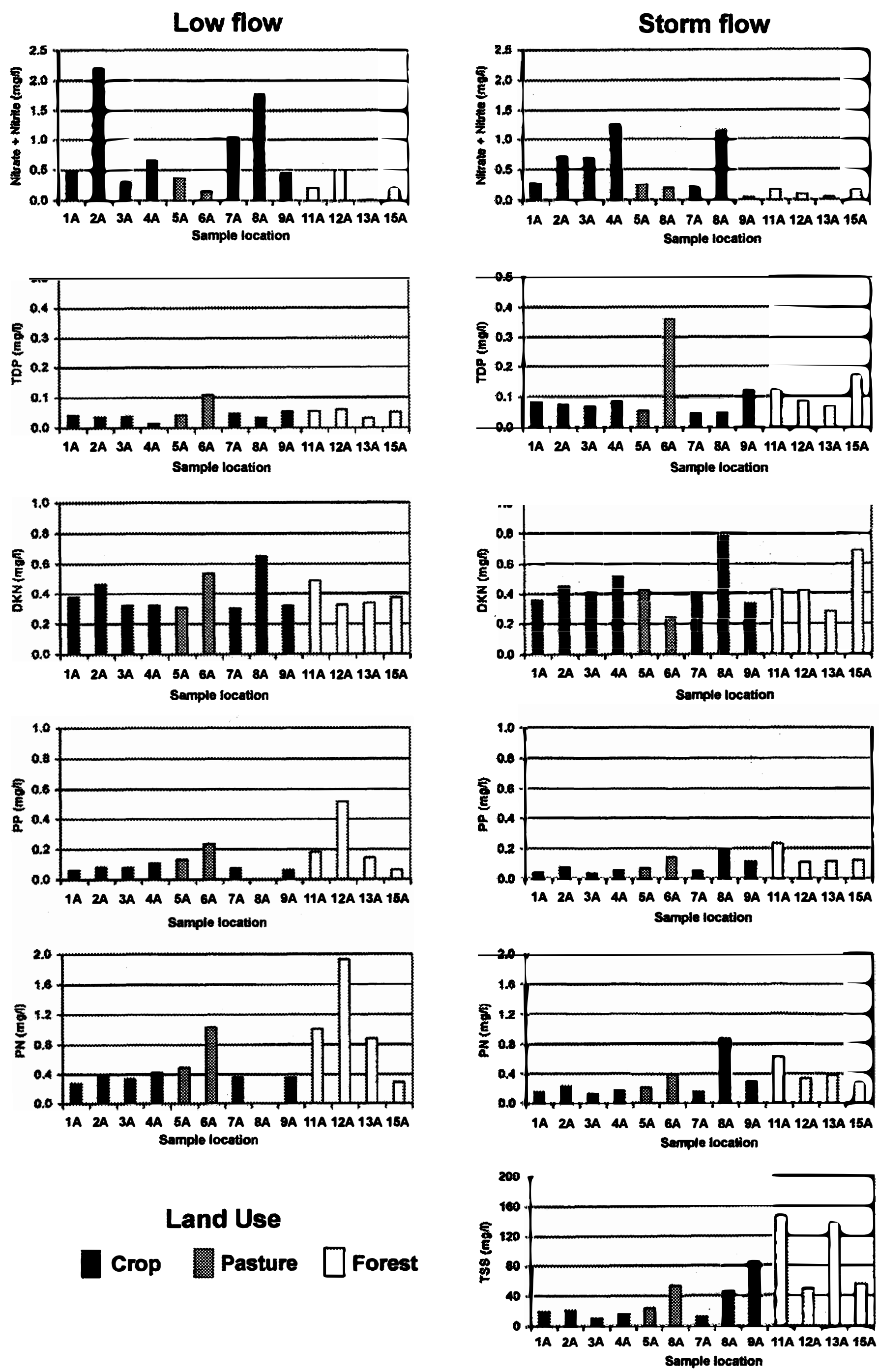

Figure 2. Average pollutant concentrations at each sampling location during both storm flow and low flow conditions in relation to land use.

determine whether the means of the three land use groups were significantly different, and the post hoc Scheffe test, used to determine, specifically, which land use groups had significantly different pollutant concentrations. These results are summarized in Table 1.

The average pollutant concentration data show that the cultivated fields contributed a relatively large proportion of nitrate-plus-nitrite to the total basin export due to the leaching of unused nitrogen-based fertilizer from fields. Mean concentrations during low flow and storm flow were 0.877 and 0.665 mg/l, respectively, both significantly higher than either the pasture or forest sample means. This suggests that nitrification occurs readily in these soils, because nitrate must be converted from the ammonia form found in fertilizer. Phosphorus concentrations at the site draining the pasture (6A) were consistently high due to leaching and/or runoff of phosphorus in livestock waste. The forested portion of the basin contributed disproportionately large amounts of PN and PP to the total basin export, specifically under low flow conditions, where mean concentrations were at least double those found in samples draining cropland (Table 1). Somewhat surprisingly, TSS values were also significantly elevated in the forested area, with mean concentrations almost three times those found under crop or pasture. This was the result of the erosion of highly unstable, devegetated ditch banks just upstream from site 13A which then drained directly into the main collector ditch at site 11A. TSS values were also significantly higher at site 9A in the main channel and at site 8A, a tributary ditch draining tobacco and cotton fields. The main channel site at 9A was just downstream of the ditch site at 10A (see Figure 1) which had become clogged with several tons of sediment eroded off the adjacent field via an extensive network of rills. Although some of this sediment made it out of the ditch system and into the main channel, elevating TSS values there, it is clear that dense vegetation in and around the cropland ditches contributed to the trapping of sediment, making them in effect long-term stores of material. Thus, on-site rates of erosion on these fields are most likely much higher than downstream yields suggest. In fact, runoff samples collected from field slopes adjacent to the ditches at 10A and 11A during the September 28 storm showed TSS concentrations *at least* an order of magnitude greater than those sampled at the basin outlet. Similar findings have been reported by others working in basins in this region (see Slattery *et al.*, 1998).

Temporal patterning

The pollutant concentration data for all

Table 1. Mean pollutant concentrations for all sites during low flow and storm flow conditions.

Low Flow

	NO3 + NO2 (mg/l)	TDP (mg/l)	DKN (mg/l)	PP (mg/l)	PN (mg/l)
Crop	0.877	0.039	0.379	0.077	0.345
Pasture	0.315	0.061	0.373	0.163	0.651
Forest	0.241	0.048	0.374	0.215	0.987

Storm Flow

	NO3 + NO2 (mg/l)	TDP (mg/l)	DKN (mg/l)	PP (mg/l)	PN (mg/l)	TSS (mg/l)
Crop	0.665	0.084	0.457	0.121	0.342	51.095
Pasture	0.248	0.131	0.381	0.086	0.254	31.345
Forest	0.139	0.123	0.486	0.153	0.421	91.016

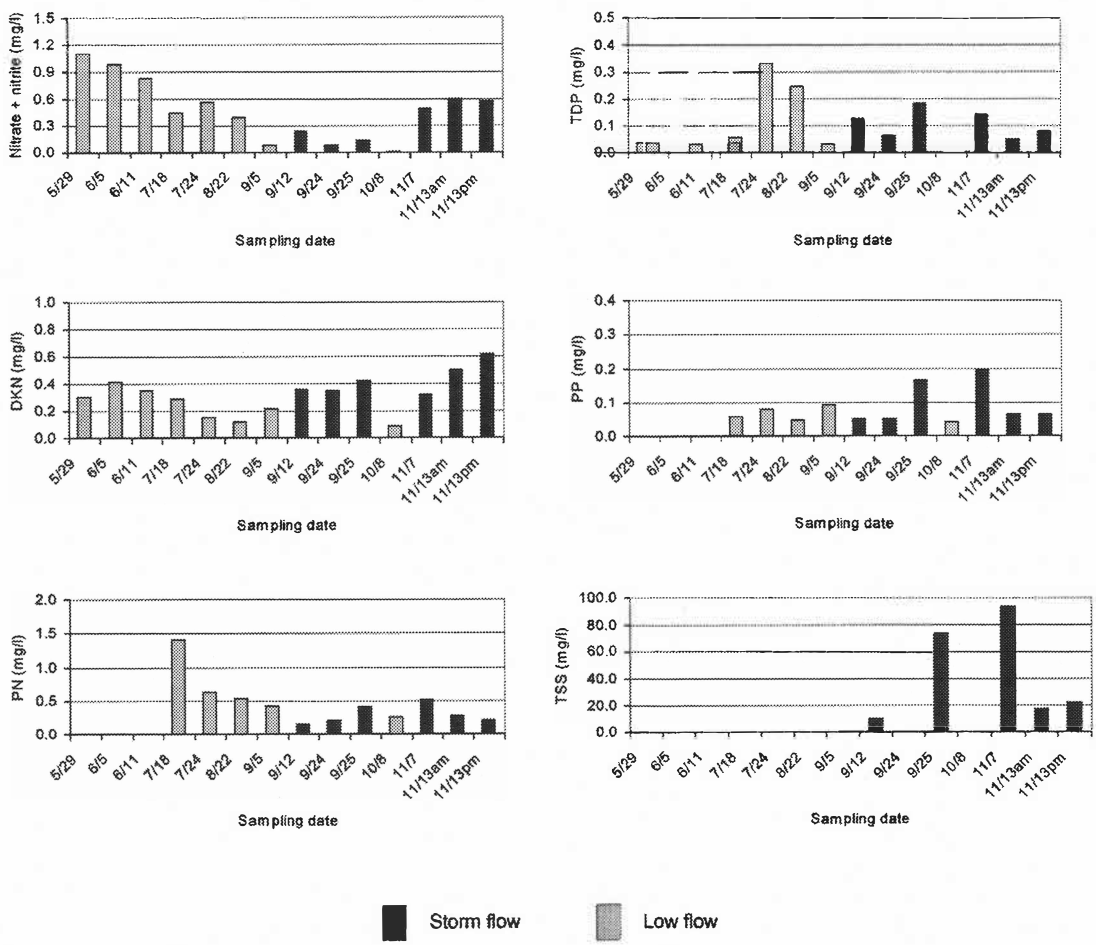

Figure 3. The pollutant concentration data for all sites averaged for each sampling date during the study period.

sites were averaged for each sampling date and then graphed to show temporal variation during the study period (Figure 3). Under low flow conditions, nitrate-plus-nitrite, DKN and PN all show a clear declining trend during the summer period, reaching their lowest values during the early fall (i.e., October 8). TDP showed little temporal variation with the exception of elevated concentrations on July 24 and August 22. Similarly, PP concentrations were also relatively uniform during the sampling period. During storm conditions, however, pollutant concentrations became elevated, specifically for nitrate-plus-nitrite, DKN, TDP and PP. Because TSS concentrations were measured only during storm events, the only discernible pattern in Figure 3 is that levels were highest during the November 7 storm, when runoff was greatest.

The data shown in Figure 3 were examined more closely with regard to the timing and rates of fertilizer application, crop harvest, precipitation, and discharge. While spatial averaging of the data was useful in detecting general temporal trends, pollutant flux still had to be examined at *each* sampling point over time due to the distinct spatial aspects of fertilizer application and crop harvesting, and also because subtle

Table 2. Mean pollutant concentrations during low flow and storm flow conditions at the basin outlet.

	NO3 + NO2 (mg/l)	TDP (mg/l)	DKN (mg/l)	PP (mg/l)	PN (mg/l)
Low Flow	0.506	0.042	0.379	0.065	0.273
Storm Flow	0.661	0.085	0.456	0.125	0.348

temporal patterns became masked at the more general scale.

Fertilizer application took place in April on the cotton, corn, and tobacco fields, and again in June on the cotton fields. The fertilizer used contained different proportions of nitrogen, phosphorus, and potash (a combination of potassium and oxygen) for each crop. The steady decrease in nitrogen-based pollutants over the summer period, specifically nitrate-plus-nitrite, therefore fits well with the expected leaching of fertilizer which tends to occur fairly soon after application. The cotton was harvested in mid to late November while corn was harvested in late October. The tobacco was harvested in stages beginning in mid July and was completed by September. The difficulty here was determining whether the fall and early winter increase in nutrient concentrations was the result of increased flow or the crop harvest itself. Certainly, nitrogen is most readily lost through leaching to drainage waters and streams during periods of heavy rain. But it is also well known that when crops mature and are harvested, much soluble nitrogen remains in the soil, mainly in the form of nitrates. If the nitrogen is not captured by a cover crop planted at harvest time, as was the case at Littlefield, the nitrogen is subject to leaching during the spring and winter months. The most likely scenario here is that both effects are manifest in the data.

Mean pollutant concentrations were then computed for each pollutant for all samples taken at the basin outlet under both low flow and storm flow conditions (Table 2). An independent sample t-test was subsequently performed on the data to determine whether the base flow and storm flow concentrations were significantly different. While the storm flow pollutant concentrations all appear to be consistently higher than the base flow concentrations, onlyTDP and PP were found to be statistically significantly different.

The storm data were subjected to more detailed hydrograph and chemograph analysis, including analysis of storm hysteresis loops for each pollutant. While the results of this analysis are presented in detail elsewhere (Slattery and Cappiella, in prep.), two points are worth noting here. First, we found that, generally, PP, PN, and TSS were directly related to discharge during storms, while nitrate-plus-nitrite was inversely related to discharge (TDP and DKN showed no clear relationship with discharge). And second, the two September storms were generally characterized by positive hysteresis (i.e., pollutant-discharge lead), while the November storms generally showed negative hysteresis (i.e., pollutant-discharge lag). The flushing out of sediment and particulates stored in the stream channel was the cause of positive hysteresis in the TSS, PP, and PN relationship during the September 24-25 storm. On November 7, TSS, PP, and PN concentrations showed negative hysteresis with discharge, which suggests that the source of these pollutants is the severely eroded upper basin ditch banks, which were shown earlier to contribute a disproportionately high amount of these pollutants to the total basin export. Negative hysteresis shown by nitrate-plus-nitrite concentrations on November 12-14 indicated that a large proportion of this pollutant was transported in subsurface flow. This was confirmed by field runoff data collected on several slopes. These data showed that the concentrations of all pollutants, with the exception of nitrate-plus-nitrite, decreased with the movement of storm water from the field slopes to the basin outlet. In particular, the TSS, PP, and PN concentrations found at the outlet are at least an order of magnitude lower than those found on the slopes. This indicates that a significant amount of deposition occurs in the fields and along the stream channel. TDP and DKN concentrations were higher in the field runoff than at the outlet due to the transformation of ammonia to nitrate and the sedimentation of phosphorus in the stream channel, as well as the uptake of orthophosphate and ammonia by aquatic plants. Nitrate-plus-nitrite exports at the outlet were significantly greater than what was found in the field runoff, suggesting that much of this compound is transported by subsurface flow.

Conclusions

The goals of the NCDEM for the Neuse River basin are to reduce total nitrogen and total phosphorus concentrations by 30% and 50%, respectively, through the implementation of Best Management Practices, which also reduce erosion of sediment. The pollutant concentrations and exports found in this study are, *overall*, relatively low and may not contribute significantly to pollutant levels in the Neuse River. However, possible problem areas identified in this study include the leaching of nitrate from croplands, and the erosion of certain portions of the study basin. The latter problem may not ultimately affect water quality in the Neuse River because the majority of the sediment does not leave the study site; however, it does have implications for soil fertility, agricultural costs, and water quality within the study area. Possible solutions for this problem include stabilization of the ditches in the upper basin with vegetative buffers, and use of Best Management Practices on croplands to prevent rill formation and soil erosion. Specific ways to reduce leaching of nitrate from croplands include: using time release fertilizers, nitrification inhibitors, and no-till methods, as well as by denitrifying standing pools of collected runoff from fields.

The results of this study may be applicable to the coastal plain in general, or to catchments with similar soil types, drainage, topography, and basin areas. More studies of this type are needed to further increase our understanding about how non-point source pollutants are processed in their movement from fields to the basin outlet in order to reduce sediment and nutrient pollution in the Neuse River basin.

References

Jacobs, T.C. and **Gilliam, J. W.** (1993) *Nitrate Loss from Agricultural Drainage Waters: Implication for Nonpoint Source Control.* WRRI report no. 209. Chapel Hill, NC: Water Resources Research Institute.

North Carolina Division of Environmental Management (NCDEM) (1997) *Neuse River Basinwide Water Quality Management Plan*. Raleigh, NC: NCDEM.

Phillips, J.D.; Wyrick, M.J.; Robbins, J.G. and **Flynn, M.** (1993) "Accelerated Erosion on the North Carolina Coastal Plain," *Physical Geography* 14: 114-130.

Phillips, J.D. (1997) "A Short History of a Flat Place: Three Centuries of Geomorphic Change in the Croatan,." *Annals of the Association of American Geographers* 87: 197-216.

Phillips, J.D.; Golden, H.; Cappiella, K.; Andrews, B.; Middleton, T.; Downer, D.; Kelli, D. and **Padrick, L.** (1999) "Soil Redistribution and Pedologic Transformations in Coastal Plain Croplands," *Earth Surface Processes and Landforms* 24: 23-39.

Slattery, M.C.; Gares, P.A. and **Phillips, J.D.** (1998) "Quantifying soil erosion and sediment delivery on North Carolina Coastal Plain croplands," *Conservation Voices* 1(2): 20-25.

Slattery, M.C. and **Cappiella, K.** in prep. "Pollutant dynamics in a small coastal plain watershed, North Carolina."