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Abstract

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA) and the New England Interstate Water Pollution Control Commission (NEWIPCC), has developed a water-quality model, called SPARROW (Spatially Referenced Regressions on Watershed Attributes), to assist in regional total maximum daily load (TMDL) and nutrient-criteria activities in New England. SPARROW is a spatially detailed, statistical model that uses regression equations to relate total nitrogen and phosphorus (nutrient) stream loads to nutrient sources and watershed characteristics. The statistical relations in these equations are then used to predict nutrient loads in unmonitored streams.

The New England SPARROW models are built using a hydrologic network of 42,000 stream reaches and associated watersheds. Watershed boundaries are defined for each stream reach in the network through the use of a digital elevation model and existing digitized watershed divides. Nutrient source data is from permitted wastewater discharge data from USEPA's Permit Compliance System (PCS), various land-use sources, and atmospheric deposition. Physical watershed characteristics include drainage area, land use, streamflow, time-of-travel, stream density, percent wetlands, slope of the land surface, and soil permeability.

The New England SPARROW models for total nitrogen and total phosphorus have R-squared values of 0.95 and 0.94, with mean square errors of 0.16 and 0.23, respectively. Variables that were statistically significant in the total nitrogen model include permitted municipal-wastewater discharges, atmospheric deposition, agricultural area, and developed land area. Total nitrogen stream-loss rates were significant only in streams with average annual flows less than or equal to 2.83 cubic meters per second. In streams larger than this, there is nondetectable in-stream loss of annual total nitrogen in New England. Variables that were statistically significant in the total phosphorus model include discharges for municipal wastewater-treatment facilities and pulp and paper facilities, developed land area, agricultural area, and forested area. For total phosphorus, loss rates were significant for reservoirs with surface areas of 10 square kilometers or less, and in streams with flows less than or equal to 2.83 cubic meters per second.

Applications of SPARROW for evaluating nutrient loading in New England waters include estimates of the spatial distributions of total nitrogen and phosphorus yields, sources of the nutrients, and the potential for delivery of those yields to receiving waters. This information can be used to (1) predict ranges in nutrient levels in surface waters, (2) identify the environmental variables that are statistically significant predictors of nutrient levels in streams, (3) evaluate monitoring efforts for better determination of nutrient loads, and (4) evaluate management options for reducing nutrient loads to achieve water-quality goals.

Introduction

Excessive nutrient (nitrogen and phosphorus) concentrations are common in rivers and lakes throughout the United States and New England and frequently result in water-resource impairments (U.S. Environmental Protection Agency, 2000a and 2000b). Although nitrogen and phosphorus are essential for healthy plant and animal life, elevated concentrations of these nutrients can cause eutrophication of waterbodies. Elevated amounts of phosphorus are the common cause of eutrophic freshwater rivers and lakes that often exhibit dense growths of algae or other nuisance aquatic plants, depressed dissolved oxygen levels, loss of fish and submerged aquatic vegetation, and foul odors. More than 30 percent of the lakes in New England were classified by State and Federal agencies as eutrophic in 2000 (U.S. Environmental Protection Agency, 2000b). Eutrophication of coastal waters from excessive nitrogen loadings is also common in the United States and locally in New England (National Research Council, 2000; U.S. Environmental Protection Agency, 2000b).

Sources of phosphorus and nitrogen to rivers, lakes, and coastal waters include permitted and unpermitted wastewater discharges (termed point sources), and runoff from the land surface, ground waters, and the atmosphere (a source primarily for nitrogen only) that collectively are called nonpoint sources. Agricultural and urban land uses are major sources of nutrients

(Carpenter and others, 1998) and are typically a greater source of nutrients than wastewater discharges (Howarth and others, 1996).

Numerous studies have assessed nutrient discharges to coastal waters of the eastern United States because of coastal eutrophication concerns. Many of these studies are summarized by the National Research Council (2000). Howarth and others (1996) report that riverine discharges of nitrogen to coastal waters have increased 5 to 20 times since pre-industrial times and that the increased human population, use of nitrogen fertilizers, increased imports of human food and animal feed, and atmospheric deposition are the principal sources of the increasing levels of nitrogen to coastal waters. Nitrogen levels during the later years of the 20th century in forested watersheds of the northeastern United States continued to increase in contrast to urbanized rivers that have experienced stable nitrogen levels (Roman and others, 2000). Roman and others (2000), Robinson and others (2003), and Litke (1999) show that phosphorus concentrations in streams have declined since the 1960s as a result of phosphate detergent bans and improved wastewater treatment at municipal sewage facilities. Nutrient loads to coastal waters of New England were characterized by the National Oceanic and Atmospheric Administration (NOAA) (1987). Boyer and others (2002) and Mullaney and others (2002) estimated the loads of nitrogen to coastal waters of the eastern United States and to Long Island Sound from Connecticut, respectively, and the relative importance of point and nonpoint sources to the total loads.

Managing and reducing nutrient loads to rivers has been a major water-pollution-control activity of individual states and U.S. Environmental Protection Agency (USEPA) under the Clean Water Act since the 1970s. In the 1990s, the USEPA implemented two programs to facilitate the management of nutrients in the Nation's waters. The Nutrient Criteria program was designed to create waterbody-specific nutrient-concentration criteria for rivers, lakes, and estuaries. The Total Maximum Daily Load (TMDL) program was designed to assess and manage contaminant loads to waterbodies with designated-use impairment. Numeric criteria for concentrations of nitrogen and phosphorus to protect the designated uses of waterbodies are being generated by ecoregions and USEPA regions by the individual states and the USEPA (1998a). Available nutrient data for waterbodies also are being analyzed and new data are being collected during the process of creating the nutrient criteria.

USEPA implements the TMDL program for waterbodies not meeting designed uses because of some form of contamination. TMDLs define the amount of contaminant allowable in the waterbody so that designated uses are met, and allocate allowable pollutant loadings from point and nonpoint sources that contribute the contaminants (U.S. Environmental Protection Agency, 2003). States and the USEPA are charged with identifying streams, rivers, and other waterbodies that have nutrient levels causing designated-use impairment and may require management action. In New England, nearly 2,000 waterbodies do not meet designated uses due to nutrient and organic enrichment, noxious aquatic plants, and low dissolved oxygen (U.S. Environmental Protection Agency, 2003).

Because water-quality data for New England waterbodies are limited for generating nutrient criteria and TMDLs, generating new data through field sampling or modeling to characterize nutrient levels is needed. Statistical modeling that relates nutrient conditions in waterbodies to watershed characteristics is an approach recommended by the National Research Council (2001) for the TMDL program. Such models can include measures of model prediction uncertainty, which can be useful when developing and implementing TMDLs (National Research Council, 2001; Shabman, 2002). The National Research Council study also recommended that approaches to TMDL development incorporate physical (deterministic) characteristics along with stochastic models that provide estimates of the errors involved in the predictions.

The spatially referenced regression model SPARROW (Spatially Referenced Regressions on Watershed attributes), by Smith and others (1997), provides a modeling approach recommended by the National Research Council for water-quality assessments, including assessments needed for the TMDL program. The SPARROW model is designed to characterize nutrient loads in rivers based on a regression equation that includes terms for nutrient sources, land-to-water delivery of nutrients, and riverine transport and loss. The model also relies on geographic information system (GIS) technology to link river segments (termed reaches) and contributing drainage areas together. The SPARROW modeling technique has been successfully applied for predicting total nitrogen and phosphorus loads for streams in the continental United States (Smith and others, 1997) and New Zealand (Alexander and others, 2002), and for estimating total nitrogen loads for the Chesapeake Bay watershed in the eastern United States (Preston and Brakebill, 1999) and in the Albemarle-Pamlico watersheds in North Carolina (McMahon and others, 2003).

Purpose and Scope

This report describes results of two New England SPARROW models—one each for total nitrogen and total phosphorus —that have been developed for assisting water-resources managers with TMDL and nutrient-criteria development in New England. The models were developed by the U.S. Geological Survey (USGS), in cooperation with the New England Interstate Water Pollution Control Commission (NEIWPCC) and the USEPA. The New England models for total nitrogen and total phosphorus are calibrated for the early to mid-1990s and designed to refine national SPARROW results (Smith and others, 1997) by providing enhanced spatial detail and calibrated models on the basis of regional data. These enhancements are desirable because of national-model limitations that include (1) coarse stream resolution for parts of New England; (2) an inability to accurately predict nutrient loads in watersheds less than 65 km^2 (Focazio and others, 1998); (3) the use of only agricultural and non agricultural land-use categorizations; and loss of nutrients within watersheds, and to show prediction or confidence intervals associated with these assessments. Previously, these forms of data have not been available for most New England stream reaches.

Weaknesses of the model and results can be linked to the modeling process and the data used to calibrate and provide predictions of nutrient conditions. Smith and others (1997) note that the SPARROW model structure inherently oversimplifies nutrient transport processes. Many factors locally and regionally affect the transport and loss of nutrients in streams, many of which cannot be accounted for in the SPARROW model. However, model results do indicate that certain transport processes are regionally important. Also, there are limitations with the data used in the modeling process. These limitations include the following:

1. The model requires long-term water-quality datasets that include multiple samples per year. Because of this requirement, the models only incorporate data from limited number of sites throughout the entire New England region. Load datasets, with a greater number of load sites than were used in the existing SPARROW models, may increase the ability to identify statistically significant explanatory variables.
2. Predictor variables may be coarse (such as land uses) or of relatively poor quality (such as point source loads). These data sets may introduce error in the ability of the model to explain and predict the effect of these data on stream water quality. Because of the regional nature of the model, only data that were available for the entire study area could be used. This restriction prevents the use of many locally more precise data or data that characterize other nutrient source or transport processes.
3. Model results also have more uncertainty in smaller watersheds that tend to be further away from monitoring sites. This reflects a lack of monitoring data in New England for watersheds under 25-40 km^2. (There are only 2 sites in the nitrogen and phosphorus datasets with watersheds less than 25 km^2 and only 4 sites with watersheds less than 40 km^2.)
4. Finally, the models only predict mean-annual conditions, not necessarily critical conditions such as low-flow conditions that may be of more concern to water-quality managers and scientists.

Model Estimates of Nutrient Loads

The calibrated SPARROW models allow for the prediction of nutrient loads for nearly 42,000 unmonitored stream reaches throughout New England. The spatial variability of nutrient loads is an important consideration for water-resources managers and planners in prioritizing areas for management actions. Nutrient loads are predicted by applying the SPARROW regression equation to each reach catchment. Starting at the headwater catchments, the regression equation is applied and predicted nutrient loads from that catchment are used as sources in the calculation of the load prediction for the next reach downstream. This process continues downstream until the terminal reach at the mouth of the river is encountered. Reach-level catchment predictions of nutrient loads obtained from SPARROW-model runs are shown in figures 8 and 9. Considerable spatial detail from the use of the NHD can be observed in the predicted results. These predictions represent source-load conditions from 1992-1993.

Several other deterministic and stochastic nutrient models have been used to estimate nutrient balances in New England watersheds. Although these studies have different time frames and use different techniques, they are available for comparison with the New England SPARROW model predictions.

Nitrogen

The predicted nitrogen load generated by each of the 42,000 reach-catchment areas is expressed as a nitrogen yield (delivered to the catchment outlet) by dividing the predicted load generated from within each catchment (including only sources from within the catchment) by the area of the catchment. (Thus, yields are loads normalized by area.) Median catchment yield of nitrogen for the entire study area is 336 $kg/km^2/yr$ with the 10- and 90-percent quantiles at 134 and 782 $kg/km^2/yr$, respectively. The relative contributions from the various source inputs are also predicted by the SPARROW model. The contributions from these sources that go into the catchment yield (fig. 8) are apparent by comparing predicted catchment yield with predicted yield from atmospheric deposition of nitrogen (fig. 9a); predicted developed-land nitrogen yield (fig. 9b); and predicted agricultural-land nitrogen yield (fig. 9c). Because discharge is localized and not a distributed yield, the permitted wastewater discharge is not shown in figure 9.

The primary, or largest, contributing nitrogen source for each catchment is identified in figure 9d. Catchments having permitted municipal wastewater discharge as the primary nitrogen source are also typically in the highest yield category of nitrogen shown in figure 8 (over 1,000 $kg/km^2/yr$). These yields are especially high because the wastewater from a given sewer system is discharged to a single stream reach.

For the entire model area, SPARROW estimates that 86,100 metric tons (86.1 million kilograms) of nitrogen enter New England rivers and streams per year. Of this total, 50 percent (42,700 metric tons/year) is estimated to be from atmospheric deposition; 21 percent (18,000 metric tons/year) is estimated to be discharged from permitted municipal wastewater discharges; 15 percent (13,000 metric tons/year) is estimated to be from other developed land sources; and 14 percent (12,400 metric tons/year) is estimated to be from agricultural lands. The large contributions of atmospheric deposition to nitrogen loads in New England is a major finding of the New England SPARROW model for nitrogen. Model estimates of

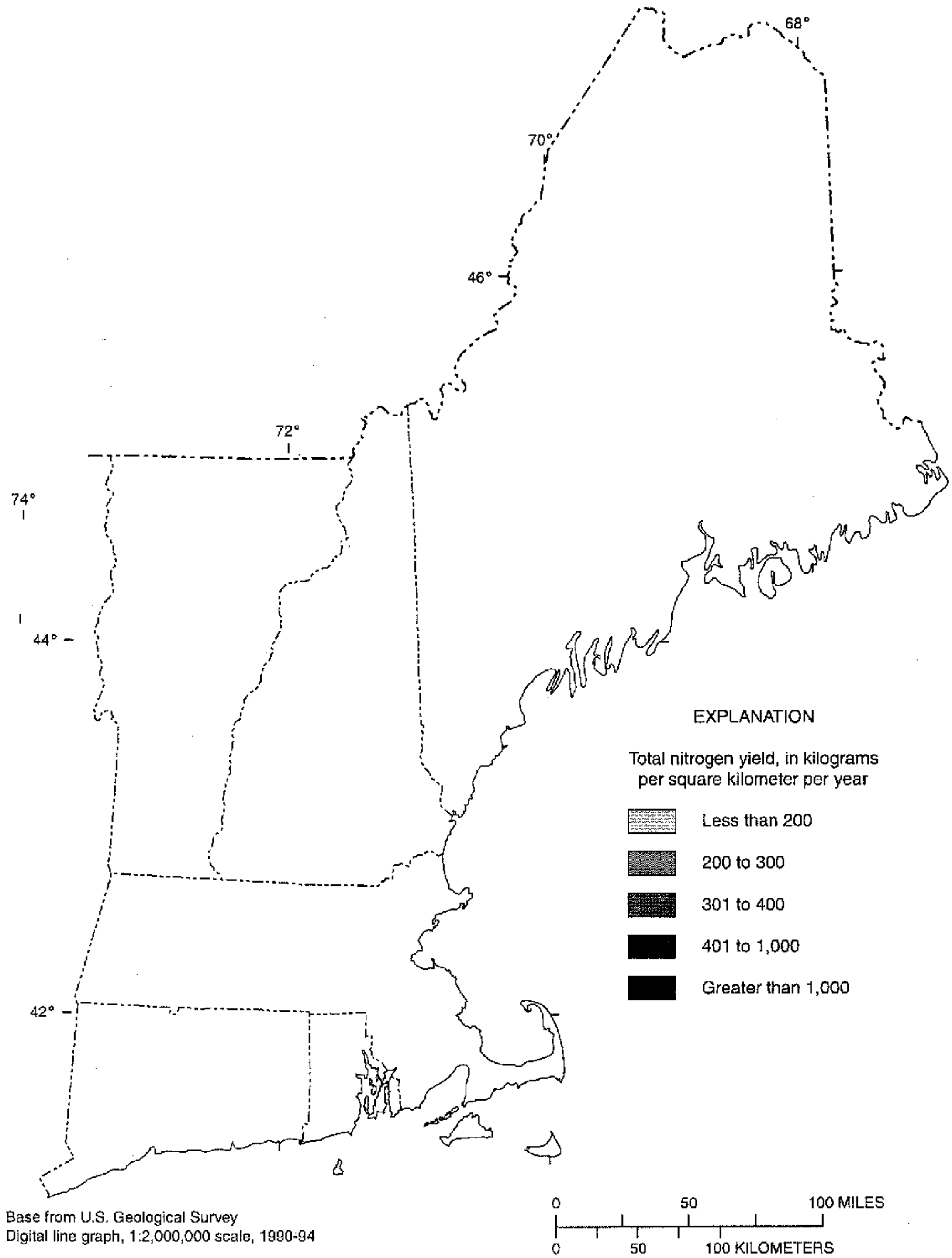
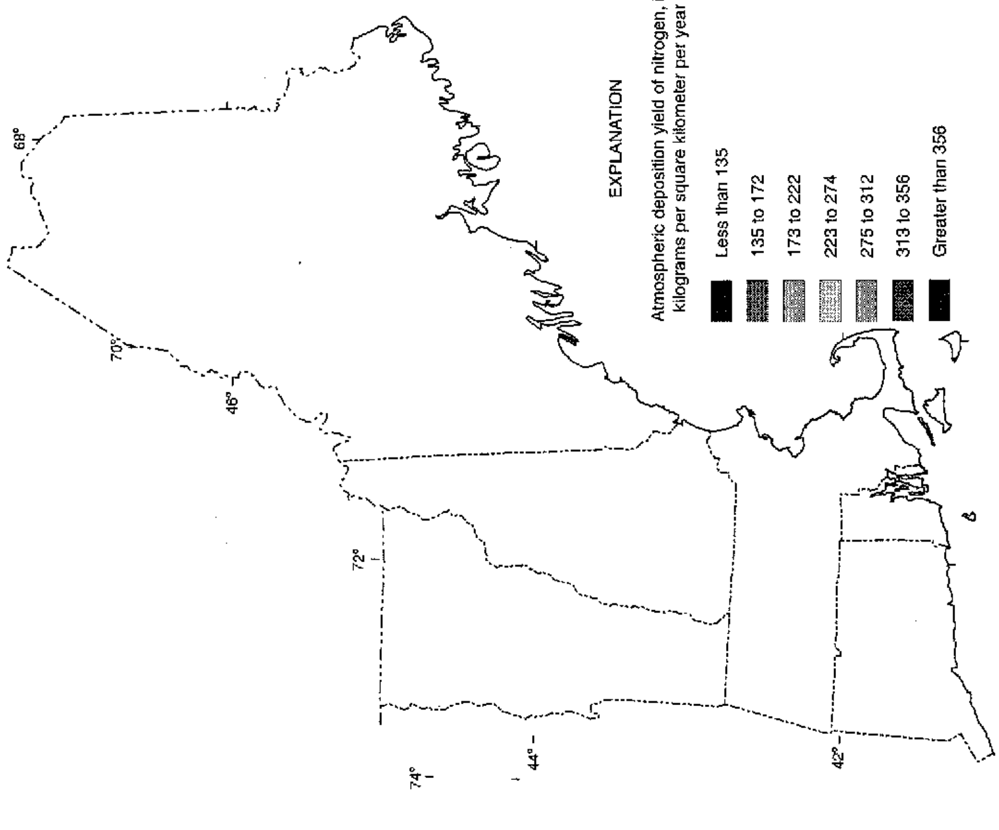


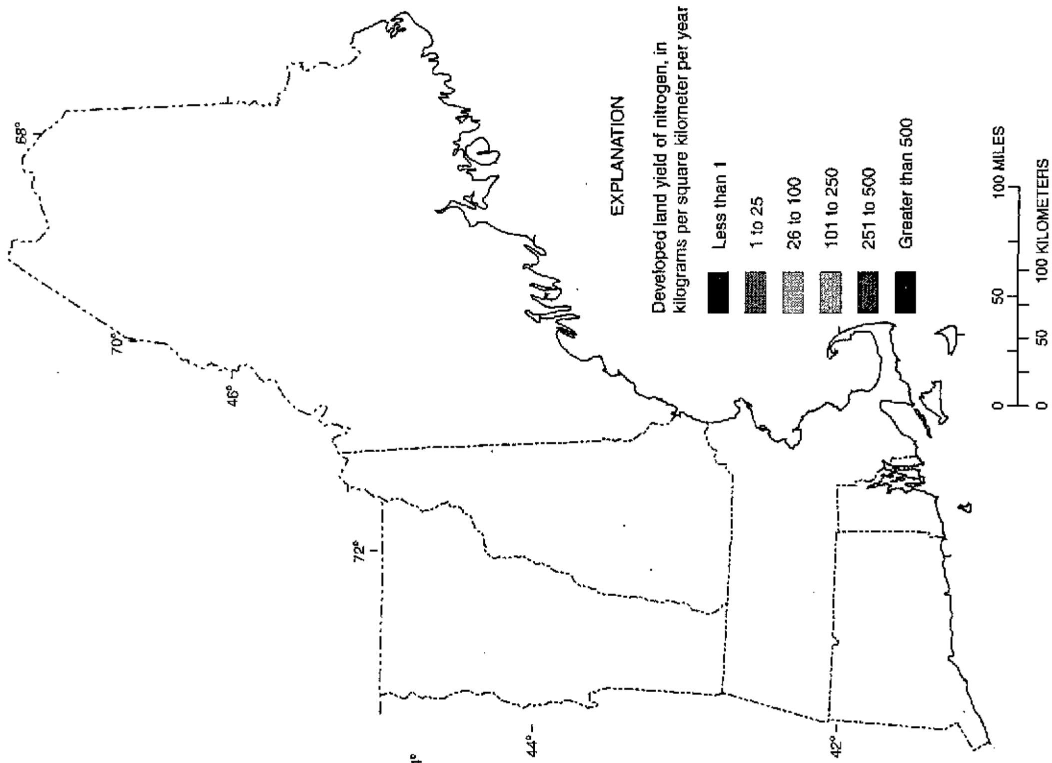
Figure 8. Predicted total nitrogen catchment yield from the New England SPARROW model based on source loads from 1992-93.

A.



Base from U.S. Geological Survey
Digital line graph, 1:2,000,000 scale, 1990-94

B.



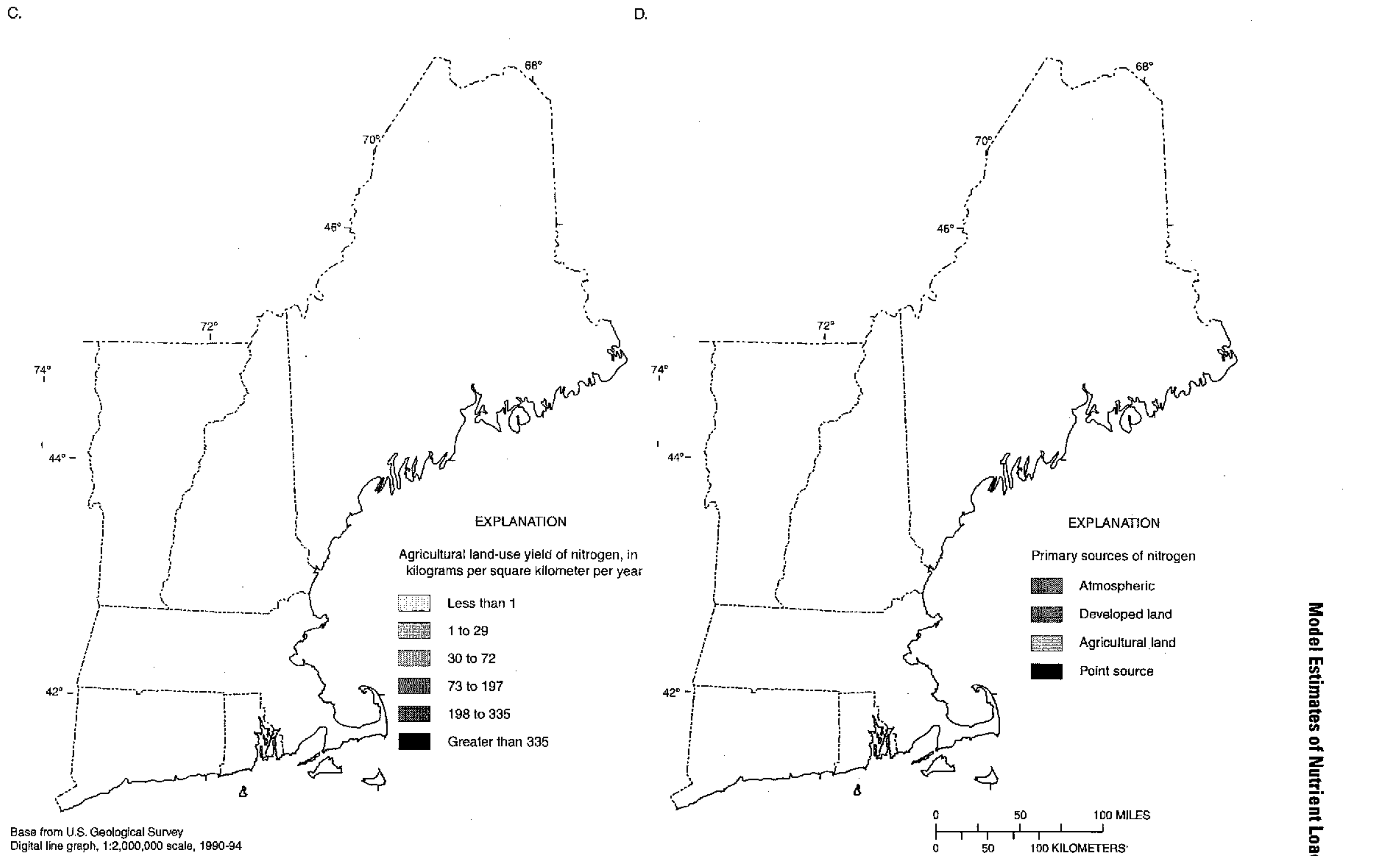


Figure 9. Contribution predicted by the New England SPARROW model of total nitrogen catchment yield from (A) atmospheric deposition of nitrogen, (B) developed land areas, (C) agricultural land-use areas, and (D) primary sources of nitrogen loads in the model.

the nitrogen loads and the percentages related to the various sources by State are summarized in table 5. The SPARROW model estimates of nitrogen loads for 13 major basins in New England are summarized in table 6, along with the relative contributions by each State within each basin, and the percentages related to the various sources for each State.

There are several other deterministic and stochastic models that have been used to estimate nitrogen loads in New England basins. Although five of these models have different time frames and use different techniques, they can be compared with the New England SPARROW model predictions (table 7). These models include the (1) national SPARROW (Smith and others, 1997); (2) National Coastal Pollutant Discharge Inventory conducted by the National Oceanic and Atmospheric Administration (NOAA) (Percy A. Pacheco, NOAA, written commun., 1994); (3) Long Island Sound TMDL Study, an analysis to achieve water-quality standards for dissolved oxygen in Long Island Sound (New York Department of Environmental Conservation/Connecticut Department of Environmental Protection, 2000; Paul Stacey, Connecticut Bureau of Water Management, written commun., 2003); (4) HSPF deterministic model for the State of Connecticut (Paul Stacey, written commun., 2003); and (5) a regression model used to relate watershed characteristics to nutrient loads by Mullaney and others (2002). All of these compare nitrogen estimates at the mouth of selected rivers

Predictions are also available for comparison with a study of the anthropogenic nitrogen sources and relations to riverine nitrogen export in the Northeast (Boyer and others, 2002) (table 8). These predictions, however, are for the farthest downstream USGS water-quality stations, and not at the mouth of the river.

The New England SPARROW model predictions selected for major river basins (table 7) generally have an average of ± 30 percent difference from those of other models presented in table 7, with a maximum difference of 127 percent for the Charles River in Massachusetts. The Charles River Basin is considered an outlier and was excluded from the average of ± 30 percent. The national SPARROW model predicted more than twice (127 percent more) the nitrogen load that the New England SPARROW model predicted for the Charles River Basin. This is largely because the offshore municipal-wastewater discharge for metropolitan Boston is not considered part of the basin nitrogen load in the New England model. However, the national model includes this point source as part of the Charles River model prediction. When compared to the predictions from the model by Boyer and others (2002), the New England SPARROW model predictions have an average of ± 35 percent of the other predictions, with a maximum difference (111 percent) at the Penobscot River water-quality station (table 8). The cause for this large difference is not known.

Phosphorus

Reach-level predictions of the phosphorus loadings by stream catchment are shown in figures 10 and 11. Median catchment yield of phosphorus for the entire study area is 17.6 kg/km^2/yr with the 10- and 90-percent quantiles at 11.5 and 41.0 kg/km^2/yr, respectively.

The relative contributions from the various source inputs are apparent by a comparison of figure 10 with its source components—predicted yield from forested areas (fig. 11a), predicted yield from developed areas (fig. 11b), and predicted yield from agricultural areas (fig. 11c). The permitted wastewater discharges are not shown because these are localized and not a distributed yield. The primary, or largest, contributing source for each catchment is shown in figure 11d. Catchments where discharges from permitted municipal and pulp and paper wastewater discharges are the primary source are identified in black in figure 11d. These are also catchments within the highest yield category shown in figure 10 (over 118 kg/km^2 of phosphorus per year).

For the entire model area, SPARROW estimates that 7,380 metric tons (7.38 million kilograms) of phosphorous enter New England rivers and streams per year. Of this amount, 52 percent (3,860 metric tons/year) is estimated to be from permitted municipal and pulp and paper wastewater discharges;

Table 5. Summary of predicted nitrogen loads by state from the New England SPARROW model for total nitrogen.

[km^2, square kilometers; values not adjusted for the stream loss downstream of the reach of nutrient origin]

State	Drainage area (km^2)	Total nitrogen (metric tons)	Predicted percent of nitrogen load from			
			Atmospheric deposition	Agricultural lands	Developed lands	Municipal wastewater
Maine	79,071	20,476	68	16	7	9
Massachusetts	19,402	20,481	32	6	25	37
New Hampshire	24,009	12,862	59	12	12	16
Connecticut	12,644	11,660	39	12	28	21
Vermont	23,565	11,420	55	30	6	10
Rhode Island	2,561	3,729	24	3	19	54

Table 6. Predicted nitrogen loads by major basin and state from the New England SPARROW model for total nitrogen.

[km^2, square kilometers; values not adjusted for the stream loss downstream of the reach of nutrient origin]

River or lake basin State/Province	Drainage area (km^2)	Total nitrogen (metric tons)	Predicted percent of nitrogen load from			
			Atmospheric deposition	Agricultural lands	Developed lands	Municipal wastewater
Connecticut:	29,172	18,489	49	14	14	23
Vermont	10,162	4,367	65	21	4	9
New Hampshire	7,941	3,568	66	16	7	12
Massachusetts	7,048	6,470	37	10	15	38
Connecticut	3,726	3,978	35	12	28	25
Quebec	294	96	65	30	4	0
Maine	1	0	100	0	0	0
Merrimack:	12,944	10,796	39	9	19	32
New Hampshire	9,840	6,250	52	12	15	20
Massachusetts	3,105	4,546	22	5	24	50
Lake Champlain:	19,212	9,851	51	32	6	11
Vermont	10,766	5,726	47	36	6	11
New York	7,102	3,518	60	22	4	14
Quebec	1,344	607	43	50	7	0
Providence:	2,251	4,913	15	3	14	68
Rhode Island	1,258	2,987	16	2	15	67
Massachusetts	993	1,913	18	4	14	65
Penobscot:						
Maine	21,866	4,299	78	8	4	10
Kennebec (excluding Androscoggin):						
Maine	15,320	4,552	65	18	5	12
Housatonic:	5,036	3,880	45	16	18	21
Connecticut	3,185	2,762	41	14	20	26
Massachusetts	1,294	816	53	17	18	11
New York	557	302	60	34	7	0
Androscoggin:	9,135	3,546	66	16	6	12
Maine	7,284	2,960	62	18	7	13
New Hampshire	1,851	585	87	3	2	8
Thames:	3,807	2,591	50	19	16	15
Connecticut	3,006	2,038	52	21	16	10
Massachusetts	644	490	39	10	17	34
Rhode Island	156	63	82	12	5	0

Table 6. Predicted nitrogen loads by major basin and state from the New England SPARROW model for total nitrogen.—Continued

[km^2, square kilometers; values not adjusted for the stream loss downstream of the reach of nutrient origin]

River or lake basin State/Province	Drainage area (km^2)	Total nitrogen (metric tons)	Predicted percent of nitrogen load from			
			Atmospheric deposition	Agricultural lands	Developed lands	Municipal wastewater
Saco:	4,397	1,981	73	13	6	8
Maine	2,148	1,088	63	18	9	11
New Hampshire	2,249	892	85	7	3	5
Piscataqua (Portsmouth Harbor):	2,608	1,802	46	13	20	21
New Hampshire	1,977	1,414	44	12	21	22
Maine	630	388	52	15	16	16
Taunton:						
Massachusetts	1,392	1,646	31	4	30	36
Charles:						
Massachusetts	767	844	31	5	44	21