Effects of Stream Channelization on Exports of Nitrogen and Phosphorus from North Carolina Coastal Plain Watersheds

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ABSTRACT / Nitrogen and phosphorus exports from channelized-stream watersheds were elevated over those from nearby natural swamp-stream watersheds. Nitrate exports were significantly greater from channelized-stream watersheds, and higher exports were attributed to faster groundwater drawdown, continual streamflow, and transformation of former floodplain to croplands following channelization. Exports of total organic nitrogen and total nitrogen were also significantly greater from channelized-stream watersheds. Differences in the exports of ammonium, filterable reactive phosphorus, and filterable unreactive phosphorus between the two watershed types were not detectable. Particulate phosphorus exports were significantly higher from channelized-stream watersheds, presumably because of greater erosion potential of nearby croplands and steep channel banks in the altered watersheds. The presence of nonpoint sources of pollution increased watershed exports of nutrients regardless of stream morphology. Examination of nutrient budgets for a portion of swamp floodplain at the base of one natural-stream watershed revealed that changes in local groundwater hydrology and stream morphology associated with channelization appeared to have greater effect on nutrient exports than simply the loss of bordering forested floodplain.

Bottomland hardwood swamps occur along many small streams originating in the coastal plain of North Carolina. Many of these swamp-stream systems have been eliminated by stream channelization, which is performed to facilitate runoff and to lower groundwater tables in croplands bordering stream floodplains. Channelization isolates streams from their former floodplains by deepening channels and creating spoil berms along the sides of the streams. After channelization former floodplains often become croplands.

The loss of swamp floodplains in this manner could significantly alter exports of nitrogen and phosphorus from previously swamp-drained agricultural watersheds. Several researchers have shown that forested swamps can effectively trap nutrients, thus lessening exports to downstream rivers and estuaries. A hardwood swamp in Florida retained significant amounts of total nitrogen inputs (Boyt and others 1977). Forested swamps in Illinois, Florida, Canada, North Carolina, and Louisiana filtered out portions of phosphorus received in rainfall, streamflow, sewage effluent, and livestock wastes (Mitsch and others 1979, Boyt and others 1977, Nessel 1978, Hartland-Rowe and Wright 1975, Yarbro 1983, Day and others 1976). Data gathered to examine the effects of channelization of swamp-streams on water quality (Kuenzler and others 1977) are used here to calculate budgets of nitrogen and phosphorus for watersheds drained by swamp-streams (natural) and channelized streams. Budgets of nitrogen and phosphorus for a swamp floodplain at the base of one natural-stream watershed were calculated to determine whether the floodplain itself was responsible for smaller nutrient exports from natural-stream watersheds.

KEY WORDS: Watersheds; Budgets; Nitrogen; Phosphorus; Channelization; Swamps; Floodplain

Study Area

Seven watersheds in the coastal plain of North Carolina were selected for study (Figure 1). The streams draining three watersheds were natural, shallow and broad with bordering floodplain swamp, whereas streams draining four watersheds had been channelized 2–55 years prior to our study (Table 1). The study area is flat to gently rolling with interstream areas in the upper portions of the watersheds characterized by pocosins, boggy lands with very low relief covered by ericaceous shrubs and pond pine (*Pinus serotina*). Stream slopes are low, 0.022%–0.094% (Table 1). Soils are primarily acidic, strongly leached sands and clays deposited during Pleistocene rises in sea level, and fluvial and aeolian sands of Holocene age (Sumsion 1970, US Dept. of Agriculture 1974). Sediments in stream bottoms and floodplains are mostly silt and clay with considerable organic matter in some areas (Maki and others 1980).

The climate is temperate and moist with cool winters and

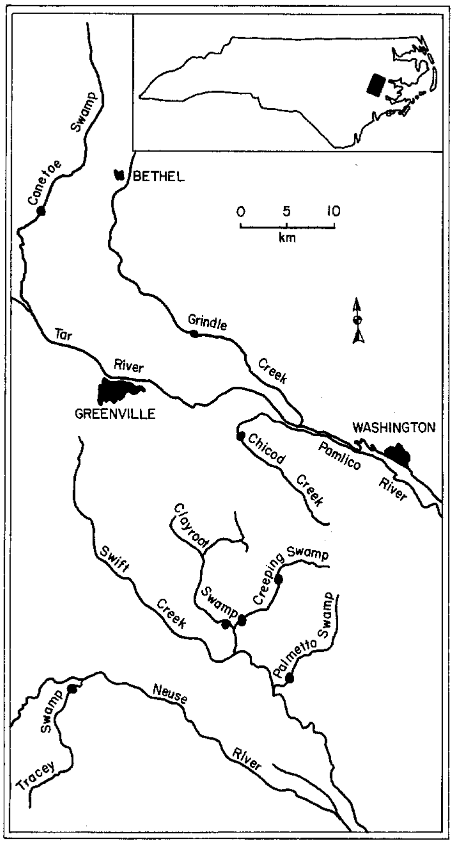

Figure 1. The study region in the coastal plain of North Carolina. Solid circles show location of stream sampling stations. From Kuenzler and others (1977).

warm summers. Precipitation averages 122 cm/yr and is evenly distributed throughout the year (Sumsion 1970). Runoff and floodplain inundation are seasonal with maxima in the winter and early spring and minima in late summer and autumn (US Geological Survey 1975–1979), but daily streamflow at all times of the year may vary widely in response to rainfall events. During the summer and autumn, streamflow, particularly in the natural streams, may become intermittent. However, heavy rainfall during the growing season may result in high discharge and flooding of natural-stream floodplains. Channelized streams may flow over their banks or berms for a few days during infrequent heavy storm events in the winter. Annual runoff is 25%–40% of precipitation with channelized streams having relatively greater runoff than natural streams (US Geological Survey 1975–1979).

The watersheds studied range from 54 to 176 km^2 in area, and most are predominantly wooded (Table 1). Nonwooded areas consist of cropland, recently timbered areas, and young pine plantations. Cropland drainage is improved by ditching, but fields are not tiled. Human population densities varied from 8.7 to 29 people per km^2 (Table 1) in the respective watersheds during the study period. Highest densities in Tracey Swamp and Grindle Creek watersheds resulted from contributions from small urban and suburban areas. Hog and chicken raising occurred to a greater extent than cattle raising, but greatest differences among watersheds occurred in the number of chickens per square kilometer. Streams in four watersheds directly received pollutants during our study: Chicod Creek, Creeping Swamp, and Clayroot Swamp received wastes from livestock farms, and Grindle Creek received sewage effluent from the town of Bethel (7500 kg total nitrogen/yr and 2000 kg total phosphorus/yr).

Water quality of the natural streams is typical of those of the southeastern coastal plain: moderately acid (pH 5.0–6.3), yellow-stained (color 75–127 std. Pt units) but clear (turbidity 5.6–15 JTU) and having relatively low specific conductance (66–122 μmhos/cm) and levels of nutrients (Kuenzler and others 1977). Flow-weighted average concentrations of ammonium, nitrate, and total organic nitrogen range from 0.03 to 0.70, 0.02 to 0.27, and 0.20 to 0.35 mg/l, respectively, whereas average flow-weighted filterable reactive and particulate phosphorus concentrations range from 0.002 to 0.08, and 0.004 to 0.13 mg/l, respectively. Channelized streams tend to be higher in pH (6.0–7.0), more turbid (15–34 JTU), and to have greater specific conductance (69–172 μmhos/cm) but less color (40–84 std. Pt units). Flow-weighted concentrations of ammonium, total organic nitrogen, and filterable reactive phosphorus in channelized streams are similar to values found in natural streams, but levels of particulate phosphorus and nitrate are, in general, greater in channelized streams. However, statistical differences (two-tailed Wilcoxon signed rank test) between stream types were significant ($P < 0.05$) only for nitrate concentrations (Kuenzler and others 1977).

Methods

Hydrologic Measurements

The US Geological Survey maintained stream gauging stations on Creeping Swamp, Palmetto Swamp, Conetoe Creek, and Chicod Creek (1976 only). Annual runoff for Grindle Creek was estimated by using runoff values from nearby Conetoe Creek for the same time period. Runoff from Chicod Creek during 1975 was calculated by using runoff from the downstream Creeping Swamp gauging station. Runoff from Tracey Swamp and Clayroot Swamp was estimated as 1.2 times runoff from downstream Creeping Swamp because data from a nearby gauged channelized stream was not available and runoff from channelized streams tended to be slightly greater than runoff from natural streams on an areal basis (US

Table 1. Characteristics of watersheds chosen for study.

Watershed	Watershed area (km^2)	% Area in forests	Stream slope (%)	Human population density[3] (no./km^2)	Livestock densities (no./km^2) Cattle	Hogs	Chickens[4]
Natural streams							
Upstream Creeping Swamp	32	62	N/A[2]				
Downstream Creeping Swamp	80	68	0.059	15	3.3	20	230
Palmetto Swamp	54	61	0.076	14	1.5	8.7	96
Chicod Creek	132	56	0.094	14	4.6	27	330
Channelized streams							
Tracey Swamp (1973)[1]	141	68	0.054	22	2.4	16	180
Grindle Creek (1966)[1]	140	59	0.038	29	5.0	32	450
Conetoe Creek (1971)[1]	176	48	0.027	8.7	8.8	26	72
Clayroot Swamp (1919)[1]	110	60	0.022	16	5.0	32	450

[1]Date channelization completed.

[2]Not available.

[3]1977 census.

[4]Broilers constituted about 90% of all fowl but are not included in these numbers. Values, therefore, are low by a factor of ~10.

Geological Survey, 1975–1979). During simultaneous gauging at both locations on Creeping Swamp for several years, runoff from the upstream station was about 90% of runoff from the downstream station. Runoff from the upstream station in 1977 and 1978 was calculated by applying this fraction to runoff from the downstream station over the same period.

Instantaneous discharge from tributaries entering the Creeping Swamp study area was obtained from discharge-water-level relationships calibrated on site for each stream by Mulholland (1979). Annual runoff from these tributaries was estimated by regressing daily discharge at the downstream gauging station (CP-10) with periodic measurements of daily discharge from each tributary (r^2 = 0.72–0.93). The slope of the regression was then multiplied by the annual runoff (in meters) from Creeping Swamp to obtain runoff values for each tributary.

Precipitation was measured daily at the North Carolina Forest Service fire tower in Wilmar, NC, about 5 km from the study area.

Field Sampling

Each of the seven major streams was sampled at bridge crossings (Figure 1) during appreciable flow (>0.05 m^3/s). All streams, except Clayroot Swamp, were sampled at six-week intervals during 1975 (Table 1). In 1976, all streams except Conetoe Creek and Grindle Creek were sampled at monthly intervals, and sampling of the Creeping Swamp tributaries began. Sampling at monthly intervals and during three storm runoff events continued in Creeping Swamp through 1978. Intensive study of Creeping Swamp during 1976–1978 included sampling of the creek (CP-20, CP-10) and its major tributaries (TB-01, TB-02, TB-03, TB-04, TB-07) (Figure 2).

Water samples for nitrogen and phosphorus determinations were collected from the centers of the streams. Unfiltered samples were poured directly into acid-washed polyethylene bottles. Samples for filterable forms of nutrients were passed through prewashed 0.45-μm-membrane filters (Gelman Metricel GA-6) with prewashed glass fiber (Gelman AE) prefilters and stored in acid-washed polyethylene bottles. All samples were either frozen immediately or stored on ice, returned to the laboratory and frozen there.

Bulk precipitation was collected at three stations in the Creeping Swamp study area by polyethylene funnels mounted on wooden frames 1.0–1.5 m above the ground and connected to plastic bottles by rubber tubing. The funnels were covered by nylon mesh (0.25 mm) and contained glass wool to exclude debris. Precipitation volumes were measured every two weeks, and samples for nitrogen and phosphorus analysis were collected every four weeks from August 1976 through August

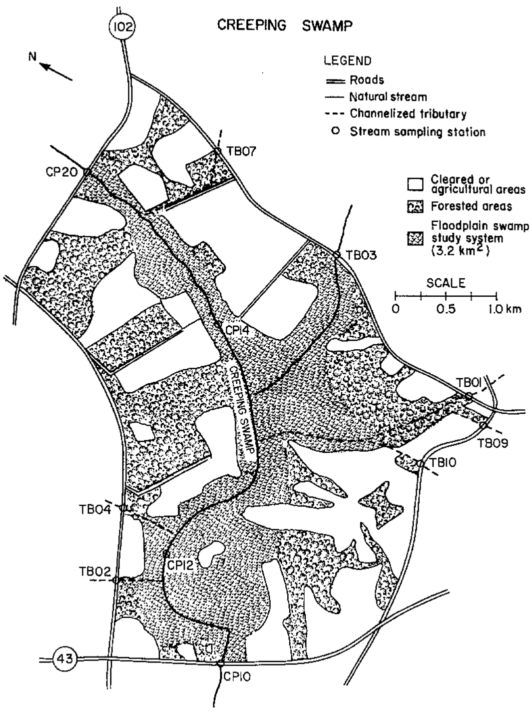

Figure 2. The Creeping Swamp floodplain study area.

1978 and consisted of rainfall intercepted during the previous two weeks. Samples were preserved in the field using $HgCl_2$ (American Public Health Association 1975).

Laboratory Analyses

Duplicate analyses of the various forms of nitrogen and phosphorus were made using a Technicon AutoAnalyzer. Nitrate (NO_3^-) was measured by the hydrazine reduction technique (US Environmental Protection Agency 1974), ammonium (NH_4^+) by a phenolate colorimetric technique (US Environmental Protection Agency 1974), and total (unfiltered) organic nitrogen (TON) was determined by measurement of total Kjeldahl nitrogen (TKN), from which ammonium concentrations were subtracted ($TON = TKN - NH_4^+$). Total Kjeldahl nitrogen was measured by digestion and phenolate colorimetric analysis of the evolved ammonium (US Environmental Protection Agency 1974). Recoveries of known additions of organic nitrogen were only about 60% because of incomplete sample digestion; therefore TKN concentrations were corrected by multiplying by 1.67. Recoveries of standard additions of ammonium and nitrate were nearly complete.

Phosphorus species were separated by filtration and chemical analysis into the following forms: (a) filterable reactive phosphorus (FRP), (b) total filterable phosphorus (TFP), and (c) total phosphorus (TP). FRP was determined by the stannous chloride method (US Environmental Protection Agency 1974). Beginning in 1977, interference by the natural color of the water was corrected using color blanks. TFP and TP were measured by persulfate oxidation followed by the stannous chloride procedure. Filterable unreactive phosphorus (FUP) was calculated as the difference between TFP and FRP, and particulate phosphorus (PP) was calculated as the difference between TP and TFP.

Data Analysis

Annual weighted mean concentrations of nitrogen and phosphorus in stream water and bulk precipitation were calculated using instantaneous discharge and rainfall volumes, respectively, as weighting factors. Annual fluxes were calculated as the product of the annual flow- or volume-weighted mean concentrations and annual runoff and annual precipitation volumes, respectively (Likens and others 1977). Nitrogen concentrations in precipitation were measured only in 1976, and average values from this year were multiplied by 1975 volume data to obtain fluxes for 1975. As an indication of the nutrient retention capacity of the watersheds, total annual nitrogen and phosphorus exports were compared with precipitation inputs. Differences in exports between the two watershed types were tested statistically by using a two-tailed Wilcoxon signed rank test (Sokal and Rohlf 1981).

Results

Watershed Fluxes of Nitrogen and Phosphorus

Precipitation inputs of total nitrogen to the seven watersheds varied from 700 to 910 $kg/km^2/yr$ in 1975 and 1976 and were distributed relatively evenly among the three nitrogen species (Figure 3). Phosphorus inputs in precipitation were considerably smaller than nitrogen inputs, varying from 41 to 81 kg $TP/km^2/yr$ (Figure 4).

Most watershed exports of nitrogen were less than precipitation inputs, and, in general, exports were considerably lower in watersheds with natural streams than in watersheds with channelized streams (Figure 3). Lowest nitrogen exports were observed in the relatively undisturbed upstream portion of the Creeping Swamp watershed, comprising only 7.6% and 9.4% of total precipitation inputs for 1975 and 1976, respectively. Total organic nitrogen was the largest component of nitrogen export from the upstream portion of Creeping Swamp. Nitrogen exports from the entire Creeping Swamp watershed (which included the upstream watershed) were greater than exports from the upstream portion of the watershed, particularly for nitrate and ammonium. The increase in exports

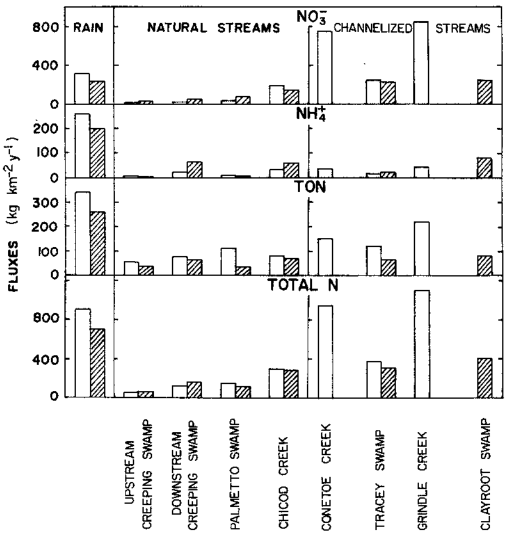

Figure 3. Nitrogen inputs to watersheds via bulk precipitation and exports of nitrogen from natural- and channelized-stream watersheds. Open bars represent data from 1975; cross-hatched bars represent data from 1976.

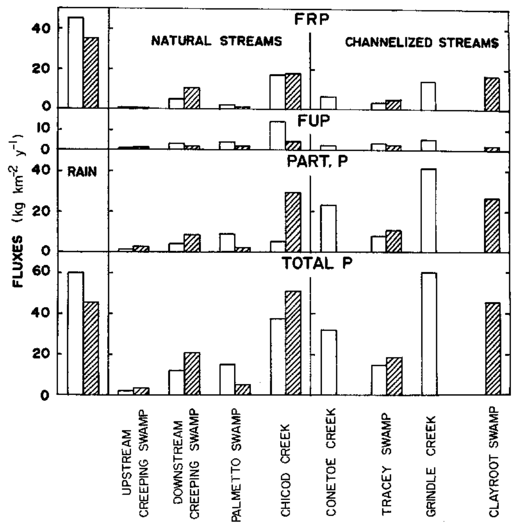

Figure 4. Phosphorus inputs to watersheds via bulk precipitation and exports of phosphorus from natural- and channelized-stream watersheds. Open bars represent data from 1975; cross-hatched bars represent data from 1976.

resulted in part from hog farm wastes discharged into the lower portion of the Creeping Swamp floodplain. Total nitrogen exports from the entire Creeping Swamp and Palmetto Swamp watersheds were 13%–16% and 17%–24% of annual precipitation inputs in 1975 and 1976, respectively. The Chicod Creek watershed, which received wastes from several hog and chicken farms, had the highest nitrogen exports of the natural-stream watersheds, 33% and 40% of precipitation inputs for 1975 and 1976, respectively.

Total nitrogen exports from channelized-stream watersheds were significantly ($P < 0.01$) greater than exports from natural-stream watersheds, largely as the result of significantly ($P < 0.01$) higher nitrate exports (Figure 3). TON exports from the channelized-stream watersheds were significantly ($P = 0.05$), but only slightly, greater than natural-stream watershed exports, and ammonium exports were similar in both watershed types. Greatest total nitrogen export occurred from Grindle Creek, which received treated sewage effluent. Among the channelized-stream watersheds, lowest nitrate losses were observed from Tracey Swamp whose stream, despite channelization, most closely resembled natural swamp streams in color, and concentrations of nitrogen and phosphorus (Kuenzler and others 1977). Total nitrogen exports from Conetoe Creek and Grindle Creek watersheds were slightly greater than total precipitation inputs in 1975. Nitrogen losses from Tracey Swamp and Clayroot Swamp ranged from 37% to 47% of precipitation inputs.

Phosphorus exports were considerably lower than nitrogen exports, and differences between natural streams and channelized streams were less distinct (Figure 4). Significant differences between watershed types were found only for exports of particulate phosphorus ($P = 0.05$). Lowest annual losses of phosphorus occurred in the upstream portion of Creeping Swamp watershed, comprising 4.0% and 7.6% of precipitation inputs in 1975 and 1976, respectively. Most of the phosphorus was exported as the particulate fraction. Phosphorus exports from the entire Creeping Swamp watershed increased sharply over those of the upstream watershed, particularly for FRP, probably because of large inputs from the hog farm. Exports from the Palmetto Swamp watershed were intermediate between the two Creeping Swamp watersheds, and exports from the Chicod Creek watershed were the highest calculated for any of the natural watersheds (60% and 111% of 1976 and 1976 precipitation inputs). FRP comprised the largest fraction of Chicod Creek exports.

Phosphorus exports from the channelized Conetoe Creek and Grindle Creek watersheds were much greater than exports from any of the natural-stream watersheds. Tracey Swamp exports were similar to those of entire Creeping Swamp watershed, and exports from Clayroot Swamp watershed were close to those observed in the Chicod Creek watershed. FUP losses from the channelized-stream watersheds were low compared with exports of other forms of phosphorus. Phosphorus exports were 22% to 107% of precipitation inputs in the channelized-stream watersheds.

Table 2. Annual budgets of nitrogen and phosphorus in the 3.2 km^2 area of Creeping Swamp floodplain.

	Import or export (kg/yr)							
	NO_3	NH_4	TON	TN	FRP	FUP	PP	TP
1976								
Imports								
Precipitation	770	640	830	2,200	110			150
Streams								
CP-20	790	120	1,200	2,100	11	28	74	110
TB-01	540	33	270	840	6.4	6.3	19	32
TB-03	170	30	120	320	1.8	3.5	4.4	9.7
TB-07	160	42	260	460	9.1	4.5	21	35
TB-04	350	54	310	710	18	10	44	72
TB-02	1,500	7,600	1,900	11,000	1,600	64	610	2,300
Unmeas. runoff[1]	390	71	290	750	4.2	3.4	10	23
Total	4,700	8,600	5,200	18,000	1,800	120	780	2,700
Export								
CP-10	3,900	5,000	5,000	14,000	870	160	680	1,700
% Retained:	17	42	4.8	22	52	0	13	37
1977								
Imports								
Precipitation					190			260
Streams								
CP-20					85	130	160	380
TB-01					13	18	54	85
TB-03					6.4	15	22	43
TB-07					20	20	20	60
TB-04					33	38	69	140
TB-02					880	190	270	1,300
Unmeas. runoff[1]					13	31	45	89
Total					1,200	440	640	2,400
Export								
CP-10					230	530	590	1,400
% Retained:					81	0	8	42

[1]Calculated using CP-20 areal runoff value for 12.8 km^2 of uplands inside study area and TB-03 annual weighted concentrations.

Nitrogen and Phosphorus Budgets for the Creeping Swamp Floodplain Ecosystem

Inputs of nitrogen and phosphorus to the Creeping Swamp floodplain occurred primarily in precipitation and streamwater (Table 2). Inputs via groundwater inflow were very low because of low groundwater influx rates (<5% of total CP-10 runoff, Yarbro 1979) and low concentrations of nitrogen and phosphorus in shallow groundwaters (Kuenzler and others 1977). Exports from the floodplain occurred only in surface runoff at CP-10 (Winner and Simmons 1977).

Precipitation inputs of nitrogen and phosphorus were small compared with the total input from streams, although they were comparable to or exceeded levels brought in by some of the tributaries (Table 2). In 1976, extremely high loads of all forms of nitrogen and FRP were introduced by TB-02, which was channelized and received wastes from a poorly managed hog farm. Much lower inputs were calculated for the other tributaries, especially for TB-03 which had a natural channel and drained swamp floodplain. Ammonium inputs were usually quite low, except in TB-02 where inputs were 69% of the total nitrogen input. Particulate phosphorus was the most important constituent of total phosphorus inputs in all streams except TB-02.

In 1976, total nitrogen and phosphorus exports from the floodplain ecosystem were less than total inputs, but greater amounts of organic phosphorus (FUP) left the swamp than entered it. Nitrate inputs to the swamp exceeded exports by only 17%. Ammonium and FRP were strongly retained within the swamp, and approximately 13% of the particulate phosphorus entering the swamp was retained in 1976. Overall inputs and exports of phosphorus were less in 1977 because of much smaller inputs via TB-02. The hog farm ceased operating in December 1976, but phosphorus concentrations in

TB-02 had not declined to levels similar to other tributaries as late as June 1978 (Yarbro 1979). Slow release of sorbed FRP and flushing of phosphorus-laden particles were probably responsible for the maintenance of high concentrations. A larger fraction of FRP inputs was retained by the swamp in 1977 than in 1976, but greater exports of FUP and a lower retention efficiency for PP resulted in similar retention percentages of total phosphorus for both years.

Discussion

Atmospheric precipitation was not the only source of nitrogen and phosphorus to the watersheds. Fertilizers applied to croplands, septic tank drainage, and hog and chicken farm wastes also contributed nitrogen and phosphorus. Therefore, even for those watersheds where exports were somewhat greater than precipitation inputs, net retention probably occurred. Watersheds with greatest retention of nitrogen and phosphorus were drained by natural streams with bordering floodplain, suggesting that attributes of the natural systems may contribute significantly to nutrient removal. Two primary characteristics were altered by channelization: (a) local groundwater hydrology and the morphology of the stream beds, and (b) the substitution of natural forest vegetation bordering streams by cropland. We now consider how these changes might have influenced fluxes of the different forms of nitrogen and phosphorus from these watersheds.

Natural-stream watersheds exported less nitrate than channelized-stream watersheds, and nitrate exports via natural streams were a wide-ranging fraction (3%–62%) of inputs in bulk precipitation. However, the nitrogen budget of the Creeping Swamp floodplain was nearly in balance with respect to apparent nitrate fluxes, suggesting that the presence of forested swamp floodplain per se was not responsible for lower nitrate exports from natural stream watersheds. We refer to "apparent" nitrate fluxes, because we cannot evaluate the contribution of nitrification of ammonium to nitrate fluxes in either type of watershed. Rather, altered stream morphology resulting from channelization and concomitant changes in land use along stream channels may have produced conditions conducive to greater nitrate loss from channelized-stream watersheds. Deepening of stream channels resulted in greater and sustained base flow derived from local groundwater. Main stream beds in natural floodplains were 0.4–1.0 m below the level of nearby floodplain, whereas beds of channelized streams were 1.3–3.0 m lower than nearby land surfaces. Continuous summertime discharges and significantly higher levels of pH, calcium, magnesium, potassium, aluminum, and silicate in channelized streams indicated the greater contribution of groundwater to streamflow (Kuenzler and others 1977). Continuous streamflow provided a greater opportunity for transport of nitrate from channelized-stream watersheds, particularly during the growing season when applications of fertilizer nitrogen were made. The overriding influence of altered local groundwater hydrology and channel morphology is apparent in the case of nitrate exports from the Clayroot Swamp watershed. This stream was channelized 56 years prior to this study and the channel had been poorly maintained since that time. Considerable siltation in the channel had occurred and forests had grown up along the stream. Nevertheless, nitrate exports were elevated over those from natural stream watersheds.

Lowering of groundwater tables near stream channels after channelization often led to the conversion of former floodplain to cropland. Creation of aerobic soil conditions following drawdown of groundwater tables may have led to greater mineralization rates of soil organic matter and to greater nitrification of ammonium derived from soil organic matter and fertilizers. Gambrell and others (1974) have documented high nitrate concentrations (7–12 mg N/l) in shallow groundwaters of well-drained agricultural soils near our study area. In poorly drained agricultural soils, concentrations were much lower, ranging from 0.2 to 2.5 mg N/l. Gambrell and others found that well-drained conditions resulted in the contribution of three times more nitrate to surface waters than did poorly drained conditions, and they attributed this difference principally to denitrification in poorly drained soils. Denitrification may have been an important process in natural-stream watersheds, but we attribute greater nitrate losses from channelized-stream watersheds to: (a) enhanced transport owing to continuous streamflow derived from lowering of local groundwater tables, (b) the presence of soil conditions conducive to nitrification but not denitrification, and (c) greater local nitrogen inputs via fertilizer application to croplands bordering stream channels.

The small nitrate exports from natural-stream watersheds may be attributed primarily to: (a) longer residence times of shallow groundwater in soils, allowing denitrification to proceed under saturated conditions, (b) the lack of continuous streamflow, particularly in the growing season, and (c) the location of croplands at a considerable distance from stream channels, with forest floodplain intervening. Our results corroborate the study of Jones and others (1976), who found that agricultural watersheds containing wetlands had lower nitrate losses.

Within the Creeping Swamp study area, apparent nitrate retention was not as dramatic as for the entire watershed. The actual removal of nitrate may have been considerably more than appears from the net change if a large portion of the observed ammonium removal took place by nitrification within the swamp system. The hydrology of the Creeping Swamp study area may account for the lack of apparent nitrate removal from incoming surface waters and precipitation. The floodplain is an area of deep-aquifer discharge (Winner and Simmons 1977), thus providing little opportunity for nitrate-laden surface waters to reach underlying anaerobic sediments where denitrification might occur. Conditions conducive to water-column denitrification may have occurred for short periods in pools isolated on the floodplain and for longer periods in stream channel pools when discharge ceased. Most of the time, however, floodwaters were flowing and aerated. Therefore, in the Creeping Swamp watershed, most nitrate removal probably occurred in poorly drained soils in higher portions of the watershed before shallow groundwater reached stream channels.

Ammonium exports from natural and channelized-stream watersheds appeared more closely related to the presence or absence of anthropogenic sources than to stream morphology (Figure 3), and all watersheds showed retention of ammonium. In the Creeping Swamp floodplain, large ammonium removal was observed despite extremely high inputs. Our study does not provide data on relative rates of nitrification, denitrification, and biological immobilization, but Qualls (1981) reported that immobilization by leaf litter was sufficient to remove 25% of the inorganic nitrogen in one linear kilometer of Creeping Swamp.

All watersheds exported less total organic nitrogen than they received in bulk precipitation, but losses were significantly greater from channelized-stream watersheds (Figure 3). Small amounts of total organic nitrogen were retained by the Creeping Swamp floodplain (Table 2), but the difference between inputs and exports is probably within the estimate error. Large inputs from the polluted tributary close to the outlet may have resulted in disproportionately high exports from the floodplain. Natural sources of total organic nitrogen include erosion of soil organic matter and leaching of organic materials; no differentiation among sources for the two watershed types is possible.

All watersheds and the Creeping Swamp floodplain retained net amounts of filterable reactive phosphorus, despite, in some cases, high anthropogenic inputs, but no significant differences in exports between the two watershed types were found. Removal probably occurred via biotic uptake and sorption to clay minerals abundant in surface soils (Parfitt 1978). In the Creeping Swamp floodplain, Yarbro (1983) attributed most short-term net removal of filterable reactive phosphorus to uptake by algae and sorption by the flooded forest floor. The affinity of the highly leached silt and clay soils of the study area for filterable reactive phosphorus undoubtedly lowered the rates and quantities of FRP reaching groundwaters where it was then susceptible to transport from the watershed.

Exports of filterable unreactive phosphorus were similar for all watersheds, despite differing stream morphologies and sources of phosphorus. Net exports were observed in the Creeping Swamp floodplain, agreeing with observations of net exports of organic carbon (Mulholland 1981). From 1976 to 1977, inputs and exports of filterable unreactive phosphorus more than doubled for all streams in the Creeping Swamp study area. Annual surface runoff was twice as high in 1977 as in 1976, suggesting that some of the increased fluxes could be attributed to water-volume-dependent leaching by floodwaters.

Particulate phosphorus losses were significantly greater from channelized-stream watersheds than from natural-stream watersheds. Greater losses from channelized-stream watersheds may have been due to increased erosion potential of exposed stream banks and nearby croplands and to greater stream velocities during storm flow. The Creeping Swamp floodplain retained small amounts of incoming particulate phosphorus carried, for the most part, at low concentrations in stream waters (0.005–0.038 mg P/l, Yarbro 1979). These levels may represent a lower limit of retention capacity of the swamp system.

In general, concentrations of particulate phosphorus and other particulate materials in all the streams were low, a characteristic of coastal plain blackwater streams. This is undoubtedly one reason why the presence of natural forest vegetation bordering stream channels appeared less important in regulating nutrient fluxes from watersheds. Other workers have documented that maintenance of natural streamside vegetation is particularly effective in the removal of sediment and sediment-borne materials from surface runoff (Karr and Schlosser 1978), but has little influence on the removal of dissolved materials carried in subsurface runoff (Omermik and others 1981).

Finally, from a management perspective, the significance of increased total nitrogen exports from channelized-stream watersheds must be considered. The increasing rate of channel modification and land drainage to accommodate agricultural expansion coupled with the sensitivity of downstream nitrogen-poor estuaries to increasing nitrogen inputs suggest that the direct and downstream effects of these land management practices should be weighed carefully against the improvements accrued for agricultural production.

Conclusions

Although comparison of watershed exports with bulk precipitation inputs showed that most watersheds retained nitrogen and phosphorus, exports of some forms of these nutrients were greater from channelized-stream watersheds than from natural-stream watersheds. Greatest differences between watershed types were observed for nitrate exports. Elimination of swamp floodplain, a direct and obvious effect of stream channelization, was probably not so important in altering exports of nitrate as were the effects of groundwater draw-down, continual streamflow, and transformation of former floodplain into cropland. However, the presence of point and nonpoint sources of nutrients, such as sewage effluent and livestock wastes, increased watershed exports regardless of stream morphology. Exports of total organic nitrogen were also greater from channelized-stream watersheds, and overall, losses of total nitrogen were much higher from the altered watersheds. We found no substantial differences in exports of ammonium, filterable reactive phosphorus and filterable unreactive phosphorus between the two watershed types. Losses of particulate phosphorus were higher from channelized-stream watersheds and may have been due to increased erosion potential of steep stream banks and nearby croplands.

Nitrogen and phosphorus budgets for a portion of floodplain at the base of one natural-stream watershed showed retention of 22% and 37%–42% of total nitrogen and total phosphorus, respectively. Most of the retention occurred as ammonium and filterable reactive phosphorus. Limited apparent nitrate retention by the swamp floodplain was attributed to maintenance of aerated conditions in most nitrate-laden surface waters, and to deep-aquifer discharge into the swamp, which prevented surface waters from reaching anaerobic soils where denitrification could occur. Greater nitrate retention may have occurred in the swamp system than was observed if some of the incoming ammonium was nitrified to nitrate and then either denitrified and lost as a gas or exported as nitrate.

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