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NUTRIENT MASS BALANCE FOR THE ALBEMARLE-PAMLICO DRAINAGE BASIN, NORTH CAROLINA AND VIRGINIA, 1990[1]

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ABSTRACT: A 1990 nitrogen and phosphorus mass balance calculated for eight National Stream Quality Accounting Network (NASQAN) basins in the Albemarle-Pamlico Drainage Basin indicated the importance of agricultural nonpoint sources of nitrogen and phosphorus and watershed nitrogen retention and processing capabilities. Basin total nitrogen and phosphorus input estimates were calculated for atmospheric deposition (which averaged 27 percent of total nitrogen inputs and 22 percent of total phosphorus inputs); crop fertilizer (27 and 25 percent); animal-waste (22 and 50 percent, respectively); point sources (3 percent each of total nitrogen and total phosphorus inputs); and biological nitrogen fixation (21 percent of total nitrogen inputs). Highest in-stream nitrogen and phosphorus loads were measured in predominantly agricultural drainage areas. Intermediate loads were observed in mixed agricultural/urban drainage areas; the lowest loads were measured in mixed agricultural/forested drainage areas. The difference between the sum of the nutrient input categories and the sum of the in-stream nutrient loads and crop-harvest nutrient removal was assigned to a residual category for the basin. The residual category averaged 51 percent of total nitrogen inputs and 54 percent of total phosphorus inputs.

(KEY TERMS: mass balance; nutrients outputs; nutrient inputs; nutrient flux; nonpoint source pollution; water quality.)

INTRODUCTION

Despite hundreds of billions of dollars spent during the past two decades on addressing the nation's water-quality concerns, much remains to be learned about how much the nation's water quality has improved. Knopman and Smith (1993) suggested that among the most important remaining scientific challenges are understanding the relative importance of point and nonpoint sources of pollutants for the nation's water quality, and developing well documented and consistent methods for collecting and analyzing data to support such an understanding.

The sources and transport of nutrients into the Albemarle-Pamlico estuary are important regional water-quality concerns. During the past decade, efforts have been made at the national and state levels to identify nitrogen and phosphorus sources and to estimate the amounts of these constituents entering coastal waters (Stanley, 1989, 1993; Dodd *et al.*, 1992; North Carolina Department of Environment, Health, and Natural Resources, 1992, 1993a, b; Smith *et al.*, 1993; Research Triangle Institute, 1994; Puckett, 1995). This article reports on the first systematic estimation of nutrient input and output fluxes for major river basins of the Albemarle-Pamlico drainage system.

The study, which was conducted as part of the U.S. Geological Survey's National Water-Quality Assessment Program (Leahy *et al.*, 1990), estimates the 1990 total nutrient inputs for eight Albemarle-Pamlico National Stream-Quality Accounting Network (NASQAN) basins (Figure 1). Estimates also are presented of annual in-stream loads of nitrogen and phosphorus, nutrient removal through crop harvest, and residual nutrients that cannot otherwise be accounted for. Data for 1990 were the most recent available for all compartments of the mass balance.

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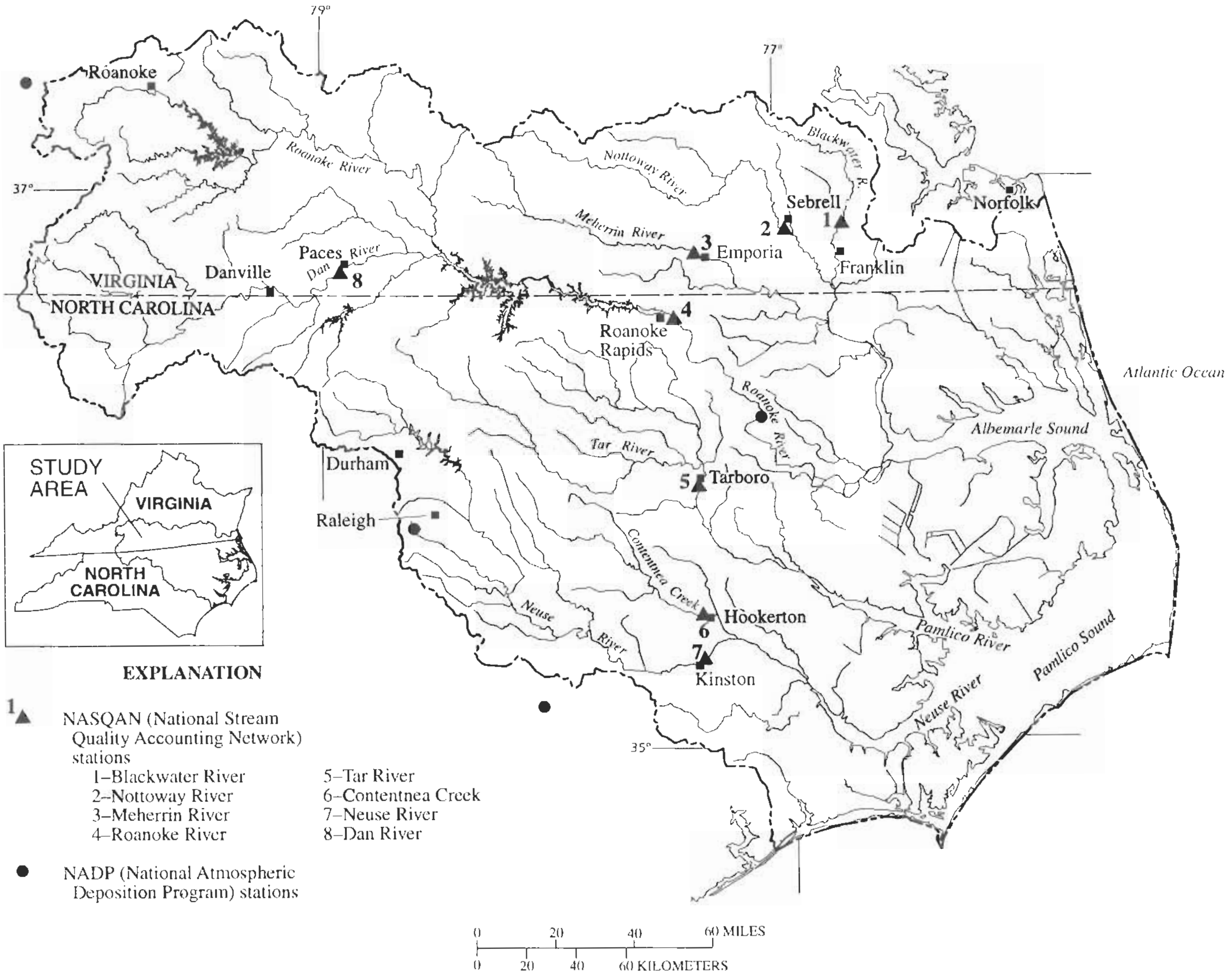


Figure 1. Locations of NASQAN and NADP Stations in and Near the Albemarle-Pamlico Drainage Study Area.

METHODS

Basin Characteristics

The eight basins represent three basin types-agricultural, agricultural/urban, and agricultural/forested (Table 1). This classification, derived from a system presented in Smith *et al.* (1993), can be used for comparing study-area load estimates with national estimates and for understanding differences among the stations. The agricultural class is directly derived from the Smith classification system, whereas the other two categories combine several Smith categories. The Contentnea Creek, Tar River, and Roanoke River Basins had a mix of agricultural and urban characteristics that did not fit neatly into the classification and the final classification of these basins was based on local knowledge. Generally, gaging stations are situated at a location within each basin such that they have a high stream order and can be characterized as low gradient, meandering streams. The exceptions, in the Roanoke and Meherrin basins, are located immediately below reservoirs.

Nutrient Inputs: Atmospheric Deposition

Atmospheric loads of nitrogen were calculated by using water year 1990 (October 1989-September 1990) data from four National Atmospheric Deposition Program/National Trends Network (NADP/NTN) sites located in or adjoining the Albemarle-Pamlico study area (Figure 1; National Atmospheric

TABLE 1. Summary of Agriculture, Agriculture/Urban, and Agriculture/Forest Land-Use Information for the National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area.

[Land-Use Types: Agriculture: greater than 40 percent agricultural land use, less than 40 percent forested, less than 10 percent developed; Agriculture/Urban: greater than 25 percent agricultural, population density greater than 100 people per square mile; Agriculture/Forest: greater than 50 percent forested, less than 40 percent agricultural, less than 10 percent developed; USGS, U.S. Geological Survey; mi^2, square mile; people/mi^2, people per square mile.]

Station Name	Map Location (Figure 1)	USGS Downstream Order Identification Number	Drainage Area (mi^2)	Major Land-Use Types as a Percent of Basin Drainage Area: Developed	Agricultural	Forested	Wetlands	1990 Estimated Population Density (people/mi^2)
Agriculture								
Contentnea Creek at Hookerton, NC	6	02091500	737	4.9	50.6	37.4	7.1	129
Agriculture/Urban								
Dan River at Paces, VA	8	02075500	2,587	4.9	28.0	65.0	1.0	119
Neuse River at Kinston, NC	7	02089500	2,712	8.9	37.7	50.5	1.8	275
Tar River at Tarboro, NC	5	02083500	2,222	4.5	39.1	51.1	6.4	91
Agriculture/Forested								
Blackwater River near Franklin, VA	1	02049500	610	2.8	29.8	59.3	5.3	44
Meherrin River at Emporia, VA	3	02052000	745	2.3	30.2	67.1	.1	37
Nottoway River near Sebrell, VA	2	02047000	1,441	2.5	28.3	66.2	3.5	30
Roanoke River at Roanoke Rapids, NC	4	02080500	8,474	4.7	33.3	60.2	.2	97

Deposition Program (NRSP-3)/National Trends Network, 1991). The total nitrogen contribution from atmospheric deposition was calculated as the sum of nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) wet deposition, NO_3-N dry deposition, NO_3-N droplet deposition, NO_3-N urban area wet deposition, and NO_3-N urban dry deposition. Deposition in each of these categories was calculated by multiplying the associated deposition rate by the corresponding area of the drainage basin and a conversion factor changing the nitrogen units from ionic to elemental nitrogen (Table 2; Sisterson, 1990). Deposition estimates are conservative since data were not available for dry ammonia and organic nitrogen deposition.

Nitrate (2.8 tons of nitrate nitrogen per square mile [ton/mi^2] of drainage area) and ammonium nitrogen (0.80 ton/mi^2) wet deposition rates were calculated as the average of wet nitrate and ammonium deposition rates during water year 1990 at four NADP/NTN sites in or near the study area (Figure 1; Harned *et al.*, 1995; McMahon and Lloyd, 1995). Average wet deposition values for the entire study area were used because there was little variability in NO_3-N and NH_4-N deposition rates among the four stations, and interpolation of these data using contours to indicate spatial variability would not have provided substantially different information.

Other deposition rates were calculated by using a methodology described in Sisterson (1990). The dry NO_3-N deposition rate was estimated by multiplying the wet NO_3-N deposition rate by a ratio of dry to wet deposition in North Carolina and Virginia reported in Sisterson (1990). This dry deposition rate was multiplied by the entire area of the Albemarle-Pamlico drainage basin to estimate dry NO_3-N deposition.

The nitrate droplet deposition rate associated with elevations greater than 2,000 feet [ft] was calculated by multiplying the sum of the wet and dry nitrate rates by a factor of 3, reflecting increased exposure of land surfaces to clouds and fog (Sisterson, 1990). The droplet deposition rate was then multiplied by the land area in these higher elevation zones – less than 1 percent of the study area – to estimate droplet deposition. Urban wet and dry NO_3-N deposition rates were estimated by multiplying wet and dry nitrate deposition rates by factors – 1.75 and 5, respectively, as reported in Sisterson (1990). Urban deposition rates were multiplied by urban land areas to estimate urban deposition.

TABLE 2. Summary of Deposition Rates Used to Calculate Atmospheric Nutrient Deposition.

[Sources: Nitrogen – Sisterson (1990); Phosphorus – Dodd *et al.* (1992); T/mi^2/yr, tons per square mile per year.]

Item	Deposition Source	Rate (T/mi^2/yr)
1	Nitrate nitrogen, wet deposition	2.8
2	Ammonia nitrogen, wet deposition	.80
3	Nitrate nitrogen, dry deposition	0.82* [1][a]
4	Nitrate nitrogen, droplet deposition	3* ([1] + [3])[b]
5	Nitrate nitrogen, urban dry deposition	5* [3]
6	Nitrate nitrogen, urban wet deposition	1.75* [1]
7	Ammonia nitrogen, dry deposition	Not done
8	Organic nitrogen deposition	Not done
9	Total phosphorus deposition	0.19

[a] Dry nitrate nitrogen is calculated by multiplying wet nitrate nitroagen deposition by an estimate of the rates of dry to wet deposition for North Carolina (from Sisterson, 1990). In North Carolina this ratio, in units of kilotonnes, is 23/28 or 0.82.

[b] For areas with elevations greater than 2,000 feet.

The total phosphorus component of atmospheric nutrient loads was based on a literature-derived value of 0.19 ton of total phosphorus deposited per square mile of drainage basin; no indication of phosphorus deposition rates was available for wet and dry deposition categories (Dodd *et al.*, 1992). This rate is similar to that used in the estimation of a nutrient mass balance for the Chowan River Basin (Kuenzler and Craig, 1986), and somewhat larger than the 0.14 ton/mi^2 used by Stanley (1993) in estimating atmospheric phosphorus deposition for the Pamlico Estuary.

Nutrient Inputs: Crop-Related

Estimates of the 1990 total nitrogen and total phosphorus inputs to the eight basins from major agricultural crops were made by using (1) crop acreages for major crops within a basin; (2) recommended fertilizer application rates for various major crops, including corn, cotton, tobacco, barley, oats, wheat, Irish potatoes, and sweet potatoes; and (3) estimates of biologically mediated nitrogen fixation associated with soybeans and peanuts (College of Agriculture and Life Sciences, 1991; McMahon and Lloyd, 1995). Crop acreages were based on 1990 crop statistics for harvested acreage reported by county in North Carolina and Virginia. County harvested acreage data were apportioned among the major drainage basins according to the proportion of agricultural land in each county within the associated drainage basin (Table 3). Estimates of fertilizer use were made by multiplying recommended application rates (Table 4) by harvested acres per crop, and then summing all crop types. Estimates of biologically fixed nitrogen inputs were made by multiplying harvested acres of soybeans and peanuts by nitrogen fixation constants of 105 and 112 pounds per acre, respectively.

Crop-related nutrient estimates are likely to be conservative for several reasons. The use of harvested rather than planted acres produces a conservative estimate of fertilizer use, because generally there are fewer harvested acres than planted acres on which fertilizer was applied in a basin. Recommended fertilizer application rates were used in this study because of the uncertainty associated with apportioning county-level fertilizer sales data to fertilizer use in a particular county. Using recommended application rates also results in lower fertilizer-use estimates than those obtained by basing estimates on county fertilizer sales data. When 1990 county fertilizer sales data are allocated to the eight basins, nitrogen and phosphorus fertilizer-use estimates result that may be as much as 220 and 990 percent higher, respectively, than estimates based on recommended application rates (Table 5). Puckett (1995) reported on studies indicating that farmers may apply 24 to 38 percent more fertilizer than suggested because of uncertainties regarding weather and soil-nutrient status. Finally, crop-related nutrient input estimates do not include nutrients introduced by nitrogen-fixing forage crops because of data unavailability. Urban fertilizer sources were not considered because of the lack of information for these basins.

Nutrient Inputs: Animal Waste

County livestock inventories for chickens, cattle, hogs, and turkeys were obtained from the U.S. Department of Agriculture's 1987 Census of Agriculture, the most recent year relative to 1990 for which data are available for all study-area counties (U.S. Bureau of Census, 1990). County livestock inventories were allocated to the basins by using a method

TABLE 3. Percentages of Acres Harvested, by Individual Crop, and Major Livestock Categories for the National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area, 1990.

[Harned *et al.*, 1995; Numbers in parentheses are site numbers in Figure 2; <, less than; NA, not available.]

	Blackwater River Near Franklin, VA	Nottoway River Near Sebrell, VA	Meherrin River at Emporia, VA	Roanoke River at Roanoke Rapids, NC	Dan River at Paces, VA	Tar River at Tarboro, NC	Neuse River at Kinston, NC	Contentnea Creek at Hookerton, NC
Corn and Soybeans	59	58	59	42	35	46	61	64
Grains[a]	< 1	13	14	27	30	15	19	17
Cotton	< 1	2	1	1	0	12	3	5
Peanuts	29	22	2	1	0	12	< 1	1.0
Tobacco	< 1	4	23	28	35	12	13	12
Potatoes	0	0	0	< 1	< 1	3	3	2
Livestock[b]	NA	NA	Cattle, Hogs	Cattle	Cattle	NA	Cattle, Hogs	Hogs, Chickens

[a] Grains include wheat, sorghum, barley, and oats.

[b] Dominant livestock types are reported where livestock-related waste nutrients compose more than 20 percent of total station nutrient inputs (see Table 6).

TABLE 4. North Carolina Cooperative Extension Service Recommended Fertilizer Application Rates Applied to Major Agricultural Crops (from McMahon and Lloyd, 1995).

	Nitrogen (pounds per acre)				Phosphorus (pounds per acre)			
Crop	Applied at Planting[a]	Applied as Side-Dressing[a]	Range of Application[a]	Application Rate Used in Mass Balance	Applied at Planting[a]	Applied as Side-Dressing[a]	Range of Application[a]	Application Rate Used in Mass Balance
Barley	20	80-100	100-120	110	0-20	0	0-20	10
Corn (as grain)	20-25	100-140	120-160	140	30-50	0	30-50	40
Cotton	20	50-70	70-90	80	0-20	0	0-20	10
Irish Potatoes	120-160	0	120-160	140	60-80	0	60-80	70
Oats	20	80-100	100-120	110	0-20	0	0-20	10
Peanuts	0	0	0	112[b]	0	0	0	0
Sorghum	20	60-80	80-100	90	0-20	0	0-20	10
Soybeans	0	0	0	105[b]	0-20	0	0-20	10
Sweet Potatoes	30	60	90	90	60	0	60	60
Tobacco[c]	35-40	0-40	35-80	50	0	0	0	0
Wheat	20	80-100	100-120	110	0-20	0	0-20	10

[a] Unless otherwise noted, amounts reported for application at planting, at sidedressing, and range are from North Carolina State University, College of Agriculture and Life Sciences (1991).

[b] Biological fixation (Craig and Kuenzler, 1983).

[c] Flue-cured; does not include plant bed fertilizer.

similar to that described for crop allocation. Livestock inventories were multiplied by estimates of annual per-animal waste nutrient content from Barker (1991; Table 6), and waste nutrient loads were summed for all livestock types in a drainage basin to estimate total livestock-related nutrient generation. The assumption was made that all animal feed is imported into the basin (J. Barker, North Carolina State University, oral communication, 1996), and that all waste is land applied.

Nutrient Inputs: Point Sources

Because of limits in available data, different methods were used to estimate the 1990 total nitrogen and

TABLE 5. Two Methods of Estimating Fertilizer Nutrient Inputs at National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area (from Harned *et al.*, 1995).

[Comparison of estimates are from recommended fertilizer application rates and county-based fertilizer sales information (College of Agriculture and Life Sciences, 1991). Estimates are presented in tons of elemental nitrogen (N) or Phosphorus (P).]

Station Name	Map Location (Figure 1)	Fertilizer Application Rate Method [A]		Fertilizer Sales Method [B]		Difference in Estimated Nutrient Inputs (in percent) [(B-A)/A]	
		N	P	N	P	N	P
Blackwater River near Franklin, VA	1	2,010	255	2,705	778	34.6	205.2
Contentnea Creek at Hookerton, NC	6	5,770	655	9,075	1,836	57.3	180.3
Meherrin River at Emporia, VA	3	465	50	1,435	413	208.6	725.6
Neuse River at Kinston, NC	7	9,730	1,095	19,075	3,857	96.0	252.2
Nottoway River near Sebrell, VA	2	2,320	290	3,885	1,118	67.5	285.5
Roanoke River at Roanoke Rapids, NC	4	6,920	525	22,170	5,708	220.4	987.3
Tar River at Tarboro, NC	5	6,535	670	13,274	2,684	103.1	300.7

TABLE 6. Nutrients Produced in Animal Wastes.

[McMahon and Lloyd, 1995; Units of measure are in pounds per animal per year.]

	Cattle			Chickens				
Nutrient	All Cattle	Dairy	Beef	All Chickens	Layers	Broilers	Hogs	Turkeys
Fisher *et al.* (1988)								
Nitrogen	75.8	122.7	60.9	–	0.95	0.77	31.9	3
Phosphorus	–	–	–	–	–	–	–	–
North Carolina Department of Natural Resources and Community Development (1985)								
Nitrogen	142.7	237.2	113.1	–	1.46	0.73	21.9	7.3
Phosphorus	33.5	47.5	29.2	–	.37	.18	7.3	1.8
Barker (1991)								
Nitrogen	106.5	156	90.8	0.9	0.95	0.89	20.3	2
Phosphorus	26.7	32.8	24.8	.26	.34	.25	6.6	.79

total phosphorus loads generated by point-source dischargers in Virginia and North Carolina. Permitted dischargers in both states were primarily municipal wastewater-treatment plants. The Virginia Water Control Board supplied daily discharge data for 106 permitted point-source dischargers in the Virginia portion of the Albemarle-Pamlico drainage basin, along with Standard Industrial Codes (SIC) describing the type of activity, such as a municipal wastewater-treatment plant, associated with each permit (Robert McEarren, Virginia Water Control Board, written and oral communication, April 1993). These facilities discharge approximately 170 million gallons per day (Mgal/d) of waste effluent. The number of discharge measurements reported by each discharger ranged from 2 to 48 during 1990. Annual nutrient load estimates were obtained by (1) calculating the median value of the daily discharge values, (2) multiplying the median value by a total nitrogen and total phosphorus concentration value based on the SIC to estimate daily nutrient loads (National Oceanic and Atmospheric Administration, 1993), and then (3) multiplying the product obtained in step 2 by 365 (days).

The North Carolina Department of Environment, Health, and Natural Resources, Division of Environmental Management, supplied 1990 monthly average discharge and nutrient concentration data for 172 point-source dischargers in the North Carolina drainage basins that reported discharges in 1990. These facilities' combined discharge was approximately 280 Mgal/d. Most dischargers had monthly average flow and concentration data for all 12 months of 1990, and there was a small, but statistically significant, negative correlation between flow and concentration for these dischargers. For these dischargers, monthly load estimates were calculated by multiplying the average daily discharge for a given month by the average total nitrogen and total phosphorus concentration values for the same month. Monthly load estimates for each discharger having a 12-month data set were summed over the entire year. For dischargers having less than 12 months of 1990 data, annual nutrient loads were calculated in the same manner as those for Virginia dischargers. The median of all reported daily discharge data for a discharger was multiplied by the median total nitrogen and phosphorus concentrations for the same discharger in order to estimate daily loads, and these loads were summed to produce an annual estimate.

Nutrient Outputs: In-Stream Loads

In-stream loads for 1990 were estimated for the annual mass of total nitrogen and total phosphorus transported past each station. Estimates also were made for nutrients removed from each basin by crop harvest. Finally, a nutrient residual estimate was made by subtracting nutrients removed from the basin (by stream transport or by crop harvest) from the total 1990 estimated nutrient inputs.

The total mass of a constituent transported by a stream is correlated with the quantity of streamflow (Belval *et al.*, 1994)). When calculating loads, it is desirable to have water-quality samples representing all parts of the flow regime of a stream, especially the less frequently occurring high-flow periods when a high proportion of annual sediment and nutrient load are transported by the stream.

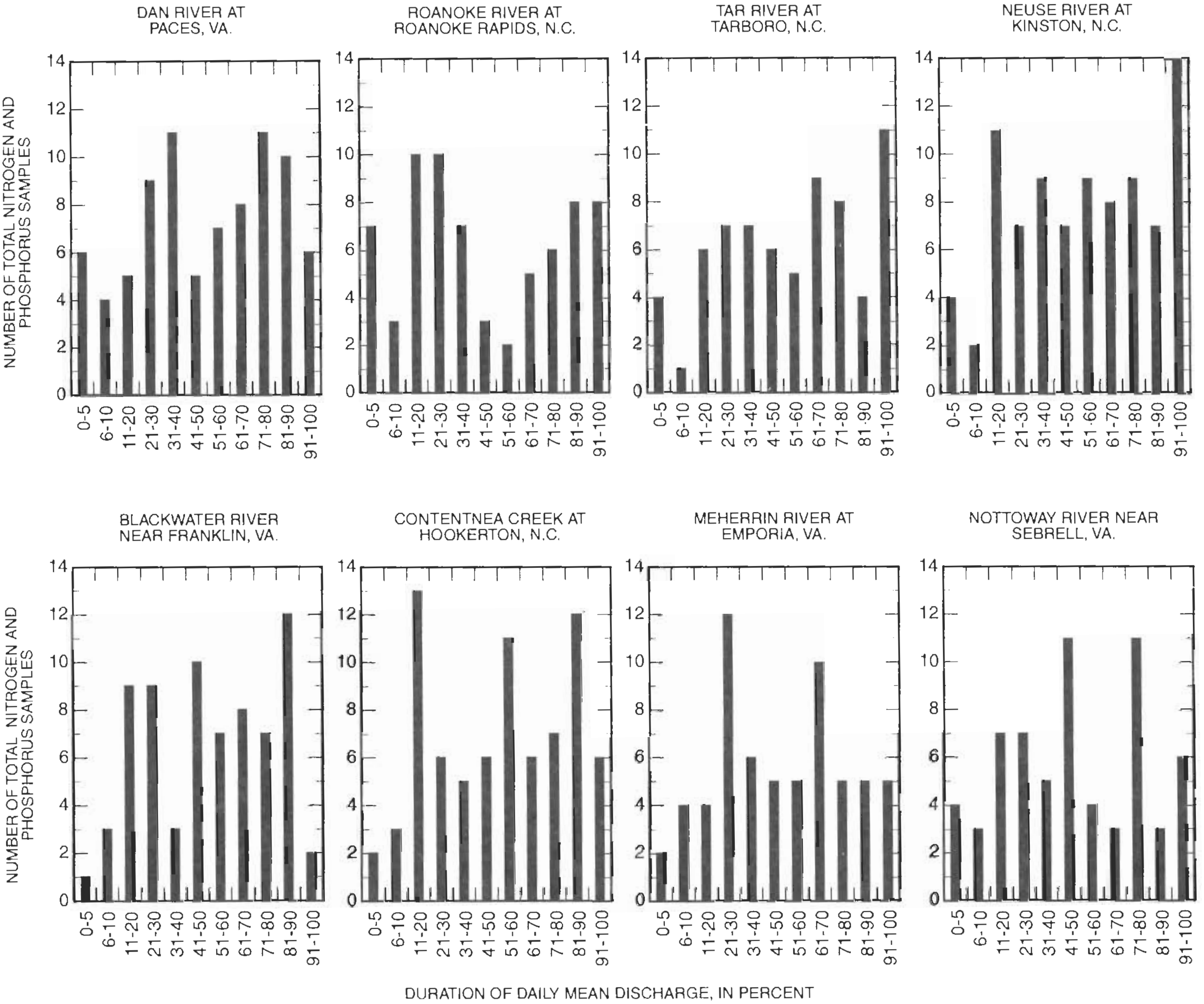
Annual loads of total nitrogen and total phosphorus were calculated for water years 1980-92. A log-linear regression model was used to produce minimum-variance unbiased estimates (MVUE) of seven parameters that were used, in turn, to estimate loads (Cohn *et al.*, 1989, 1992). The dependent variable, constituent load, is based on concentrations of total nitrogen and total phosphorus and, thus, reflects contributions of sediment-related nutrients. Explanatory variables include a constant, and two flow-dependent parameters, two parameters for time trends, and two parameters for seasonal effects (Harned *et al.*, 1995). The 1980-92 time period included a wide range of annual-mean discharges. The lowest annual-mean discharges at all eight stations for the period of record occurred during water years 1980-92. At least one of the highest ten annual-mean discharges was recorded at each of the eight stations during 1980-92. Although low and high annual-mean discharges were recorded during the load estimation period, the flow duration curve for 1980-92 is similar to the flow duration curve for the period of record at each of the eight stations.

While the discharge record during the time period for a load analysis adequately represents extreme flow regimes, the accuracy of load calculations depends on the availability of constituent samples that are distributed throughout low, medium, and high streamflows. The percentage of nutrient samples collected during high streamflows (flows of less than 10-percent duration of the daily mean discharge) ranged from 4 to 14 percent of the total number of samples collected at each of the eight stations during water years 1980-92 (Figure 2). The percentage of nutrient samples collected during low streamflows (flows of greater than 89-percent duration of the daily mean discharge) ranged from 2 to 14 percent of the total number of samples collected.

Nutrient Outputs: Crop Harvest and Residual

Estimates of nitrogen and phosphorus removal were made by allocating 1990 county-level crop harvest data to the eight basins using the same technique described for allocating crop acreage data. Data for average nutrient content of harvested crop materials were used in conjunction with harvest estimates to calculate harvest nutrient removal (Zublena, 1991).

A residual term is calculated as the difference between total nutrient inputs and the sum of in-stream load and crop harvest categories. This category represents nutrients that otherwise cannot be accounted for in the mass balance because of a lack of knowledge about terrestrial and aquatic nutrient cycling associated with processes such as denitrification, retention in forest ecosystems, uptake by stream biota, soil and streambed storage, and losses to ground water. This category also arises due to uncertainty in estimates of the input and output categories used in this study


DAN RIVER AT PACES, VA.

ROANOKE RIVER AT ROANOKE RAPIDS, N.C.

TAR RIVER AT TARBORO, N.C.

NEUSE RIVER AT KINSTON, N.C.

BLACKWATER RIVER NEAR FRANKLIN, VA.

CONTENTNEA CREEK AT HOOKERTON, N.C.

MEHERRIN RIVER AT EMPORIA, VA.

NOTTOWAY RIVER NEAR SEBRELL, VA.

Figure 2. Number of Total Nitrogen and Phosphorus Samples Corresponding to the Duration of Daily Main Discharge for National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area (Harned *et al.* 1995).

RESULTS

Nutrient Inputs: Atmospheric Deposition

Examined in terms of total nutrient input percentages (Table 7), atmospheric sources of nitrogen ranged from nearly 11 to 44 percent and, on average, made up 27 percent of total nitrogen inputs in the eight basins in 1990. Atmospheric phosphorus inputs, as a percent of total phosphorus inputs, ranged from about 8 to 31 percent and averaged 22 percent of phosphorus inputs for the eight basins. Measured as a percent of all inputs, atmospheric nitrogen inputs, on average, were the largest input category, while atmospheric phosphorus inputs, on average, are less important than commercial fertilizer and animal waste.

The areal nitrogen deposition rate was relatively constant; higher rates reflected increased deposition associated with urban areas or higher elevations (Table 8; Figure 3). Atmospheric nitrogen inputs averaged 1.93 ton/mi^2 and total phosphorus inputs averaged 0.19 ton/mi^2 across the eight basins. On average, areal atmospheric nitrogen deposition rates were greater than animal waste rates, and less than the rates for fertilizer and nitrogen fixation. Because of

TABLE 7. Summary of Total Nitrogen and Total Phosphorus Inputs and Outputs, as a Percent of Total Station Nutrient Inputs, for National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area, 1990.

[Harned *et al.*, 1995; N, total nitrogen; P, total phosphorus; –, not applicable.]

	Blackwater River Near Franklin, VA		**Nottoway River Near Sebrell, VA**		**Meherrin River at Emporia, VA**		**Roanoke River at Roanoke Rapids, NC**		**Dan River at Paces, VA**		**Tar River at Tarboro, NC**		**Neuse River at Kinston, NC**		**Contentnea Creek at Hookerton, NC**	
Category	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**
Inputs																
Atmospheric Deposition	17.9	21.0	25.5	26.1	39.8	30.5	38.1	25.5	44.0	30.9	20.6	16.9	20.9	14.9	10.9	7.9
Commercial Fertilizer	31.9	46.6	22.9	28.7	13.8	11.0	16.2	8.6	17.8	9.1	31.6	27.9	34.9	32.6	43.8	37.8
Nitrogen Fixation	40.3	–	35.2	–	15.8	–	6.2	–	5.1	–	24.9	–	20.6	–	22.1	–
Animal Waste	9.7	32.0	16.1	43.6	29.9	57.4	34.8	61.9	25.4	48.3	21.5	52.9	19.1	48.1	22.1	53.4
Point Sources	.2	.4	.3	1.6	.7	1.1	4.7	4.0	7.7	11.7	1.4	2.3	4.5	4.4	1.1	.9
Outputs																
Crop Harvest	63.8	82.3	47.8	51.0	23.5	18.8	14.6	13.2	14.8	14.3	35.9	35.8	32.5	34.4	41.0	40.1
In-Stream Load	10.1	4.6	8.8	7.4	14.0	8.8	14.4	4.8	30.4	25.4	14.4	12.1	15.7	9.9	10.2	9.0
Residual	26.1	13.1	43.4	41.6	62.5	72.4	71.0	82.0	54.8	60.3	49.7	52.1	51.8	55.7	48.8	50.9

TABLE 8. Summary of Total Nitrogen and Total Phosphorus Inputs and Outputs, in Tons Per Square Mile of Basin Drainage Area, for National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area, 1990.

[Harned *et al.*, 1995; N, total nitrogen; P, total phosphorus.]

	Blackwater River Near Franklin, VA		**Nottoway River Near Sebrell, VA**		**Meherrin River at Emporia, VA**		**Roanoke River at Roanoke Rapids, NC**		**Dan River at Paces, VA**		**Tar River at Tarboro, NC**		**Neuse River at Kinston, NC**		**Contentnea Creek at Hookerton, NC**	
Category	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**
Inputs																
Atmospheric Deposition	1.831	0.186	1.816	0.186	1.799	0.186	1.941	0.186	1.980	0.186	1.949	0.186	2.160	0.186	1.958	0.186
Commercial Fertilizer	3.258	.413	1.633	.204	.624	.067	.825	.063	.802	.055	2.994	.307	3.614	.407	7.872	.894
Nitrogen Fixation	4.125	.000	2.502	.000	0.711	.000	0.317	.000	0.231	.000	2.364	.000	2.129	.000	3.977	.000
Animal Waste	.989	.284	1.144	.310	1.349	.349	1.774	.450	1.145	.290	2.045	.582	1.978	.600	3.977	1.262
Point Sources	.023	.003	.023	.011	.034	.007	.243	.029	.347	.071	.133	.025	0.464	.054	.205	.020
Total Inputs	**10.226**	**.886**	**7.118**	**.711**	**4.517**	**.609**	**5.100**	**.728**	**4.505**	**0.602**	**9.485**	**1.100**	**10.345**	**1.247**	**17.989**	**2.362**
Outputs																
Crop Harvest	6.524	0.729	3.403	0.362	1.060	0.114	0.745	0.096	0.668	0.086	3.406	0.392	3.358	0.427	7.374	0.948
In-Stream Load	1.037	.041	.627	.054	.631	.054	.734	.036	1.368	.154	1.368	.133	1.620	.121	1.828	.211
Residual	2.665	.116	3.088	.295	2.826	.441	3.621	.596	2.469	.362	4.711	.575	5.367	.699	8.787	1.203

the estimation methodology, atmospheric total phosphorus inputs on a ton-per-square-mile basis were constant.

Atmospheric input rates, measured in tons of nitrogen or phosphorus per square mile of drainage basin area, have been estimated for the Neuse, Tar-Pamlico, and Chowan River Basins (Dodd *et al.*, 1992); the entire Albemarle-Pamlico drainage basin (Stanley, 1989); the Chowan River Basin (Kuenzler and Craig, 1986); the upper Potomac River Basin above

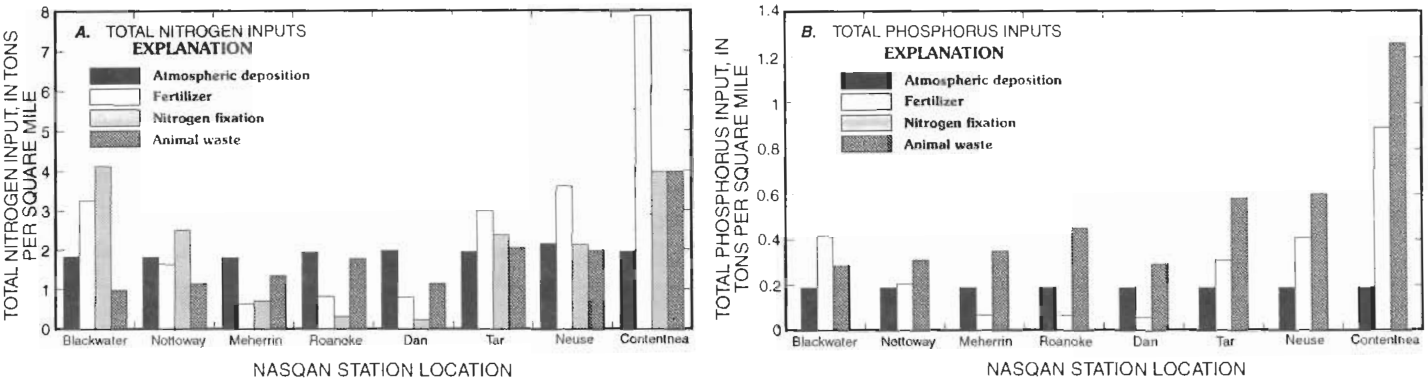


Figure 3. Nonpoint Source (A) Total Nitrogen and (B) Total Phosphorus Inputs, Measured in Tons Per Square Mile of Basin Drainage Area, for National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area, 1990 (Harned *et al.*, 1995).

TABLE 9. Comparison of Nitrogen and Phosphorus Input Loading Rates.

[–, no data.]

	Atmospheric Deposition		Crop Fertilizer		Animal Waste		Point Sources	
Study	**Total Nitrogen**	**Total Phosphorus**	**Total Nitrogen**	**Total Phosphorus**	**Total Nitrogen**	**Total Phosphorus**	**Total Nitrogen**	**Total Phosphorus**
ALBE NASQAN Stations (average for eight basins)	1.93	0.19	2.7	0.3	1.8	0.52	0.18	0.03
Neuse, Tar-Pamlico, and Chowan Basins (Dodd *et al.*, 1992)	3.5	–	2.8	.28	–	–	–	–
Chowan Basin (Kuenzler and Craig, 1986)	2.5	.19	4.1	1.3	–	–	–	–
Albemarle-Pamlico Drainage (Stanley, 1989)	–	.11	3.7	.88	2.91	.82	.12	.04
Upper Potomac Basin (Jaworski *et al.*, 1992)	3.8	.22	2.2	.81	5.8	1.7	.29	.09
Chesapeake Bay Drainage (Fisher and Oppenheimer, 1991)	4.08	–	2.7	–	–	–	.71	–
National Study of 114 Basins (Puckett, 1995)								
Western U.S.	.49	–	20.83	2.40	7.51	1.80	.00	.00
Central U.S.	1.11	–	9.77	1.09	4.03	1.06	.46	.09
Southeastern U.S.	1.83	–	11.54	1.31	5.46	2.06	.14	.03
Northeastern U.S.	2.83	–	6.57	1.94	10.37	2.40	.29	.03

Washington, D.C. (Jaworski *et al.*, 1992); the entire Chesapeake Bay drainage area (Fisher and Oppenheimer, 1991); and for 114 drainage basins across the continental United States (Puckett, 1995) (Table 9). Nitrogen deposition rates for the eight basins were generally similar or lower than the deposition rates in these studies. Deposition rates in basins located in the western and central regions of the United States were lower than those calculated for the Albemarle-Pamlico NASQAN stations (Puckett, 1995). Atmospheric total phosphorus input rates in the other studies that measured or calculated these rates were similar to those used for the stations.

Nutrient Inputs: Crop-Related

Estimates of crop fertilizer nutrients ranged from about 14 to 44 percent of total basin nitrogen inputs and represented, on average, 27 percent of total nitrogen inputs. Nitrogen fixation inputs ranged from about 5 to 40 percent of total basin nitrogen inputs, and averaged 21 percent for the eight basins (Table 7). Phosphorus from commercial fertilizer ranged from about 9 to 47 percent of total phosphorus inputs, and averaged about 25 percent of total inputs.

On a tons-per-square-mile-per-year basis, combined crop-related nitrogen fertilizer and nitrogen fix were the largest sources of nitrogen in six of the eight basins (Table 8; Figure 3). The highest areal nitrogen fertilizer input rates were in the Contentnea (7.9 ton/mi^2), Neuse (3.6 ton/mi^2), and Blackwater (3.3 ton/mi^2) Basins. The highest areal input rates of biological nitrogen fixation are in the Contentnea (3.9 ton/mi^2), Blackwater (4.1 ton/mi^2), and Nottoway (2.5 ton/mi^2) Basins. Almost 90 percent of the Blackwater Basin crop acreage was devoted to corn, soybeans and peanuts, with high percentages of these high nitrogen using or fixing crops among the total crop acreages of the Nottoway (80 percent), Contentnea (almost 70 percent), and the Neuse (more than 60 percent) Basins (Table 3). Across the eight basins, the average 1990 input rates for nitrogen and phosphorus were 2.7 and 0.30 ton/mi^2, respectively, while the average rate for nitrogen fixation was 2.0 ton/mi^2.

Crop fertilization input rates, measured in tons per square mile of drainage basin area, also have been estimated in a number of other studies (Table 9). Although these rates were generally comparable to the average nitrogen fertilization rate for the eight basins, agricultural nitrogen-input rates for the Chowan (Kuenzler and Craig, 1986) and for the entire Albemarle-Pamlico drainage areas, including the land area adjoining the estuaries (Stanley, 1989), were higher than the input rate used at the stations. The high level of agricultural activity in these areas near the estuaries may have exerted a greater influence on estuary water-quality than nitrogen originating in areas upstream from the stations. Nitrogen and phosphorus fertilizer rates for the national study (Puckett, 1995) were estimated using fertilizer sales information, rather than using recommended application rates, and differed by as much as an order of magnitude from estimates for the basins.

Nutrient Inputs: Animal Waste

Animal-related nitrogen inputs ranged from about 10 to 35 percent of total nitrogen inputs, and averaged 22 percent for the eight drainage areas (Table 7). Phosphorus loads from animal waste ranged from 32 to 62 percent of total phosphorus inputs, and averaged 50 percent for the eight basins (Table 7). These data indicate that phosphorus derived from animal waste was the largest source of phosphorus inputs, as is also evident for phosphorus inputs on a tons-per-square-mile basis (Table 8; Figure 3). Animal-waste phosphorus inputs averaged 0.52 ton/mi^2 in 1990, while nitrogen inputs averaged 1.8 ton/mi^2.

Nutrient Inputs: Point Sources

In 1990 point-source contributions of total nitrogen ranged from 0.2 percent of total nitrogen inputs in the Blackwater River Basin to 7.7 percent in the Dan River Basin, and averaged 3 percent; whereas, point-source phosphorus contributions at the same stations ranged from 0.4 percent of total phosphorus inputs to 11.7 percent, and averaged 3 percent (Table 7). The Neuse River Basin had the highest point-source areal loading rate for nitrogen inputs (0.46 ton/mi^2), while the Dan River Basin had the highest areal input rate for phosphorus (0.07 ton/mi^2). Point-source contributions averaged 0.18 and 0.03 ton/mi^2 for nitrogen and phosphorus, respectively.

In four of the eight basins, point sources contributed relatively small amounts of nutrients, when point-source inputs were considered as a percent of in-stream load (Figure 4). Point sources of nitrogen accounted for less than 10 percent of in-stream nitrogen load in four of the eight basins and less than 50 percent of the in-stream load in all eight basins. Point sources of phosphorus contributed less than 10 percent of in-stream phosphorus loads in two of the eight basins, and less than 50 percent of in-stream load in seven of eight basins. In the Roanoke Basin, samples were taken immediately downstream from a series of impoundments, so that in-stream phosphorus loads were dominated by dissolved phosphorus species rather than sediment-attached phosphorus. In seven of the eight basins, point sources of phosphorus contributed more to in-stream nutrient loads than point sources of nitrogen. The point-source proportion of total basin inputs were comparable to the proportions reported in Puckett (1995) and suggest that nonpoint sources were the dominant sources of in-stream nutrient loads in the eight basins.

Point-source nutrient input rates, measured in tons per square mile of drainage basin area, also have been estimated in several other studies (Table 8). The nitrogen and phosphorus input rates estimated for the Albemarle-Pamlico Basin (Stanley, 1989) and the basins in the southeastern United States (Puckett,

1995) were comparable to the point-source input rates for the eight stations. The higher rate in Fisher and Oppenheimer (1991) reflected the inclusion of the Washington, D.C., point-source discharges.

Nutrient Outputs: In-Stream Nitrogen Loads

During the period for which the load estimation model was calculated, total nitrogen concentrations were generally less than 3 milligrams per liter [mg/L] (Harned *et al.*, 1995). Streams in this region that are relatively unaffected by human activity might be expected to have total nitrogen concentrations no higher than 0.7 to 1.2 mg/L (Simmons and Heath, 1979; Caldwell, 1992).

In-stream loads of total nitrogen and total phosphorus, representing the mass of a constituent moving past a station during a year, are reported for 1990 as an areal rate (Tables 8, 10). In-stream annual nitrogen loads for 1990 ranged from 0.62 ton/mi^2 in the Nottoway Basin, to 1.8 ton/mi^2 in the Contentnea Basin, and averaged 1.1 ton/mi^2 in water year 1990.

The mean annual in-stream nitrogen loads for 1980-1992 and the loads for water year 1990 varied according to the intensity of agricultural and population density (Table 10). The highest loads were reported at Contentnea Creek, a predominantly agricultural basin. Next in magnitude were the Neuse, Dan, and Tar River Basins, which were agricultural basins having relatively high population densities as well as similar basin sizes and flow regimes.

In-stream nitrogen loads in the Neuse, Tar, and Dan River Basins were comparable, even though the Neuse and Tar River Basins had higher overall nitrogen input rates than the Dan River Basin (Table 8). The higher than expected in-stream loads in the Dan River Basin could be related to the relative importance of point-source nutrients in this basin, measured as a percent of all nutrient inputs (Table 7) and as a percent of in-stream nutrient loads (Figure 4). Because point-source inputs are introduced directly into the water body, their impact may be disproportionately larger than more diffuse nonpoint nutrient sources.

The Blackwater River Basin data indicated evidence of relatively low in-stream nitrogen loads, despite having the third highest nitrogen input rate among the basins. The Blackwater River is a low-gradient Coastal Plain stream, and the relatively

TABLE 10. Annual In-Stream Loads of Total Nitrogen and Total Phosphorus at National Stream Quality Accounting Network Stations in the Albemarle-Pamlico Drainage Study Area.

[Harned *et al.*, 1995; Basin Types: Agriculture: greater than 40 percent agricultural land use, less than 40 percent forested, less than 10 percent developed; Agriculture/Urban: greater than 25 percent agricultural, population density greater than 100 people per square mile; Agriculture/Forest: greater than 50 percent forested, less than 40 percent agricultural, less than 10 percent developed; ton/mi^2, tons per square mile.]

		Nitrogen Loads (ton/mi^2)		**Phosphorus Loads (ton/mi^2)**	
Station Name	**Map Location (Figure 1)**	**1980-1992 Mean Annual Load**	**1990 Load**	**1980-1992 Mean Annual Load**	**1990 Load**
	Agriculture				
Contentnea Creek at Hookerton, NC	6	1.6	1.8	0.21	0.21
	Agriculture/Urban				
Dan River at Paces, VA	8	1.02	1.37	.14	.15
Neuse River at Kinston, NC	7	1.26	1.62	.13	.12
Tar River at Tarboro, NC	5	1.00	1.37	.12	.13
	Agriculture/Forest				
Blackwater River near Franklin, VA	1	.86	1.04	.03	.04
Meherrin River at Emporia, VA	3	.57	.63	.05	.05
Nottoway River near Sebrell, VA	2	.58	.62	.04	.05
Roanoke River at Roanoke Rapids, NC	4	.53	.73	.03	.04

large area of riparian wetlands could enhance nitrogen processing by denitrification and by providing opportunities for uptake by riparian vegetation (Kuenzler and Craig, 1986).

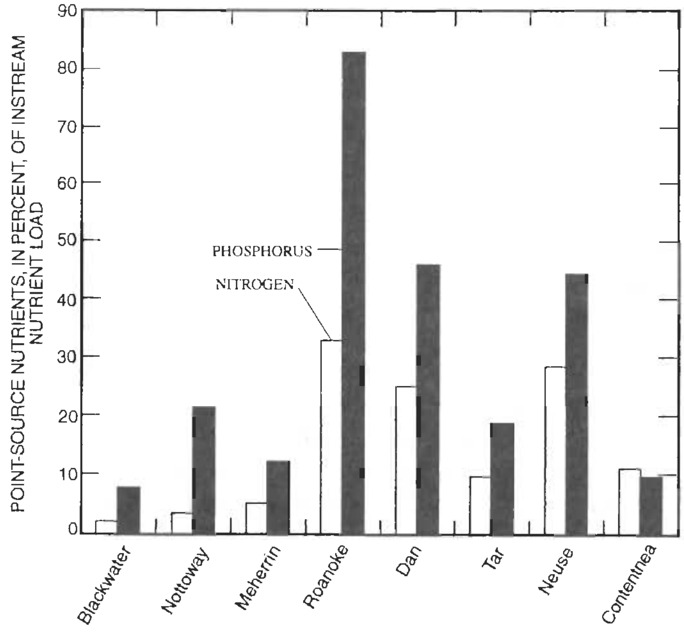


Figure 4. Point Source Nitrogen and Phosphorus as a Percent of Instream Nutrient Loads for Stations in the Albemarle-Pamlico Drainage Study Area.

In-stream nitrogen loads, as a percent of total nitrogen inputs, ranged from about 9 percent in the Nottoway Basin to about 30 percent in the Dan River Basin, and averaged 15 percent of total nitrogen inputs (Table 7). This average is close to the 17 percent river export proportion reported by Jaworski *et al.* (1992) for the upper Potomac River Basin.

Nutrient Outputs: In-Stream Phosphorus Loads

During the period for which the load estimation model was calculated, total phosphorus concentrations were generally less than 0.10 mg/L at half the stations and generally less than 0.40 mg/L at the remaining stations (Harned *et al.*, 1995). Streams in this region that are relatively unaffected by human activity might be expected to have total nitrogen concentrations no higher than 0.03 to 0.04 mg/L (Simmons and Heath, 1979; Caldwell, 1992).

Estimated annual total phosphorus loads in the eight basins during water years 1980-1992 ranged from 0.03 to 0.21 ton/mi^2 (Tables 8, 10). In-stream total phosphorus loads in 1990 ranged from 0.04 ton/mi^2 in the Roanoke and Blackwater Basins to 0.21 ton/mi^2 in the Contentnea Basin, and averaged 0.1 ton/mi^2 in 1990.

When examined by land-use category, these loads followed a pattern similar to that of nitrogen loads. In-stream total phosphorus loads, as a percent of total phosphorus inputs, ranged from 4.6 percent in the Blackwater Basin to more than 25 percent in the Dan River Basin, which has higher gradient streams and the steepest slopes of the eight basins (Table 7). The high in-stream total phosphorus loads at the Dan River station may be related to simultaneously high suspended-sediment loads at this station and to the relative importance of point sources of phosphorus (Tables 7, 8; Figure 4; Harned *et al.*, 1995). In-stream fluxes in the basins averaged 10 percent of the total estimated 1990 phosphorus inputs, a proportion comparable to the 8 percent reported by Jaworski *et al.* (1992).

The Contentnea Basin, which had the highest phosphorus input rate, also had the highest in-stream phosphorus loading rate (Tables 8, 10). Intermediate-level in-stream phosphorus loads occurred in the Dan, Neuse, and Tar River Basins, although there was a relatively low phosphorus input rate in the Dan River Basin. Lowest total phosphorus loads occurred in the Blackwater, Meherrin, Nottoway, and Roanoke River Basins. Low in-stream loads in the Roanoke and Meherrin Basins could be a function of reservoirs immediately upstream from the sampling sites for these basins, because the reservoirs would lower sediment-attached phosphorus loads at downstream sampling sites.

In-stream phosphorus loads for the four basins with the highest loads (Tables 8, 10) were comparable to annual loads measured for the upper Potomac River Basin above Washington, D.C. (0.23 ton/mi^2; Jaworski *et al.*, 1992), for the Tar River Basin (0.11 ton/mi^2; Research Triangle Institute, 1994), and for the central United States (0.14 ton/mi^2; Puckett, 1995), respectively. Phosphorus load estimates in these same four basins were higher than southeastern regional in-stream total phosphorus load estimates calculated by Smith *et al.* (1993) and Puckett (1995). Smith *et al.* (1993) divided the continental United States into 14 regions and calculated in-stream phosphorus loads for each region during a similar time period using the same load estimation technique as this study. Puckett (1995) allocated data collected at 114 basins to one of four regions in the United States and calculated a median value for each region. For the South Atlantic Region, Smith and others (1993) reported a mean total phosphorus load of 0.092 ton/mi^2, whereas Puckett (1995) reported a median annual in-stream total phosphorus load of 0.06 ton/mi^2. These rates were less than the in-stream phosphorus loads estimated for agricultural and agricultural/urban basins in the Albemarle-Pamlico drainage area but were greater than the loads reported in the agricultural/forested basins. At the national level, the highest annual in-stream total phosphorus load reported by Smith and others (1993) was for the Upper Mississippi region (0.157 ton/mi^2), while the highest rate reported by Puckett (1995) was for the central region of the United States (0.14 ton/mi^2). Both of these rates are lower than the 0.211 ton/mi^2 estimated for the Contentnea Creek Basin.

Smith *et al.* (1993) also reported loads for basins having different predominant land uses and different predominant crop types. In this national study, agricultural basins having a predominance of corn and soybeans (over 50 percent of row crop area per basin) had the highest total phosphorus loads (0.163 ton/mi^2) followed by urban basins (0.119 ton/mi^2). The Albemarle-Pamlico basins located where corn and soybeans comprise more than 50 percent of total crop acreage (Contentnea, 64 percent; Neuse, 61 percent; Meherrin, 59 percent; and Nottoway, 58 percent) had in-stream phosphorus loads less than the national load estimate, except for Contentnea Creek where more than half of the drainage area was devoted to agriculture. The relatively low phosphorus loads in the agriculture/forested basins (Table 9) could be explained by the influence of reservoirs (Meherrin and Roanoke Basins), the high proportion of forested land in each basin, and the intermixed pattern of agricultural fields and forested land, which may mitigate phosphorus movement associated with sediment transport (Hunsaker and Levine, 1995).

Nutrient Outputs: Crop Harvest and Residual

Crop harvest removed, on average, slightly more than one-third of agricultural nitrogen and phosphorus inputs (crop fertilizer, nitrogen fixation, and animal waste). This was a larger proportion of total nutrient inputs removed by crop harvest than was reported for the upper Potomac Basin (Tables 7, 8). The magnitude of the residual category, averaging approximately 50 percent of total inputs for nitrogen and phosphorus for the basins, was lower than the approximately two-thirds proportion reported for the residual category in the Potomac Basin (Jaworski *et al.,* 1992) and for four small basins in the Coastal Plain of Georgia (Lowrance and Leonard, 1988).

CONCLUSIONS

Several conclusions can be drawn from this analysis related to (1) the relative importance of nonpoint sources of nutrients, (2) the equal importance of atmospheric nutrient inputs relative to other nonpoint source nutrients, (3) the general need for better nutrient management in agriculture, (4) the large amounts of nitrogen and phosphorus that cannot be directly accounted for and which may represent a large accumulation of these nutrients in the basin, and (5) specific mass balance components where better information could make a mass balance approach more useful in understanding the relative importance of point- and nonpoint-sources of nutrients (Figure 5). First, point-source nutrient inputs consistently composed a very small proportion of total nutrient inputs in the eight basins. Measured as a percent of total nutrient inputs, nitrogen from point sources ranged from 0.2 to 7.7 percent of total nitrogen inputs, and averaged 2.6 percent. Point sources of phosphorus ranged from 0.4 to 11.7 percent of total phosphorus inputs, and averaged 3.3 percent. With the exception of one basin, point source nutrients also composed less than 50 percent of in-stream nutrient loads.

These small percentages may be misleading, however, in indicating the relative importance of point sources of nutrients for water quality. The Dan River Basin, which had substantially higher point-source nutrient inputs than the other basins (measured as a percent of total nutrient inputs), also had the highest in-stream loads of these nutrients, measured as a percent of total nutrient inputs (Table 7). As a percent of total nutrient inputs, the point-source inputs and in-stream loads in the Dan River were almost twice as high as those in the Roanoke and Neuse River Basins, which had the next highest point-source inputs and in-stream nutrient loads. This suggests that even though point sources may constitute a small proportion of overall nutrient inputs, because they are discharged directly into water bodies, they may have a disproportionate impact on nutrient loads. The importance of point-source loadings in the Dan, Roanoke, and Neuse Basins also is reflected in the relative proportion of in-stream nutrient loads associated with point sources (Figure 4). At the Roanoke stream gage, located immediately downstream from a large series of reservoirs, point sources of phosphorus compose over 80 percent of total in-stream phosphorus load. It is likely that the in-stream load is associated primarily with dissolved phosphorus, which is not trapped with the same efficiency in the reservoirs as sediment-attached phosphorus species. This dissolved fraction is more likely to be associated with effluent

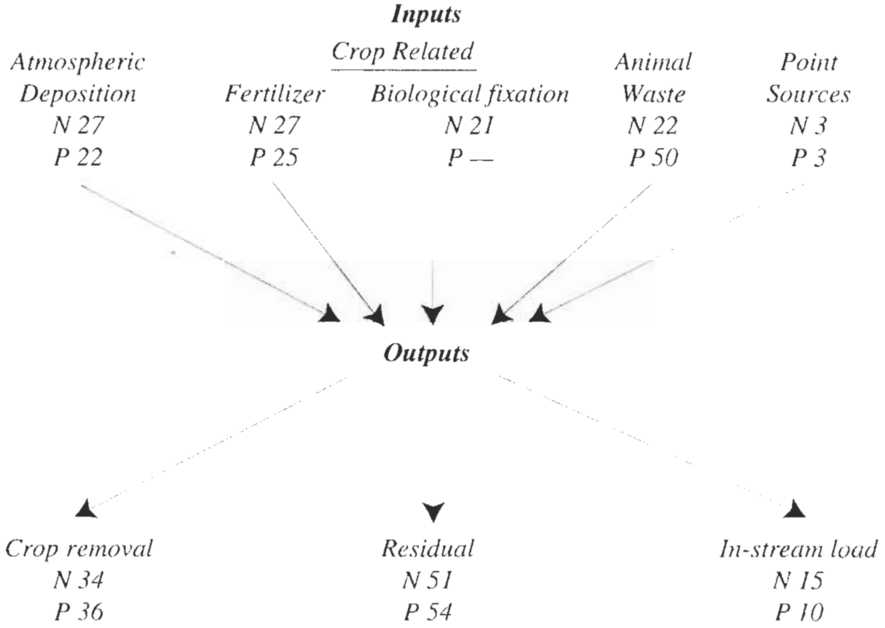


Figure 5. Average Nutrient Inputs and Outputs for the Eight Basins, as a Percent of Total Nutrient Inputs. (N – total nitrogen; P – total phosphorus; numbers in input and output categories may not add to 100 due to rounding.)

discharges than nonpoint sources. These results support the merit, from a water-quality standpoint, of historical management efforts to reduce point sources of nutrients.

Several characteristics of the allocation of nutrient inputs among the nonpoint-source categories are noteworthy. First, atmospheric sources of nitrogen and phosphorus, as a percent of total nutrient inputs, are comparable to nutrient inputs from crop fertilizer. Despite the general importance accorded to crop nutrients in many water-quality management efforts, the success of efforts to manage agricultural nutrients has been limited historically for political reasons and because of the practical difficulties of managing the myriad of individual decisions that underlie the generation of nonpoint sources of any constituent (Knopman and Smith, 1993). Atmospheric nutrient sources are even more dispersed in space and time than agricultural sources of these constituents; consequently, the relative importance of atmospheric inputs creates an especially difficult challenge for developing nonpoint-source nutrient management plans.

Another notable characteristic of nonpoint nutrient inputs is the magnitude of animal waste-related inputs, especially phosphorus, which average 50 percent of all phosphorus inputs across the eight basins. The significance of this finding is heightened by the rapid growth in the livestock industry that has occurred in the Albemarle-Pamlico drainage since 1987, the fact that a large portion of the feed stock is imported into the basin (J. Barker, North Carolina State University, oral communication, 1996), the relatively small amount of phosphorus fertilizers required for the mineral soils present in many agricultural areas of these drainage basins (J. Zublena, North Carolina State University, oral communication, 1993), and the fact that, at least on a seasonal basis, phosphorus is the limiting nutrient for phytoplankton productivity in many waters of the drainage basin (Paerl, 1987).

Achieving optimum crop yields without applying excessive nutrients is a goal of farmers for both economic and environmental reasons (Baird, 1990; Zublena, 1991). The excess of available agricultural nutrients in the eight basins, relative to nutrients removed by crop harvest, confirms the general importance of efforts undertaken to promote nutrient management (Zublena and Barker, 1991).

Finally, the residual category is larger than any of the other categories. The size of this category indicates the potential of a large mass of accumulated nitrogen and phosphorus in the estuary drainage system, but it is impossible to know with any certainty the extent to which this accumulation actually exists. The measurement or calculation of many of the mass balance variables is an inexact process, and to some extent, the residual category is an indication of the uncertainty and error associated with estimating the other mass balance compartments. For example, values for important agricultural input and output terms were calculated assuming that county-level data about crops and livestock could be allocated to drainage basins according to the proportion of agricultural land estimated to lie within the drainage boundary. If this assumption is unwarranted, or the mapped land-use data used to make this allocation is incorrect, error is introduced that can influence the size of the residual term. The county agricultural statistical summaries themselves contain measurement-related uncertainty, although estimates of this uncertainty are not available for county-level data (C. Hayes, North Carolina Department of Agriculture, oral communication, 1996). Uncertainty exists in the rate for nitrogen fixation, fertilizer use, animal-waste nutrient content and, indeed, for most other factors used in the study.

The fact that, on average, half of the input nutrients cannot be accounted for by either in-stream loads or crop harvest indicates the need for improved estimates of the input and output components of a mass balance and, perhaps, the need for estimating additional mass balance compartments to account for denitrification and storage in soils, ground water, and bed sediments. The need for better estimates is especially acute for the animal-waste input category. Some double counting probably exists for nutrient inputs associated with fertilizer used to grow crops consumed by animals within the basin, but it is not possible to estimate the extent of this double counting with the available data. Delivery of animal-waste nutrients is dependent on factors such as the extent to which livestock operations are concentrated, use of locally produced or imported food stocks, locations of livestock relative to stream networks, timing of application of stored animal wastes, availability of land on which animal waste can be applied, and capabilities of the soil and vegetative cover to utilize or store the nutrients contained in waste (Frissel, 1978; Robbins *et al.*, 1972). Relatively few studies have been conducted concerning the transport and fate of nutrients related to animal waste in watersheds. Robbins *et al.* (1972) suggest that between 5 and 10 percent of the total nutrients associated with animal waste actually reach nearby streams. Removing the remaining 90 percent of nutrients from the mass balance-type nutrient accounting system would substantially decrease the size of the residual category. The results reported by Robbins *et al.* (1972) also reinforce the importance of point-source nutrient inputs because all point-source nutrients are delivered directly to the stream network.

Uncertainty also exists in understanding how nitrogen is processed in the watershed. For example, the large amount of nitrogen in the residual category could be indicative of the high rates (70 to 90 percent) of nitrogen retention reported for forested ecosystems (Jaworski *et al.*, 1992). This process could be especially important, given the significance of atmospheric nitrogen inputs and the large areas of the basins in forested land cover. The size of the residual term also reflects the fact that denitrification is not explicitly calculated in the mass balance. Kuenzler and Craig (1986) indicate that denitrification rates as high as 17 ton/mi^2 have been reported on some poorly drained Coastal Plain soils. Uncertainty also exists in understanding the importance of wetlands in nitrogen processing, especially the response of wetland plants to long-term nitrogen inputs (Waddell, 1989). Better data on the amount of nutrients entering the basin and improved understanding of the long-term capabilities of watershed features to process nutrients will allow more informed evaluations to be made of the consequences of nutrient management efforts.

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LITERATURE CITED

Baird, J. V., 1990. Soil Facts: Nitrogen Management and Water-Quality. Raleigh, The North Carolina Agricultural Extension Service, AG-439-2.

Barker, J. C., 1991. Considerations in Developing a Waste Management Plan. North Carolina State University, Cooperative Extension Service Waste Management Institute.

Belval, D. L., M. D. Woodside, and J. P. Campbell, 1994. Relation of Stream Quality to Streamflow, and Estimated Loads of Selected Water-Quality Constituents in the James and Rappahannock Rivers Near the Fall Line in Virginia, July 1988 through July 1990. U.S. Geological Survey Water-Resources Investigations Report 94-4042, 85 pp.

Caldwell, S., 1992. Selected Water-Quality and Biological Characteristics of Streams in Some Forested Basins of North Carolina, 1985-88. U.S. Geological Survey Water-Resources Investigation Report 92-4129, 114 pp.

Cohn, T. A., D. L. Caulder, E. J. Gilroy, L. D. Zynjul, and R. M. Summers, 1992. The Validity of a Simple Statistical Model for Estimating Fluvial Constituent Loads: An Empirical Study Involving Nutrient Loads Entering Chesapeake Bay. Water Resources Research 28(9):2353-2363.

Cohn, T. A., L. L. DeLong, E. J. Gilroy, R. M. Hirsch, and D. K. Wells, 1989. Estimating Constituent Loads. Water Resources Research 25(5):937-942.

College of Agriculture and Life Sciences, 1991. Fertilizer Use. *In:* 1991 North Carolina Agricultural Chemicals Manual, Chapter 10. College of Agriculture and Life Sciences, North Carolina State University, Raleigh, North Carolina, 345 pp.

Craig, N. and E. J. Kuenzler, 1983. Land Use, Nutrient Yield, and Eutrophication in the Chowan River Basin. The University of North Carolina Water Resources Research Institute, Report No. 205, Raleigh, North Carolina.

Dodd, R. C., G. McMahon, and S. J. Stichter, 1992. Watershed Planning in the Albemarle-Pamlico Estuarine System. Report 1 – Annual Average Nutrient Budgets, Department of Environment, Health, and Natural Resources, Albemarle-Pamlico Estuarine Study Report No. 92-10, 116 pp, Raleigh, North Carolina.

Fisher, D. C. and M. Oppenheimer, 1991. Atmospheric Nitrogen Deposition and the Chesapeake Bay Estuary. AMBIO 20:102-108.

Fisher, D. C., J. Graso, T. Mathew, and U. Oppenheimer, 1988. Polluted Coastal Waters: The Role of Acid Rain. Environmental Defense Fund, 73 pp., Oakland, California,

Frissel, M. J., 1978. Cycling of Mineral Nutrients in Agricultural Ecosystems. Elsevier Press, New York, New York, 356 pp.

Harned, D. A., G. McMahon, M. D. Woodside, and T. B. Spruill, 1995. Water-Quality Assessment of the Albemarle-Pamlico Drainage Basin, North Carolina and Virginia – Summary of Water-Quality Data for Suspended Sediment, Nutrients, and Pesticides. U. S. Geological Survey Open-File Report 95-191, 131 pp.

Hunsaker, C. T. and D. A. Levine, 1995. Hierarchical Approaches to the Study of Water-Quality in Rivers. BioScience 45(3):193-203.

Jaworski, N. A., P. M. Groffman, A. A. Keller, and J. C. Prager, 1992. A Watershed Nitrogen and Phosphorus Balance – The Upper Potomac River Basin. Estuaries 15(1):83-95.

Knopman, D. S. and R. A. Smith, 1993. 20 Years of the Clean Water Act. Environment 35(1):17-41.

Kuenzler, E. J. and N. J. Craig, 1986. Land Use and Nutrient Yields of the Chowan River Watershed. *In:* Watershed Research Perspectives, D. L. Correll (Editor). Smithsonian Institution Press, Washington, D.C., pp. 77-107.

Leahy, P. P., J. S. Rosenshein, and D. S. Knopman, 1990. Implementation Plan for the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 90-174, 10 pp.

Lowrance, R. and R. A. Leonard, 1988. Streamflow Nutrient Dynamics on Coastal Plain Watersheds. Journal of Environmental Quality, pp. 745-740.

McMahon, G. and O. B. Lloyd, Jr., 1995. Water-Quality Assessment of the Albemarle-Pamlico Drainage Basin, North Carolina and Virginia-Environmental Setting and Water-Quality Issues. U.S. Geological Survey Open-File Report 95-136, 72 pp.

National Atmospheric Deposition Program (NADP)/National Trends Network (NTN) Coordination Office, 1991. NADP/NTN Annual Data Summary – Precipitation Chemistry in the United States, 1990. National Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, 475 pp.

National Oceanic and Atmospheric Administration, 1993, Point source methods document: Silver Spring, MD.

North Carolina Department of Environment, Health, and Natural Resources, 1992. State of North Carolina Water-Quality Assessment – 1992, 305(b) Report. Division of Environmental Management, Water-Quality Section, Report No. 92-06, 86 pp. + app., Raleigh, North Carolina.

North Carolina Department of Environment, Health, and Natural Resources, 1993a. Technical Support Document for the Albemarle-Pamlico Estuarine Study Comprehensive Conservation and Management Plan. Albemarle-Pamlico Estuarine Study Report No. 93-14, 122 pp. + app., Raleigh, North Carolina.

North Carolina Department of Environment, Health, and Natural Resources, 1993b. Basinwide Assessment Report Support Document-Tar-Pamlico River Basin. Division of Environmental Management, Water-Quality Section, Environmental Sciences Branch, 174 pp., Raleigh, North Carolina.

North Carolina Department of Natural Resources and Community Development, 1985. Animal Operations and Water Quality in North Carolina. Division of Environmental Management, Report No. 86-05.

Paerl, H. W., 1987. Dynamics of Blue-Green Algal (*Microcystis aeruginosa*) Blooms in the Lower Neuse River, North Carolina – Causative Factors and Potential Controls. The University of North Carolina, Water Resources Research Institute, Report No. UNC-WRRI-87-229, 164 pp., Raleigh, North Carolina.

Puckett, L. J., 1995. Identifying the Major Sources of Nutrient Water Pollution. Environmental Science and Technology 29(9):408A-414A.

Research Triangle Institute, 1994. Nutrient Modeling and Management in the Tar-Pamlico River Basin [draft report]. Research Triangle Institute, Research Triangle Park, North Carolina.

Robbins, J. W. D., D. H. Howells, and G. J. Kriz, 1972. Stream Pollution from Animal Production Units. Journal of the Water Pollution Control Federation 44(8):1536-1544.

Simmons, C. E. and R. C. Heath, 1979. Water-Quality Characteristics of Streams in Forested and Rural Areas of North Carolina. U.S. Geological Survey Water-Resources Investigations 79-108, 49 pp.

Sisterson, D. L., 1990. Appendix A: Detailed SOx-S and NOx-N Mass Budgets for the United States and Canada. *In:* Acidic Deposition: State of Science and Technology, Report 8, Relationships Between Atmospheric Emissions and Deposition/Air Quality, A. Venkatram, D. McNaughton, P. K. Karamchandani, J. Shannon, D. L. Sisterson, and M. Fernau (Editors). National Acid Precipitation Assessment Program, pp. 8A-1 to 8A-10.

Smith, R. A., R. B. Alexander, and K. J. Lanfear, 1993. Stream Water-Quality in the Conterminous United States-Status and Trends of Selected Indicators During the 1980s. *In:* National Water Summary 1990-91 – Hydrologic Events and Stream Water-Quality. U.S. Geological Survey Water-Supply Paper 2400, pp. 111-140.

Stanley, D. W., 1989. Historical Trends in Land Use, Nutrient Production, Water-Quality and Fisheries in the Albemarle-Pamlico Estuarine System. East Carolina University, Institute for Coastal and Marine Resources, Greenville, North Carolina.

Stanley, D. W., 1993. Long-Term Trends in Pamlico River Estuary Nutrients, Chlorophyll, Dissolved Oxygen, and Watershed Nutrient Production. Water Resources Research 29(8):2651-2662.

U. S. Bureau of Census, 1990. Census of Agriculture, 1987, Part 1 – Agricultural Atlas of the United States. U.S. Bureau of Census Subject Series, Vol. 2, 199 pp.

Waddell, T. E., 1989. Appendix: Watershed and Lake Processes Affecting Surface Water Acid-Base Chemistry (draft). State of Science and Technology, Report 10, National Acid Precipitation Assessment Program.

Zublena, J. P., 1991. Soil Facts: Nutrient Removal by Crops in North Carolina. The North Carolina Cooperative Extension Service, AG-439-16, Raleigh, North Carolina.

Zublena J.P. and J. C. Barker, 1991. County-by-County Nutrient Assessment and Distribution of Animal Manure in North Carolina. North Carolina State University, Department of Biological and Agricultural Engineering, Water Quality Group, NWQEP Notes, No. 49, pp. 3-4, Raleigh, North Carolina.