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Simulating Stream Transport of Nutrients in the Eastern United States, 2002, Using a Spatially-Referenced Regression Model and 1:100,000-Scale Hydrography

Scientific Investigations Report 2013–5102

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph:
Aerial view of the Roanoke River and
forested wetlands in North Carolina.
Photograph by U.S. Fish and Wildlife Service

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	statute mile
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
	Ratio of reach length to land area	
kilometer per square kilometer (km/km^2)	1.609	mile per square mile (mi/mi^2)
	Nitrogen and phosphorus yield	
kilograms per square kilometer per year [(kg/km^2)yr]	82.64	pounds per acre per year [(lb/ac)yr]

Abbreviations

CMAQ	Community Multi-Scale Air Quality Model
DON	dissolved organic nitrogen
NADP	National Atmospheric Deposition Program
NAWQA	National Water-Quality Assessment
NHD	National Hydrography Dataset
RMSE	root mean square error
SPARROW	Spatially Referenced Regression on Watershed attributes

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By Anne B. Hoos,[1] Richard B. Moore,[1] Ana Maria Garcia,[1] Gregory B. Noe,[1] Silvia E. Terziotti,[1] Craig M. Johnston,[1] and Robin L. Dennis[2]

Abstract

Existing Spatially Referenced Regression on Watershed attributes (SPARROW) nutrient models for the northeastern and southeastern regions of the United States were recalibrated to achieve a hydrographically consistent model with which to assess nutrient sources and stream transport and investigate specific management questions about the effects of wetlands and atmospheric deposition on nutrient transport. Recalibrated nitrogen models for the northeast and southeast were sufficiently similar to be merged into a single nitrogen model for the eastern United States. The atmospheric deposition source in the nitrogen model has been improved to account for individual components of atmospheric input, derived from emissions from agricultural manure, agricultural livestock, vehicles, power plants, other industry, and background sources. This accounting makes it possible to simulate the effects of altering an individual component of atmospheric deposition, such as nitrate emissions from vehicles or power plants. Regional differences in transport of phosphorus through wetlands and reservoirs were investigated and resulted in two distinct phosphorus models for the northeast and southeast. The recalibrated nitrogen and phosphorus models account explicitly for the influence of wetlands on regional-scale land-phase and aqueous-phase transport of nutrients and therefore allow comparison of the water-quality functions of different wetland systems over large spatial scales. Seven wetland systems were associated with enhanced transport of either nitrogen or phosphorus in streams, probably because of the export of dissolved organic nitrogen and bank erosion. Six wetland systems were associated with mitigating the delivery of either nitrogen or phosphorus to streams, probably because of sedimentation, phosphate sorption, and ground water infiltration.

Introduction

Mobilization of the nutrients nitrogen and phosphorus by human activities has caused nutrient enrichment and eutrophication in surface waters worldwide, with severe environmental impact to coastal waters (Nixon, 1995; National Research Council, 2000, Diaz and Rosenberg, 2008). National assessments of eutrophication in U.S. estuaries have related estuarine eutrophic status to stream nutrient loads and natural susceptibility and have projected future eutrophic conditions for the Nation’s estuaries based on observed trends in nutrient inputs (Bricker and others, 1999; Bricker and others, 2007; U.S. Environmental Protection Agency, 2008). National-scale watershed models of stream nutrient loads have been a critical component for these assessments; for example, the 1999 assessment of estuarine eutrophication in the United States was based on 1987 estimates of stream nitrogen loads from a national-scale Spatially Referenced Regression on Watershed attributes (SPARROW) model, calibrated and applied nationally (Smith and others, 1997).

Use of a single national-scale model as a basis for such national assessments has the advantages of uniform, consistent assessment of stream nutrient loads and consistent attribution of sources. Regional-scale SPARROW nutrient models for the conterminous United States have been developed recently (Preston and others, 2011); these models improved the previous national-scale models (Alexander and others, 2008) by

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providing greater accuracy and geographic specificity and a more recent timeframe, 2002. The models developed for the individual regions differed from one another in hydrographic scale and in the representation of sources and factors influencing land-phase and aqueous-phase transport.

To address this issue, the U.S. Geological Survey applied the SPARROW model, as part of its National Water-Quality Assessment Program, to assess the loads delivered in 2002 for estuaries and coastal waters along the Atlantic Ocean and eastern Gulf of Mexico. This study builds upon the regional-scale studies to integrate the models for the northeastern and southeastern United States wherever possible and achieve a consistent assessment of nutrient loading source attribution for estuaries along the coast of the eastern United States. The study also improves the source attribution of atmospheric sources of nitrogen to watersheds and receiving estuaries so that relative contributions from individual sources of atmospheric nitrogen (for example, vehicle or industrial emissions) can be estimated. In addition, the study examines and quantifies the specific role of freshwater wetlands in nutrient transport within eastern U.S. watersheds. Wetlands influence the transport, transformation, and fate of nitrogen and phosphorus moving towards the stream and from the stream to the outlet of the watershed, but their effect on stream transport had not been explicitly characterized or quantified in previous SPARROW models.

Purpose and Scope

This report documents the simulation of stream transport of nutrients in the eastern United States during 2002 using a spatially-referenced regression model and 1:100,000-scale hydrography (fig. 1). To accomplish this goal, the regional-scale models are calibrated for two regions—the northeastern United States (Moore and others, 2011) and southeastern United States (Hoos and McMahon, 2009; Garcia and others, 2011). Model recalibration includes (1) adjusting the regional model scales to the finest available for both original study areas (that is, to the 1:100,000 scale); (2) identifying differences in modeling approaches and adjusting the models to use the best common approach based on model performance, conceptual understanding, and professional judgment; and (3) refining and improving model specification of land-phase and aqueous-phase transformation and removal of nutrients, including characterizing the effect of freshwater wetlands on stream transport of nutrients.

Approach

A number of adjustments were made to the previously published SPARROW nutrient models for the northeastern and southeastern United States to accomplish the study objectives. The adjustments to the models reduced inconsistencies between the regional sets of source and process variables as much as possible and also introduced new predictive variables that had the potential to improve model performance and applicability. A summary of source and process representation in the previously published models (tables 1 and 2) shows that the models are similar in characterization of sources, although some differences arise in the spatial data sets used to represent the contribution from certain sources (for example, contribution from urban land in the nitrogen models and contribution from agricultural fertilizer for the nitrogen and phosphorus models). The northeast and southeast regions are less similar in characterized transport processes, but recent studies have noted that complete alignment between regional models in this respect may not be possible or even desirable because of differences in the set of geographic features that control the nutrient transport rate for each region (Preston and others, 2011; Schwarz and others, 2011).

The adjustments were tested in a stepwise manner using the previously published models as a starting point. Adjustment in hydrographic scale was tested first, followed by adjustments to source representation, and lastly, adjustments to specification of land-phase and aqueous-phase transport. The decision to retain or reject a tested adjustment followed objective, reproducible, empirical procedures: only adjustments that did not detract from (or that increased) model performance were retained. Change in model performance was assessed using stepwise comparisons of root mean square error (RMSE), coefficient of determination (r^2) of yield, and significance of all variables in explaining nutrient transport (using the model-computed p-value as the test for statistical significance at an alpha level of 0.05).

Adjustment in Hydrographic Scale Used as Model Framework

The SPARROW modeling framework is a hydrologic network of stream- or reservoir-reach segments and associated catchments. The network is used to determine flow pathways between the sources of the modeled constituents and the locations of water-quality monitoring sites; the downstream end of each reach segment corresponds to a model computation node. SPARROW can be applied at any channel network scale, but for practical purposes is applied at the finest scale required for modeling objectives and for which the digital channel network data can be assembled. The previously published SPARROW model for the northeast region is based on 1:100,000-scale hydrography; the stream reaches used in the model are equivalent to the flowlines from the 1:100,000-scale National Hydrography Dataset (NHD) for which streamflow direction has been established (U.S. Environmental Protection Agency and U.S. Geological Survey, 2010a, b). An advantage of modeling using this hydrographic network instead of coarser hydrography is that it is spatially explicit to small perennial streams having drainage areas of about 2 square kilometers (km^2) or less (table 3). In theory, the model can therefore represent aqueous transformation and removal of nutrients in streams of this size. (Not all perennial streams are represented even at the 1:100,000 scale, however.) The hydrologic network used for the previously published southeast region model was based on the U.S. Environmental Protection Agency's 1:500,000-scale Reach File 1 (RF1, U.S. Environmental Protection Agency, 1996; Hoos and others, 2008). To more closely align the models, the model framework for the southeast region was changed to 1:100,000-scale NHDPlus Version 1.1 (U.S. Environmental Protection Agency and U.S. Geological Survey, 2010a, b).

The new SPARROW modeling framework for the southeast region has 50 times as many segments as the original framework. Because the total modeled length of streams in this region increased by almost 5 times (table 3), the length of the modeled land-phase flow path decreased. For most streams in the southeast having contributing areas smaller than 80 km^2, the original, 1:500,000-scale network represents the transport pathway from land to any point in the upstream channel as primarily land-phase transport, with aqueous-phase transport along a relatively short stream segment (0.2-kilometer reach length per square kilometer of land area; table 3). The 1:100,000-scale network models the transport pathway for this set of streams as mixed land-phase and aqueous-phase transport, with aqueous-phase transport along 0.8 kilometer (km) of reach length per km^2 of land area.

Adjustment in Calibration Sets

Adjustment to a finer hydrographic scale for the southeast region model adds flexibility to the selection of water-quality monitoring sites used to calibrate the model (fig. 1*B*). Calibration sets are limited practically to include only monitoring sites associated with streams delineated in the model framework. This limit, therefore, excludes from the 1:500,000-scale model calibration set most sites for which drainage area is smaller than about 20 km^2, whereas the 1:100,000-scale model can accommodate calibration sites with contributing areas smaller than 2 km^2. Because only one monitoring site can represent a reach segment, reach segment length (also a function of hydrographic scale) places a separate restriction on calibration sets. Thus excluded from the 1:500,000-scale model calibration set are sites located less than about 4 km away, upstream or downstream, from another monitoring site; this exclusion is equivalent to an intervening drainage area of about 50 km^2. The 1:100,000-scale model can accommodate sites that are located as close as 0.5 km, which is equivalent to an intervening drainage area of about 0.4 km^2; however, it is unclear whether inclusion of close-nested sites in a calibration set improves model calibration.

The calibration set used for the northeast region phosphorus model was altered to include the estimate of mean annual stream load developed for the Chesapeake Bay Watershed model (Ator and others, 2011) for streams in that region in place of the estimates documented in Saad and others (2011) and used for streams in other parts of the northeast region. The estimates from Ator and others (2011) were derived using similar methods and period of record as the estimates documented in Saad and others (2011). However, the estimates from Ator and others (2011) are favored because of their inclusion of monitoring data from a greater number of sources (Langford and others, 2007).

Adjustments in Representation of Sources

An important objective of this work was to enhance the estimation of atmospheric deposition contributions to stream nitrogen transport; specifically, to estimate the relative contributions of individual components of atmospheric nitrogen, such as vehicle or industrial emissions (appendix 1). This modification allows the model to simulate the effects of altering individual components of atmospheric nitrogen separately. Modeled estimates of wet and dry deposition (Dennis and Foley, 2009; Dennis, 2010) were incorporated into the model to replace measured and contoured estimates of wet deposition (Wieczorek and Lamotte, 2011a, b).

Additional adjustments to representation of sources for the aligned models were tested (table 4). These adjustments allow greater specificity in simulating source contributions and also improve alignment between the northeast and southeast models, thereby allowing more direct comparisons of stream nutrient transport throughout watersheds in the eastern United States. In the northeast phosphorus model, for example, the representation of contributions from background sources was changed to a measure of phosphorus content in parent rock, replacing the surrogate measure forested land. A change in the representation of contributions from fertilizer applied to all agricultural crops to contributions split by crop type (Wieczorek and Lamotte, 2011b) allows for simulating the effects of altering these components separately. In each case, the alteration in source representation is accepted only if RMSE does not increase or does not cause loss of significance of another source term.

Representation of Processes Influencing Land-Phase and Aqueous-Phase Attenuation of Nutrients

In this study, land-phase attenuation is simulated in the aligned models using physical landscape variables that relate more directly to the physical processes of attenuation (for example, temperature, land slope, soil properties), compared to the broad regional classification variables (for example, ecoregion classification) used in previously published models. The role of wetlands in regional nutrient balance and stream transport had been investigated in the previously published phosphorus model for the southeast (table 2, Garcia and others, 2011) by quantifying the effect of soil organic matter (spatially correlated to palustrine wetlands) on land-phase attenuation of phosphorus. The aligned models presented herein explicitly characterize the effect of freshwater wetlands on both land-phase and aqueous-phase attenuation of nitrogen and phosphorus. Adjustments in the representation of land-phase and aqueous-phase processes are described in table 5.

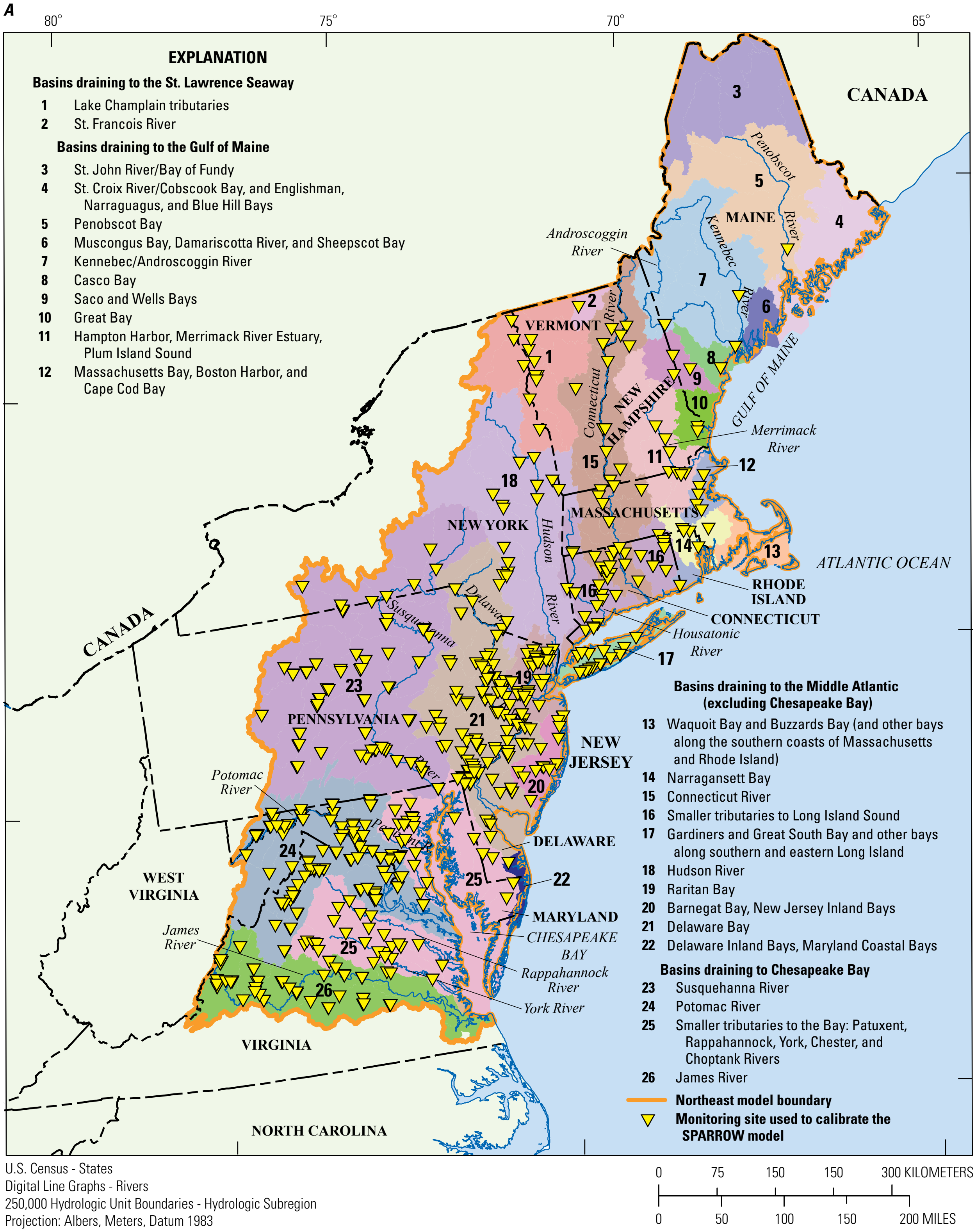


Figure 1. Regional model boundary and river basin groups for the *A*, northeastern and *B*, southeastern United States.

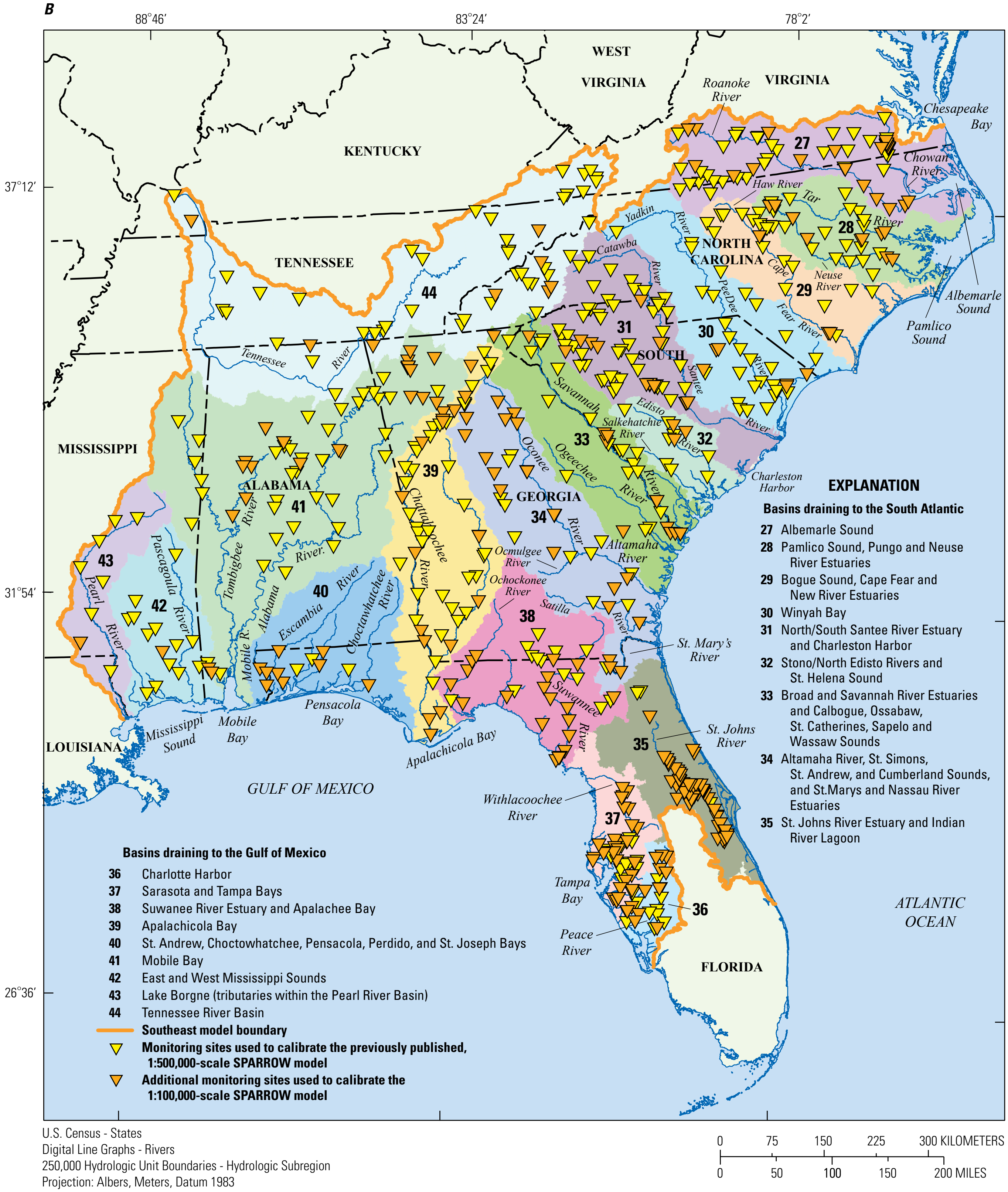


Figure 1. Regional model boundary and river basin groups for the *A*, northeastern and *B*, southeastern United States.—Continued

Table 1. Spatially Referenced Regression on Watershed attributes (SPARROW) nitrogen models previously specified and estimated independently for the northeastern and southeastern United States; published in Moore and others (2011) and Hoos and others (2009).

[NE, variable used in model for the northeastern United States; SE, variable used in the model for the southeastern United States. All variables significant at the 5-percent significance level except where noted; >, greater than; <, less than; kg/yr, kilogram per year, km^2, square kilometer; m^3/s, cubic meter per second; y/m; year per meter; ln, natural logarithm]

Model diagnostics[a]		Northeast	Southeast
Root mean square error (RMSE), log-transformed residuals		0.35	0.32
Coefficient of determination (R^2) of yield estimate		0.83	0.72
Predictor variable	**Data set used to represent model variable (varies with region)**	**Coefficient estimates**	
	Source		
Point sources	NE: Permitted municipal wastewater discharge, major facilities (kg/yr)	1.16	([b])
	SE: All permitted wastewater discharge (kg/yr)	([b])	0.79
Urban land	NE: Area of developed land (km^2)	1,422	([b])
	SE: Area of impervious surfaces (km^2)	([b])	2,470
Agricultural fertilizer	NE: Commercial fertilizer applied to corn/soybeans/alfalfa and to areas of crop rotation and fixation (kg/yr)	0.31	([b])
	NE: Commercial fertilizer applied to other[c] crops (kg/yr)	0.19	([b])
	SE: Commercial fertilizer applied to all crops (kg/yr)	([b])	0.11
Agricultural livestock	NE and SE: Manure from livestock production (kg/yr)	0.09	0.05
Atmospheric deposition	NE and SE: Wet deposition of inorganic nitrogen (kg/yr)	0.28	0.50
	Process: Variation in rates of source to water transport—enhanced[c] delivery to streams		
	NE: Ratio of nitrate to total inorganic nitrogen in atmospheric deposition (converted to natural logarithm)	2.56	([b])
	NE: Northern Piedmont Ecoregion indicator (0,1)	0.42	([b])
	NE: Valley and Ridge Ecoregion indicator (0,1)	0.59	([b])
	SE: Mean annual precipitation (ln of mm)	([e])	1.2
	SE: Fraction of catchment in Hydrologic Landscape Region[f] 4	([b])	0.26
	SE: Fraction of catchment in combined Hydrologic Landscape Regions[f] 6, 9, or 11	([b])	0.26
	Process: Variation in rates of source to water transport—reduced[c] delivery to streams		
	NE: Mean annual temperature (ln of degrees Celsius)	-0.86	([b])
	NE: Average overland flow distance to the stream channel (km)	-0.19	([b])
	SE: Depth to bedrock (ln of cm)	([b])	-0.28
	SE: Fraction of catchment in Hydrologic Landscape Region 2[f]	([b])	-0.29
	SE: Fraction of catchment in Hydrologic Landscape Region 7[g]	([b])	-0.31
	SE: Fraction of catchment in Hydrologic Landscape Region 16[f]	([b])	-0.14
	Process: Instream and in-reservoir attenuation		
Instream attenuation	NE: Time of travel in reach with mean discharge <2.83 m^3/s (days)	0.22	([b])
	SE: Time of travel in reach with mean discharge <28 m^3/s (days)	([b])	0.14
	SE: Time of travel in reach with mean discharge >28 m^3/s (days)	([b])	0.014[h]
Reservoir attenuation	NE and SE: Inverse hydraulic load (yr/m)	([e])	10.70

[a]Model diagnostics are calculated from simulations corrected using all upstream load observations.

[b]Variable was not tested for this regional model.

[c]Other means other than corn, soybeans, alfalfa, wheat, hay, and cotton.

[d]Enhanced and reduced mean relative to the rate for catchment with average values of delivery variables.

[e]Variable was tested but was not significant at the 5 percent significance level and not retained.

[f]Hydrologic landscape regions are land areas with similar land-surface form, geologic texture (permeability of the soil and bedrock), and climate, delineated based on multivariate statistical analysis (Wolock and others, 2004). Regions 6, 9, and 11 are characterized as flat (plain or plateau) regions with impermeable soils. Regions 2, 4, 7, and 16 are characterized as plains or mountains with permeable soils.

[g]Percentage of catchment in hydrologic landscape region 7 was not significant at the 5 percent significance level but was retained in order to complete the description of source to water transport across all hydrologic landscape regions.

[h]Time of travel in reach with mean discharge >28 m^3/s was not significant at the 5-percent significance level but was retained in order to complete the description of nitrogen removal across the full range of stream sizes.

Table 2. Spatially Referenced Regression on Watershed attributes (SPARROW) phosphorus models previously specified and estimated independently for the northeastern and southeastern United States; published in Moore and others (2011) and Garcia and others (2011).

[NE, variable used in model for the northeastern United States; SE, variable used in the model for the southeastern United States. All variables significant at the 5-percent significance level except where noted; >, greater than; <, less than; kg/yr, kilogram per year; m, meter; km², square kilometer; ppm-km², parts per million-square kilometer; m³/s, cubic meter per second; m, meter; y/m; year per meter; ln, natural logarithm]

Model diagnostics[a]		Northeast	Southeast
Root mean square error (RMSE), log-transformed residuals		0.65	0.54
Coefficient of determination (R^2) of yield estimate		0.60	0.67
Predictor variable	**Data set used to represent model variable (varies with region)**	**Coefficient estimates**	
	Source		
Point sources	NE: Permitted municipal wastewater discharge, major facilities (kg/yr)	1.32	([b])
	SE: All permitted wastewater discharge (kg/yr)	([b])	0.67
Urban land	NE and SE: Area of developed land (km^2)	106	88
Agricultural fertilizer	NE: Commercial fertilizer applied to corn/soybeans/alfalfa and to areas of crop rotation (kg/yr)	0.07	([c])
	NE: Commercial fertilizer applied to other[b] crops (kg/yr)	0.23	([c])
	SE: Area of catchment with agricultural land use (km^2)	([b])	48
Agricultural livestock	NE and SE: Manure from livestock production (kg/yr)	0.06	0.01
Background (parent-rock minerals)	NE: Area of catchment covered by forested land (km^2)	11.41	
	SE: Mineral content indicated by stream bed phosphorus levels, scaled by catchment area (ppm-km^2)	([b])	0.04
Phosphate mining	SE: Mineral content indicated by stream bed phosphorus levels downstream from mined land, scaled by mined land area (ppm-km^2)	([b])	0.33
	Process: variation in rates of source to water transport—enhanced[c] delivery to streams		
	NE: Eastern Great Lakes and Hudson Lowlands Ecoregion indicator (0,1)	0.97	([b])
	SE: Mean annual precipitation (ln of mm)	([c])	2.0
	SE: Soil erodibility factor (dimensionless)	([b])	4.1
	SE: Soil pH (dimensionless)	([b])	0.46
	Process: variation in rates of source to water transport—reduced[c] delivery to streams		
	NE: Percentage of streamflow coming from ground water	-1.0	([b])
	NE: Average overland flow distance to the stream channel (km)	-0.58	([b])
	NE: New England Coastal Zone Ecoregion indicator (0,1)	-0.54	([b])
	SE: Depth to the water table (m)	([b])	-0.35
	SE: Soil organic matter content (percent)	([b])	-0.17
	Process: Instream and in-reservoir attenuation		
Instream attenuation	SE: Time of travel in in reach with mean discharge <2.83 m^3/s, per unit of stream depth (days)	([c])	0.05
Reservoir attenuation	NE and SE: Inverse hydraulic load (yr/m)	2.69	29.82

[a]Model diagnostics are calculated from simulations corrected using all upstream load observations.

[b]Variable was not tested for this regional model.

[c]Variable was tested but was not significant at the 5-percent significance level and not retained.

[d]Instream attenuation was not included in the northeast model; a time of travel variable was tested but was not significant at the 5-percent significance level.

Table 3. Comparison of the hydrologic networks and calibration sets for the northeast and southeast region models.

[km²; square kilometer; km, kilometer; >, greater than; <, less than; NC, no change from the previously published model]

Attributes of network or calibration set	Northeast (previously published model)	Northeast (aligned model)	Southeast (previously published model)	Southeast (aligned model)
Attributes of networks				
Hydrographic scale	1:100,000	NC	1:500,000	1:100,000
Number of reach segments in region[a]	193,336	NC	8,321	392,918
Number of lakes or reservoirs in region	18,152	NC	173	23,748
(Number of lakes or reservoirs with surface area >5 km²)	214	NC	115	161
Total area of all catchment segments in region (km²)	447,518	NC	785,894[b]	761,030
Total length of all reach segments in region (km)	297,640	NC	114,664	581,928
Catchment drainage area for typical headwater reach (median value, km²)	2.1	NC	84	1.7
Differences in description of land-phase and aqueous-phase pathways in small drainage basins (< 80 km²)[c]				
Proportion of sum of channel length for reach segments with downstream node having drainage area <80 km², to total channel length (fraction of 1)	0.8	NC	0.2	0.9
Proportion of sum of area of all catchments for which first computation node moving downstream has drainage area <80 km² to total area (fraction of 1)	0.8	NC	0.2	0.8
Ratio of reach length to land area (km/km²) for reaches for which total drainage at downstream node is <80 km²	0.7	NC	0.2	0.8
Proportion of number of reaches for which total drainage at downstream node is <80 km² to total number of reaches (fraction of 1)	0.8	NC	0.3	0.9
Attributes of calibration set (first number is for N model, second number is for P model)				
Number of monitoring sites with estimates for mean annual load, detrended to 2002	563/575[d]	563/488[e]	637/747[f]	NC
Number of monitoring sites used to calibrate model	363/457	363/432	321/370	533/609
Average area per calibration site (km²)	1,232/979	1,232/1,036	2,369/2,055	1,427/1,240
Number of monitoring sites on streams with contributing drainage area <20 km² [g]	8/12	8/12	1/2	6/8
Number of monitoring sites for which nested area is <50 km² [h]	47/32	47/31	12/15	69/83

[a]The number of reach segments in the hydrologic network is prescribed by the number of tributary confluences; higher resolution in delineating tributary streams leads to greater number of reach segments.

[b]Total areal extent of catchment segments in the 1:500,000 model is larger (by about 5 percent) than in the 1:100,000 model due to discrepancies in inclusion of open water areas in shoreline catchment segments, in delineation of watershed divides, and of closed basins . The extent represented by the 1:100,000 model is considered more accurate.

[c]A value of 80 km² is used as a threshold as it represents the stream size below which transport is modeled as primarily in land phase in the 1:500,000 model framework.

[d]Estimates of loads at monitoring sites used in the previously published northeast models are documented in Saad and others (2011).

[e]In the aligned phosphorus model for the northeast, estimates of loads at monitoring sites in Chesapeake Bay watersheds are from Ator and others (2011); estimates of loads at monitoring sites in other streams in the northeast are from Saad and others (2011). In the aligned nitrogen model for the northeast, all estimates of loads are from Saad and others (2011).

[f]Estimates of loads at monitoring sites are from Saad and others (2011).

[g]A value of 20 km² is used as a threshold as it represents the lower limit of streams delineated in the 1:500,000 model framework for the eastern United States.

[h]A value of 50 km² is used as a threshold as it is near the lower limit that can be accommodated in the 1:500,000 model framework of intervening area between nested sites.

Table 4. Proposed adjustments in representation of sources for aligned models, relative to previously published regional models.

[N, nitrogen; P, phosphorus; NLCD, National Land Cover Dataset]

Source	Description of input dataset proposed to represent source, and *reason to adjust representation*
Point sources	For the Chesapeake Bay watersheds, test estimates of municipal wastewater discharge of P compiled by the Chesapeake Bay Program[a] in place of the estimates documented in Maupin and Ivahnenko (2011); *involvement by local agencies in compiling effluent phosphorus concentration data improves characterization of effluent load estimates* For the Southeast watersheds, test estimates of municipal wastewater discharge of N in place of estimates of all wastewater discharge (municipal, industrial, non-municipal domestic; location data may be less accurate for the latter two), *to align N model in southeast region to northeast region*
Runoff from developed land	Test area of urban land area[b] in N model for southeast region (previously published model used area in catchment of NLCD impervious area), *to align N model in southeast region to other regional models*[c]
Fertilizer applied to agricultural land	Test two separate variables (crop split) for fertilizer input[d] in N model for southeast region: estimated mass applied to corn/soybeans/alfalfa versus mass applied to all other crops (previously published model for southeast used single variable for all crops), *to align N model in southeast region to northeast region model and to better account for biological N fixation from agricultural areas*
Fertilizer applied to agricultural land	Test two separate variables to represent fertilizer input in P model for southeast region: area of land in cultivated crops versus area of land in pasture/hay[e], *to allow separate estimates of contribution of phosphorus from cultivated versus noncultivated agricultural land*
Background contribution of P	Test rank (derived from bed sediment geochemical data) of potential of watershed to contribute P from surficial geologic material[f] in P model for northeast region (previously published model for northeast used forested land area), *to align P model in northeast region to southeast region*[g]
Atmospheric deposition	Test modeled estimates of wet and dry deposition of inorganic N for models for southeast and northeast region[h] (previously published models used estimates from measurements of wet inorganic deposition of N), *to allow simulation of loads from background, and from scenarios of emission sources of atmospheric N*

[a]Estimates of phosphorus wastewater effluent load (primarily municipal) documented in U.S. Environmental Protection Agency (2009).

[b]Data set of urban land area (NLCD class 2) documented in Wieczorek and Lamotte (2011a).

[c]For runoff from developed land, align southeast representation to northeast rather than vice versa because specification for northeast aligns with all other regional models.

[d]Data set of commercial fertilizer inputs documented in Wieczorek and Lamotte (2011a).

[e]Data set of cultivated and pasture/hay land area (NLCD class 82 and 81) documented in Wieczorek and Lamotte (2011a).

[f]Data set for northeastern United States of mineral content of parent rock indicated by stream bed phosphorus levels described in appendix 1 of this report.

[g]For background contribution of phosphorus, align northeast representation to southeast rather than vice versa because southeast specification better accounts for the background component in all soils regardless of land use.

[h]Data set of wet and dry deposition of inorganic N documented in Dennis and others (2012a). In general the estimated inputs of wet and dry deposition for a catchment are approximately twice as large as the estimated inputs of wet deposition used in the previously published models.

Using the SPARROW Analysis to Quantify Net Effect of Freshwater Wetlands

The effects of freshwater wetlands nutrient transport are modeled using spatial data sets of 29 wetland systems classified by plant community types (appendix 1, tables 1-1 and 1-2). Each wetland system is further identified as riparian or nonriparian based on the respective presence or absence of hydrologic connectivity between the wetland system and streams or rivers (appendix 1). A review of literature concerning the effects of wetlands on nutrient transport (summarized below) guided decisions about how and whether to group the individual wetland systems for testing in the model.

Although wetlands are generally thought to reduce nutrient loading from watersheds (Verhoeven and others, 2006), they are also known to increase nutrient loading in some regions (Noe and Hupp 2007). Wetland hydrology typically determines whether a given wetland attenuates or enhances nutrient loading from watersheds. Both nonriparian and riparian wetlands can influence stream nutrient loads by intercepting (1) atmospheric deposition and (2) surface-water and groundwater flow paths from uplands and then changing nutrient delivery to streams. Riparian wetlands can have an additional effect on stream loads through their action on the mass of nutrients already moving in the stream.

Table 5. Proposed adjustments in representation of processes, relative to previously published regional models.

[N, nitrogen; P, phosphorus]

Adjustment in process representation	Description of input dataset proposed to represent factor, and *reason to adjust specification*
Land-phase attenuation processes (affect rate of transport from catchment to stream channel)	
Use local-scale physical landscape variables in favor of broad regional landscape classification variables	Use landscape variables that relate to the physical processes of landscape attenuation, such as cation exchange capacity, depth to bedrock, slope, to simulate spatial variation in land-phase attenuation, rather than ecoregions or hydrologic landscape regions, *permits interpreting attenuation effects of individual factors*
Differential N and P transport rate in catchments containing certain wetlands classifications compared to non-wetland catchments(i.e., higher or lower delivery to stream channel) depending on wetland classification	Use estimated area in catchment of wetlands classified by vegetation and proximity to stream[a]; *not included in previously published model because of lack of available detailed geospatial information on wetland classification*
Aqueous-phase attenuation processes (affect rate of transport of mass moving instream	
N and P attenuation in first- and second-order streams	Use time of travel in stream segment[b] estimated from segment characteristics delineated at 100,000 scale and, therefore, representing first- and second-order streams, *previously published models for southeastern United States used 1:500,000-scale hydrography and, therefore, did not represent first-and second-order streams, southeast hydrographic scale now matches northeast*
N and P attenuation in floodplain wetlands	Width of riparian wetland corridor[a], *not included in previously published model because of lack of available detailed geospatial information on wetland classification*
N and P attenuation in incremental reservoir segments	In the southeast, inverse hydraulic load estimated separately for incremental reservoir segment delineated at 1:100,000 scale[c] replaces inverse hydraulic load estimated for entire reservoir body delineated at 1:500,000 scale, *southeast hydrographic-scale and specification now matches northeast*

[a]Data set of wetlands classification and areal extent documented in this report.

[b]Time of travel in stream segment estimated as quotient of reach length and mean annual velocity, data set documented in U.S. Environmental Protection Agency and U.S. Geological Survey (2010a).

[c]Inverse hydraulic load is estimated as quotient of area of open water contiguous to the reach flowline and mean annual streamflow (resulting units are year per meter), data set documented in U.S. Environmental Protection Agency and U.S. Geological Survey (2010a).

Riparian wetlands have been shown to attenuate stream transport of nitrogen (Vidon and others, 2010) through denitrification (Triska and others, 1993; Forshay and Stanley, 2005), biotic uptake (Richardson and others, 2004), and sediment deposition during overbank flooding (Noe and Hupp, 2009). Riparian wetlands have been shown to attenuate stream transport of phosphorus by increasing phosphorus sedimentation (Noe and Hupp, 2009), biotic uptake, and inorganic phosphorus sorption processes (Reddy and others, 1999). Trapping of riverine sediment is a common mechanism for nutrient retention of both nitrogen and phosphorus in the Coastal Plain and Piedmont physiographic provinces of the eastern United States (Craft and Casey, 2000; Hupp, 2000; Noe and Hupp, 2009). However, not all riparian wetlands trap sediment; some wetlands are in geomorphic equilibrium (Hupp, 2000), and others are net erosive through high rates of streambank erosion (Schenk and others, 2012).

The effect of nonriparian wetlands on nutrient transport probably varies according to the range of water sources and connectivity to surface-water bodies. Isolated wetlands are generally considered to be nutrient sinks (Whigham and Jordan, 2003) because of limited surface-water outflow, with most water inputs exiting as evapotranspiration rather than surface-water runoff (Whigham and Jordan, 2003; Winter and LaBaugh, 2003).

Nonriparian and riparian wetlands are both known to increase concentrations of organic nutrients in flowing water, often by incorporating inorganic nutrients into biomass that is then exported as dissolved or particulate organic nitrogen or phosphorus (Yarbro, 1983; Elder, 1985; Hamilton and Lewis, 1987; Ward, 1989; Ardon and others, 2010). The proportion of catchment area occupied by wetlands is positively associated with stream dissolved organic nitrogen (DON) concentration (Pellerin and others, 2004) or proportion of total nitrogen (Scott and others, 2007). A probable mechanism by which certain wetland systems increase nutrient delivery to streams is the export of dissolved organic matter that is relatively unavailable, biologically, compared to inorganic nutrients (Wiegner and Seitzinger, 2004) and thus more likely to be transported downstream.

Because wetlands range from having mitigating to enhancing effects on nutrient transport and because no *a priori* information was available about the net effects for individual systems, each of the 29 wetland systems was tested as a separate variable in the model. The net effect (either mitigating or enhancing) of each system on the transport of nitrogen and phosphorus, from the catchment towards the stream, was determined by testing the significance in the model as land-phase transport variables. For the subset of 16 wetland systems that are riparian wetlands (tables 1-1 and 1-2), the influence on instream transport of nutrients was additionally determined by testing their significance as aqueous-phase attenuation variables. Aqueous-phase attenuation in the SPARROW models was represented as a function of both in-channel processes that vary across reach segments as a function of stream size and time of travel and out-of-bank processes that vary with riparian wetland density and time of travel. The function used to specify this concept of attenuation in the model is described in detail in appendix 1.

Results

The models described in this section are termed the "aligned models," or "models with aligned specification." These new models were evaluated by (1) examining overall model diagnostics and estimated model parameters and comparing these among the aligned models and to the previously published models; (2) interpreting the performance of attributes used in the aligned models to describe the influence of wetlands on nutrient transport; and (3) interpreting the nutrient budgets and source shares produced from the aligned-model simulations.

Model Fit Statistics and Estimated Coefficients for the Aligned Models

A single model was specified for nitrogen after determining that a uniform set of source and land-phase transport variables performed similarly (as indicated by root mean square error, or RMSE values) for each of the northeast and southeast regions compared to specifications developed separately for the northeast and southeast. The loads and yields predicted by the aligned nitrogen model closely match the observed values for nitrogen, as indicated by RMSE of 0.35 (expressed in log units), and coefficient of determination (r^2) of 0.76 (table 6). RMSE is higher than the previously published southeast nitrogen model for the southeast (RMSE = 0.32, table 1); however, this change does not necessarily indicate that alignment reduced model accuracy, because different sets of observations were used to calibrate the two models.

The RMSE values for the aligned phosphorus models for the northeast and southeast are 0.60 and 0.56, respectively, and r^2 values are 0.68 and 0.65 (table 7). The RMSE for the aligned northeast phosphorus model is smaller than that of the previously published northeast phosphorus model (0.65, table 1), whereas the RMSE for the aligned southeast model is slightly larger than that for the earlier model (0.54, table 1). The set of observations used differed, however, between northeast and southeast phosphorus models.

For the source variables that represent nutrients on the land surface (that is, for all source variables except point sources) the model-fitted source coefficient, α, describes the land-phase delivery ratio:

$$\alpha = \text{[nutrient mass delivered to the adjacent stream channel] / [measured input to the catchment]}, \quad (1)$$

where the measured input term could either be expressed in terms of (1) nutrient mass, in the case of applied fertilizer and manure, for example; (2) land area, in the case of the urban land variable; or (3) other units of measure. Coefficients associated with land-area variables can be interpreted as export coefficients that represent the mass delivered to streams per unit area.

The value reported for α in tables 6 and 7 represents the ratio for an average catchment in the model area because the delivery ratio is actually simulated as varying among catchments to account for the spatially varying physical characteristics, such as climate or geology, that influence delivery. The value of α for each land-based source therefore represents the effect, averaged for the modeled area, of all model-specified processes of nutrient transformation and attenuation during land-phase transport for that source category. For example, the α value of 0.35 for the variable *commercial fertilizer applied to corn or soybeans and mass from crop fixation* (table 6) means that for a typical watershed in the eastern United States, the model calculates that 0.35 kilogram (kg) of nitrogen is delivered to the adjacent stream channel for every kilogram of nitrogen in commercial fertilizer applied to corn or soybeans or fixed by legume crops in the catchment. A more detailed discussion of the model coefficients and their physical interpretation is provided in appendix 2.

The spatial variation across each region of the land-phase delivery ratio from the aligned models is shown in figure 2 for nitrogen sources and figure 3 for phosphorus sources. In general, watersheds in New England, New York, Pennsylvania, and the western part of the southeast region have the greatest land-phase delivery ratios for nitrogen (figs. 2*A–D*). Catchments in these areas transport a greater proportion of nitrogen to the stream, given equal nitrogen inputs, than the rest of the model area; therefore, land-phase transport in these areas is more conservative than in other areas.

For the northeast and southeast phosphorus models, the land-phase delivery ratio can be compared between regions for the three sources that are represented with aligned input variables: *phosphorus in manure from livestock production, area of developed land*, and *phosphorus from parent-rock minerals.* For the source *phosphorus in manure from livestock*

Table 6. Spatially Referenced Regression on Watershed attributes (SPARROW) nitrogen model for the eastern United States.

[Each source in the aligned model is represented by data sets that are exactly equivalent between northeast and southeast, except where indicated otherwise; all variables significant at the 5-percent significance level; kg/yr, kilogram per year; km², square kilometer; m, meter; m³/s, cubic meter per second; yr/m, year per meter; cm, centimeter; cm/d, centimeter per day; km, kilometer; m*d, meters multiplied by day; <, less than; ln, natural logarithm]

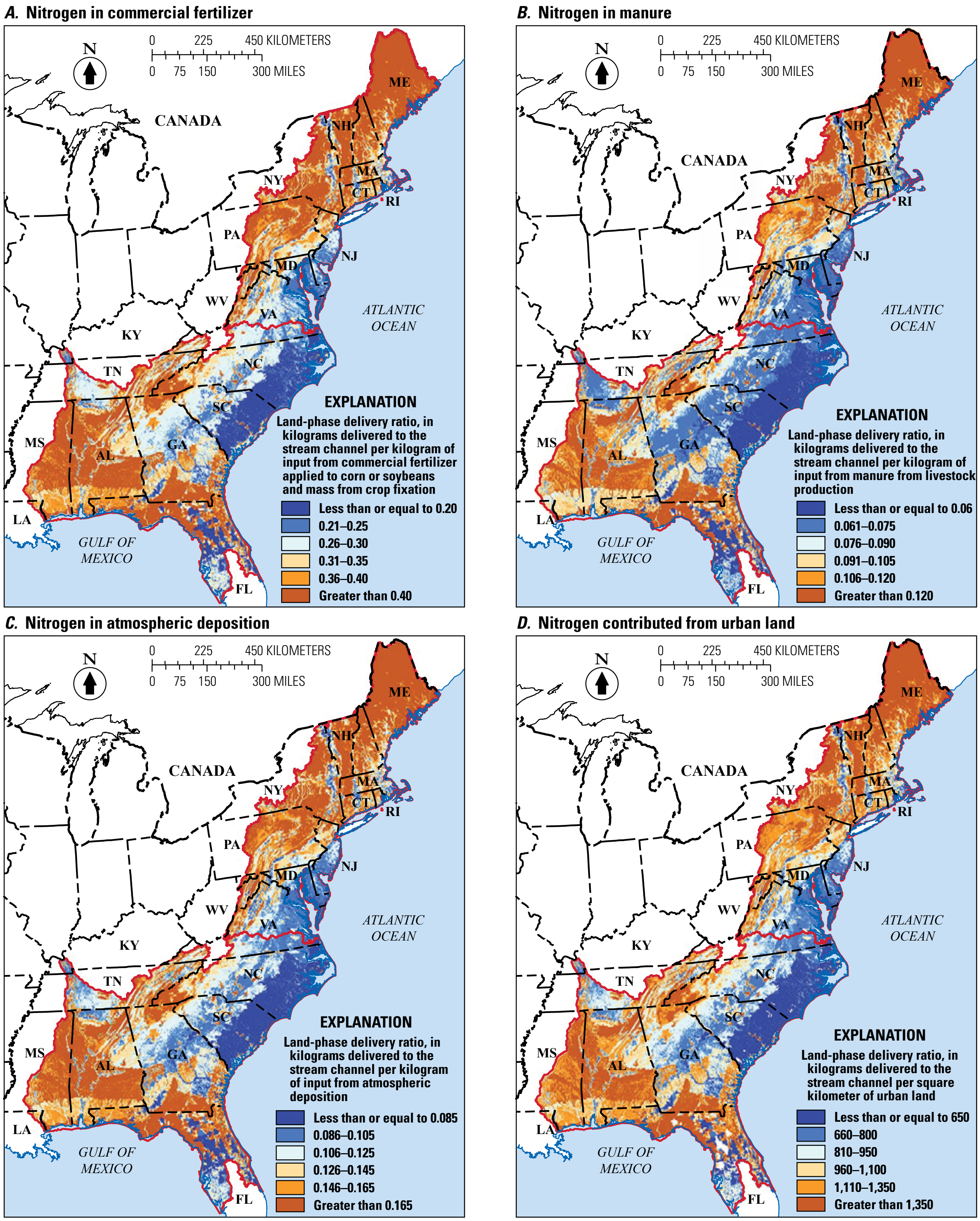
Model diagnostics[a]		
Root mean square error (RMSE), log-transformed residuals		0.35
Coefficient of determination (R^2) of yield estimate		0.76
Predictor variable	**Data set used to represent model variable**	**Coefficient estimate**
	Source	
Point sources	Permitted municipal wastewater discharge, major facilities (kg/yr)	
	New England and Lake Champlain watersheds	1.24
	Middle Atlantic watersheds (excluding Chesapeake Bay)	1.67
	Chesapeake Bay watersheds	0.95
	South Atlantic and eastern Gulf of Mexico watersheds	0.49
Urban land	Area of developed land (km²)	1,068
Agricultural fertilizer	Commercial fertilizer applied to corn or soybeans and mass from crop fixation (kg/yr)	0.35
	Commercial fertilizer applied to other[b] crops (kg/yr)	0.13
Manure from livestock	Manure from unconfined and confined livestock production (kg/yr)	0.09
Atmospheric deposition	Wet and dry deposition of inorganic nitrogen (kg/yr)	0.14
	Process: variation in rates of source to water transport (D)—enhanced[c] delivery to streams	
	Mean annual precipitation (ln of cm)	0.64
Wetlands	Ln of percentage (0-100) of catchment area occupied by:	
	East Gulf Coastal Plain Small Stream and River Floodplain Forest	0.063
	East Gulf Coastal Plain Near-Coast Pine Flatwoods	0.085
	Southern Coastal Plain Nonriverine Basin Swamp (including Okefenokee)	0.118
	Southern Coastal Plain Blackwater River Floodplain Forest	0.028
	Process: variation in source to water transport (D)—reduced[c] delivery to streams	
	Mean annual temperature (ln of degrees Celsius)	-0.58
	Depth to bedrock (ln of cm)	-0.55
	Soil permeability (ln of cm/d)	-0.17
	Soil erodibility factor for uppermost soil horizon (ln of dimensionless)	-0.46
	Overland flow distance to the stream channel (km)	-0.09
Wetlands	Ln of percentage (0-100) of catchment area occupied by:	
	Atlantic Coastal Plain Peatland Pocosin	-0.04
	Process: Instream attenuation	
In-channel processing	Time of travel in reach with mean discharge <1.98 m³/s (day)	0.27
Out-of-bank processing	Width of riparian corridor of wetland multiplied by time of travel in reach (m*day):	
	Atlantic Coastal Plain Blackwater Stream Floodplain Forest—Forest Modifier	0.0031
	Southern Piedmont Small Floodplain and Riparian Forest	0.0011
	Process: In-reservoir attenuation	
Reservoir attenuation	Inverse hydraulic load[d] (yr/m)	5.82

[a]Model diagnostics are calculated from simulations corrected using all upstream load observations.

[b]Other means other than corn, soybeans, alfalfa, wheat, hay, and cotton.

[c]Enhanced and reduced mean relative to the rate for catchment with average values of delivery variables.

[d]Inverse hydraulic load calculated as ratio of area of open water contiguous to the reach flowline to mean annual streamflow (resulting units are yr/m).



Delivery ratio expresses the efficiency of land-phase transport in the catchment and is used to calculate mass delivered to the adjacent stream channel given the amount of input to the watershed. These maps of delivery ratio therefore show the loading to the stream that would occur given uniform input across the area; high values indicate high potential for loading.

Figure 2. Spatial distribution of estimated land-phase delivery ratio for *A*, nitrogen in commercial fertilizer applied to corn or soybeans and mass from crop fixation, *B*, nitrogen in manure from livestock production, *C*, nitrogen in atmospheric deposition, and *D*, nitrogen contributed by urban land, from the aligned model.

Table 7. SPARROW phosphorus models for northeast and southeast regions with aligned specification.

[Each source in the aligned model is represented by data sets that are exactly equivalent between northeast and southeast, except where indicated as either NE (variable used in model for the northeastern United States) or SE (variable used in the model for the southeastern United States); all variables significant at the 5-percent significance level, kg/yr, kilogram per year; km², square kilometer; ppm*km², parts per million multiplied by square kilometer; m, meter; m³/s, cubic meter per second; yr/m, year per meter; m*d, meters multiplied by day; ln, natural logarithm]

Model diagnostics[a]		Northeast	Southeast
Root mean square error (RMSE), log-transformed residuals		0.60	0.56
RMSE computed from only the monitoring stations common between the aligned and previous calibration set[b]			0.53
Coefficient of determination (R^2) of yield estimate		0.68	0.65
Predictor variable	**Data set used to represent model variable**	**Coefficient estimate**	
	Source		
Point sources	NE and not in Chesapeake Bay watershed: permitted municipal wastewater discharge, major facilities (kg/yr)	1.33	([c])
	NE and in Chesapeake Bay watershed: permitted municipal wastewater discharge, major facilities (kg/yr)	0.69	([c])
	SE: All permitted wastewater discharge (kg/yr)	([c])	0.78
Urban land	Area of developed land(km^2)	58	57
Agricultural fertilizer	NE: Commercial fertilizer applied to corn/soybeans/alfalfa (kg/yr)	0.06	([d])
	NE: Commercial fertilizer applied to other[c] crops (kg/yr)	0.11	([d])
	SE: Area of catchment with row crops (km^2)	([f])	49
	SE: Area of catchment with pasture (km^2)	([f])	56
Manure from livestock	Manure from unconfined and confined livestock production (kg/yr)	0.026	0.01
Background (parent-rock minerals)	Mineral content indicated by stream bed phosphorus levels, scaled by catchment area (ppm*km^2)	0.014	0.056
Phosphate mining	Mineral content indicated by stream bed phosphorus levels downstream from mined land, scaled by mined land area (ppm*km^2)	([f])	0.12
	Process: variation in rates of source to water transport (D)—enhanced[d] delivery to streams		
	Soil erodibility factor for uppermost soil horizon (dimensionless)	4.68	3.68
	Ln of mean annual precipitation (ln of cm)	([d])	0.71
Wetlands	Percentage (0-100) of catchment area occupied by:		
	Central Interior and Appalachian Riparian Systems	0.22	([c])
	Laurentian-Acadian Floodplain Systems	0.16	([c])
	Atlantic Coastal Plain Small Blackwater River Floodplain Forest	0.05	([c])
	Process: variation in source to water transport (D)—reduced[d] delivery to streams		
	Percentage of streamflow from groundwater (ln of percent)	-0.94	([f])
	Average overland flow distance to stream channel	-0.51	([f])
	Depth to water table (cm)	([f])	-0.24
Wetlands	Percentage (0-100) of catchment area occupied by:		
	Atlantic Coastal Plain Peatland Pocosin	([c])	-0.33
	Southern Coastal Plain Nonriverine Cypress Dome	([c])	-0.08
	Southern Coastal Plain Nonriverine Basin Swamp (including Okefenokee)	([c])	-0.06
	Southern Piedmont Small Floodplain and Riparian Forest	-0.05	([d])

Table 7. SPARROW phosphorus models for northeast and southeast regions with aligned specification.—Continued

[Each source in the aligned model is represented by data sets that are exactly equivalent between northeast and southeast, except where indicated as either NE (variable used in model for the northeastern United States) or SE (variable used in the model for the southeastern United States); all variables significant at the 5-percent significance level, kg/yr, kilogram per year; km^2, square kilometer; ppm*km^2, parts per million multiplied by square kilometer; m, meter; m^3/s, cubic meter per second;yr/m, year per meter; m*d, meters multiplied by day; ln, natural logarithm]

Predictor variable	Data set used to represent model variable	Coefficient estimate	
	Process: Instream attenuation		
Out-of-bank processing in riparian wetlands	Width of riparian corridor of wetland multiplied by time of travel in reach (m*day):		
	Atlantic Coastal Plain Blackwater Stream Floodplain Forest—Forest Modifier	([c])	0.0045
	Southern Piedmont Small Floodplain and Riparian Forest	([c])	0.0012
	Process: In-reservoir attenuation		
Reservoir attenuation	Inverse hydraulic load[d] (yr/m)	6.9	29.6

[a]Model diagnostics are calculated from simulations corrected using all upstream load observations.

[b]These computations of RMSE provide a more direct comparison with model diagnostics from the previous northeast and southeast model (table 2).

[c]Variable is defined only for the other region and therefore not tested in this model.

[d]Variable was tested but was not significant at the 5-percent significance level and not retained.

[e]"Other" refers to other than corn, soybeans, alfalfa, wheat, hay, and cotton.

[f]Variable was not tested for this regional model.

[g]Enhanced and reduced mean relative to the rate for catchments with average values of delivery variables.

[h]For the Southeast model wetlands were tested only as factors that reduce delivery to streams.

[i]Inverse hydraulic load calculated as ratio of area of open water contiguous to the reach flowline to mean annual streamflow (resulting units are yr/m).

production, land-phase delivery ratios are highest (that is, land-phase transport is more conservative) over a broad region of the mid-Atlantic region and in the westernmost part of the southeast region (fig. 3*A)*. For the source *area of developed land,* land-phase delivery ratios are highest in the isolated areas of the mid-Atlantic region and southeast region (fig. 3*B*). For both these sources, modeled delivery ratios for individual catchments near the boundary between the two models are generally similar, indicating consistent estimation of transport processes by the two models. In contrast, the sharp divergence of modeled land-phase delivery ratio for *phosphorus from parent-rock minerals* near the boundary between the two models (fig. 3*C*) may indicate regional specificity in land-phase transport of this source.

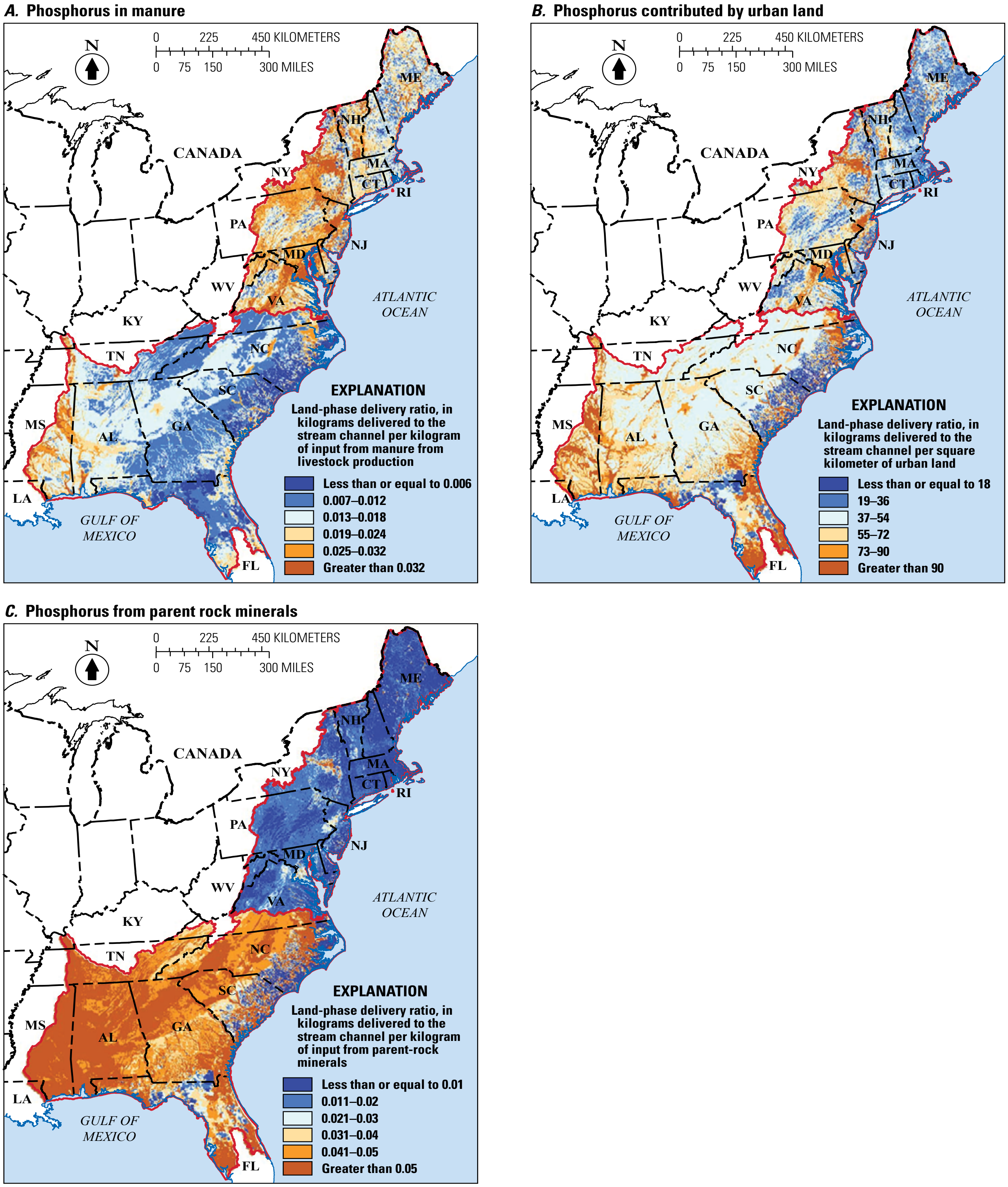
Improvements in Modeling Transport Processes

Effects of Physical Landscape Characteristics on Land-Phase Transport

Nitrogen

Several landscape characteristics were identified as enhancing or mitigating delivery of nitrogen to the streams. In this context, enhancing or mitigating respectively refer to increasing or decreasing delivery to the stream relative to the average delivery rate for the model area. The positive coefficient (0.64, table 6) associated with mean annual precipitation as determined by the model calibration indicates that enhanced delivery of nitrogen to the streams is associated with increased precipitation and the resultant increased transport of water to streams.

Characteristics associated with negative coefficients that mitigate the delivery of nitrogen to the streams include mean annual temperature, depth to bedrock, soil permeability, soil erodibility factor for the uppermost soil horizon, and overland flow distance to the stream channel (table 6). The negative coefficient (-0.58) associated with mean annual temperature may be explained by high rates of plant uptake or high microbial activity leading to relatively high denitrification or immobilization on the landscape. The negative coefficient (-0.55) associated with depth to bedrock may reflect the generalization that groundwater transport paths (and travel times) to the streams are longer in deeper soils, and longer travel times allow greater opportunity for immobilization and exposure to anaerobic conditions and denitrification. Similarly, the negative coefficient (-0.17) associated with soil permeability may be due to increased infiltration and higher associated percentage of groundwater flow, allowing for longer flow paths, more possible exposure to anaerobic conditions, and greater associated denitrification or immobilization. The negative coefficient (-0.46) associated with soil erodibility is difficult to interpret and may be due to the close relation between soil erodibility and available water-holding capacity of soils, which would be



Delivery ratio expresses the efficiency of land-phase transport in the catchment and is used to calculate mass delivered to the adjacent stream channel given the amount of input to the watershed. These maps of delivery ratio therefore show the loading to the stream that would occur given uniform input across the area; high values indicate high potential for loading.

Figure 3. Spatial distribution of SPARROW estimated land-phase delivery ratios for *A*, phosphorus in manure from livestock production, *B*, phosphorus contributed by urban land, and *C*, phosphorus from parent-rock minerals, from aligned models.

expected to restrict nitrate movement from the soil to the water table and streams. The negative coefficient (-0.09) associated with distance to the stream channel is consistent with the premise that greater travel distances to the streams provide greater opportunity for nitrogen loss to occur.

Phosphorus

Characteristics having positive coefficients, as determined by the model calibration, that enhance the delivery of phosphorus to streams include the soil erodibility factor for the uppermost soil horizon and mean annual precipitation. Positive coefficients (4.68, northeast model; 3.68, southeast model) associated with soil erodibility probably reflect the tendency of phosphorus to attach to the surface of soil particles (table 7). Soil erodibility is a measure of the susceptibility of soil particles to erosion and to subsequent transport by water; phosphorus attached to these particles is also transported and delivered to streams. A positive coefficient (0.71, southeast model) associated with mean annual precipitation indicates that an enhanced delivery of phosphorus to the streams may be due to the increased transport of water to streams resulting from precipitation. Mean annual precipitation was not a significant predictor of phosphorus delivery to streams in the northeast; a combination of soil erodibility and other transport related factors proved to be better predictors of phosphorus delivery.

Characteristics having negative coefficients that mitigate the delivery of phosphorus to the streams include the percentage of streamflow from groundwater, the average overland flow distance to stream channel, and the depth to water table. All of these factors seem to be related to phosphorus attachment to particles. Which factor(s) proved to be the best predictors were model-dependent. The negative coefficient (-0.94, northeast model) associated with the percentage of streamflow from groundwater may be related to the filtering effect that occurs with groundwater transport (table 7). Likewise, a negative coefficient (-0.51, northeast model) associated with overland flow distance to the stream channel indicates that longer overland flow paths to the streams provide greater opportunity for phosphorus to become trapped and not reach the streams. Where longer overland flow paths are correlated with shorter stream channel flow paths, the negative coefficient may reflect less opportunity for erosion of phosphorus from the streambank. A negative coefficient (-0.24, southeast model) associated with depth to water table, indicating that areas with low water-table levels transport less phosphorus to the stream, may be due to filtering and trapping along longer flow pathways from land surface to groundwater.

Effects of Wetlands on Land- and Aqueous-Phase Transport

Spatial distributions of certain riparian and nonriparian wetland systems were significant predictors of land-phase transport of nitrogen and phosphorus to streams. For the eastern U.S. nitrogen model, four wetland systems were associated with enhanced nitrogen land-phase delivery (positive coefficients, table 6; this group includes both riparian and nonriparian wetlands) and one was associated with reduced delivery (negative coefficient, table 6). For the northeast phosphorus model, three wetland systems were associated with enhanced land-phase delivery and one riparian wetland system was associated with reduced delivery. For the southeast phosphorus model, three wetland systems were associated with reduced land-phase delivery and none were associated with enhanced delivery.

Two riparian wetland systems were associated with an attenuation of aqueous-phase delivery of nitrogen and phosphorus. Both input variables *Atlantic Coastal Plain Blackwater Stream Floodplain Forest* and *Southern Piedmont Small Floodplain and Riparian Forest* reduced stream nitrogen in the eastern United States and reduced stream phosphorus in the southeast.

Aqueous-phase attenuation of nitrogen was modeled as

$$\text{Fraction of nitrogen mass removed (small stream)} = 1 - \exp(-(0.27+0.0031*R1+0.0011*R2)*TOT). \quad (2)$$

$$\text{Fraction of nitrogen mass removed (large stream)} = 1 - \exp(-(0.0031*R1+0.0011*R2)*TOT), \quad (3)$$

where

- small stream is defined as mean discharge smaller than 1.98 cubic meters per second (m3/s);
- large stream is defined as mean discharge greater than or equal to 1.98 m3/s;
- exp is the natural (base e) exponential function;
- TOT is time of travel in the reach segment, in days;
- R1 is the width of the riparian wetland corridor along the stream, in meters, of the variable Atlantic Coastal Plain Blackwater Stream Floodplain Forest – Forest Modifier;
- R2 is the width of the riparian wetland corridor along the stream, in meters, of the variable Southern Piedmont Small Floodplain and Riparian Forest; and
- 0.27, 0.0031, 0.0011 are coefficient values fitted during model calibration.

This result is interpreted to mean that both in-channel processes and out-of-bank (riparian wetland) processes attenuate nitrogen in smaller streams, whereas for larger streams, out-of-bank processes are primarily responsible for nitrogen removal.

Aqueous-phase attenuation of phosphorus was modeled for streams in the southeast as

Fraction of phosphorus mass removed

$$= 1 - \exp(-(0.0045*R1+0.0012*R2)*TOT), \quad (4)$$

where 0.45 and 0.0012 are coefficient values fitted during model calibration. This result is interpreted to mean that out-of-bank processing is primarily responsible for the removal of phosphorus in southeastern streams.

Summarizing wetland effects in terms of areal extent (reported in tables 1-1 and 1-2), 32 percent and 0 percent of the total nontidal, freshwater wetland area of the southeast and northeast regions, respectively, was associated with enhanced land-phase delivery of nitrogen. In contrast, 0 percent and 14 percent of total wetland area of the southeast and northeast regions, respectively, was associated with enhanced land-phase delivery of phosphorus. For nitrogen, 14 percent of total wetland area in the southeast region and 6 percent of the total wetland area in the northeast region was associated with reduced delivery through either land-phase or aqueous-phase processes. For phosphorus, 24 percent of the total wetland area in the southeast region and 3 percent of the total wetland area in the northeast region was associated with reduced delivery through either land-phase or aqueous-phase processes.

Multiple nitrogen and phosphorus transport processes could explain the positive and negative associations between wetlands and land-phase transport. Bank erosion in riparian wetlands can contribute large loads of nutrients associated with sediment loss and transport downstream (Kronvang and others, 2012). Bank erosion is greater where high channel hydraulic energy causes the entrainment of bank sediment, such as in headwater streams and streams along steeper topographic gradients (Hupp and others, 2013). The association with enhanced land-phase delivery of nitrogen and (or) phosphorus for the variables *Central Interior and Appalachian Riparian Systems; Laurentian-Acadian Floodplain Systems*; *East Gulf Coast Small Stream and River Floodplain Forest*; and *Atlantic Coastal Plain Small Blackwater River Floodplain Forest* (tables 6 and 7) may be due to their location in areas having steep topographic gradients and limited fluvial geomorphic development (NatureServe, 2010) that cause greater bank erosion of phosphorus and nitrogen attached to sediment and less floodplain sedimentation (removal) of nitrogen and phosphorus. Conversely, the mitigating effect on nitrogen and phosphorus delivery (both land phase and aqueous phase) for the variables *Atlantic Coastal Plain Blackwater Stream Floodplain Forest* and *Southern Piedmont Small Floodplain and Riparian Forest* (tables 6 and 7) could be due to the high floodplain sediment trapping rates that reduce nitrogen and phosphorus transport in these systems (Noe and Hupp, 2009; Schenk and others, 2012) and the high phosphate sorption capacity of soils in these systems (Walbridge and Struthers, 1993; Hogan and others, 2007).

Enhanced nitrogen delivery to the stream by some wetland systems also could be due to the export of dissolved organic nitrogen (DON). Wetlands in general, and long-hydroperiod wetlands in particular, convert inorganic nitrogen into organic nitrogen through plant uptake and then export DON that is relatively refractory (Pellerin and others, 2004, Wiegner and Seitzinger 2004, Scott and others, 2007). Exported DON is more likely to be conveyed conservatively through stream networks, whereas the more bioavailable DON is more likely to be removed instream. Wetlands along blackwater streams and rivers are noted for their export of dissolved organic matter (Beck and others, 1974). The association of the variables *Southern Coastal Plain Blackwater River Floodplain Forest* and *Southern Coastal Plain Nonriverine Basin Swamp* wetlands with enhanced land-phase delivery of nitrogen (table 6) is probably due to their export of DON. Similarly, enhanced phosphorus delivery to streams associated with the variable *Atlantic Coastal Plain Small Blackwater River Floodplain Forest* in the northeast region (table 7) may be due to the export of dissolved organic phosphorus.

Unlike most wetlands, short-hydroperiod wetlands may export dissolved inorganic nutrients. Long periods without flooding allow oxidation of wetland soils and the buildup of soil nitrate that can be exported out of the wetland during brief flooding (Bechtold and others, 2003; Noe and Hupp 2007; Huber and others, 2012). The enhanced land-phase delivery of nitrogen associated with the variable *East Gulf Coastal Plain Near-Coast Pine Flatwoods* (table 6) is most likely due to the short hydroperiod of these wetlands. The dominant vegetation of this wetland is *Pinus palustris*, a facultative upland species, soils are sandy (NatureServe, 2010), and this wetland type has the shortest period of inundation of any of the wetlands in the southeast region—all suggesting that soils are rarely anoxic, denitrification is uncommon, and the potential exists for nitrate export.

The association of *Atlantic Coastal Plain Peatland Pocosin* wetlands with reduced land-phase transport of nitrogen and phosphorus, and of *Southern Coastal Plain Nonriverine Cypress Dome* wetlands with reduced land-phase transport of phosphorus (tables 6 and 7), could be a result of their hydrology. Both systems can be depressional isolated wetlands with ombrotrophic hydrology; that is, these systems have little surface-water output, and any inputs of nutrients to these systems are unlikely to be exported by way of surface-water flow (Whigham and Jordan, 2003; Winter and LaBaugh, 2003). Groundwater flow paths have much longer residence time than surface-water flow paths and are more likely to be anoxic, increasing the likelihood of nutrient retention.

Regional Differences in Phosphorus Transport Processes

The phosphorus models remain separately specified and calibrated for the northeast and southeast regions, in contrast to the nitrogen model. The contrast in performance of variables representing agricultural sources was an important reason for maintaining separate phosphorus models for the two regions. Agricultural sources are represented in the southeast region by surrogate land-cover variables rather than by the variable *phosphorus in commercial fertilizer applied to agricultural land*, which did not meet statistical significance criteria in the southeast model (explained in Garcia and others, 2011, p. 998). Furthermore, the large difference in fitted values for several terms argues against combining the models, because fitting a single set of coefficients would cause a loss of regional specificity and accuracy within each region. The α value for *phosphorus from parent-rock minerals* is 4 times as high for the southeast region compared to the northeast region (0.056 compared to 0.014, table 7), indicating more conservative land-phase transport of this input in the southeast region. The coefficient for reservoir attenuation is almost 5 times as high for the southeast region compared to the northeast region (30 compared to 6.9, table 7), indicating much more conservative transport through reservoirs in the northeast. The contrast in rates of land-phase and aqueous-phase transport may be due, in part, to regional differences in the predominant forms of phosphorus (soluble and particulate). Different factors control the transport of one form versus others, and the proportion that is dominant can vary significantly depending on physiographic characteristics. As a result, the model transport factors should be specified differently to account for the variation of transport mechanisms. A single model for the east coast would probably not be able to ”resolve” these differences.

Using the Aligned Models to Simulate Stream Transport of Nutrients in the Eastern United States, 2002

The aligned specification models were used to simulate the 2002 stream nutrient load for every stream reach in the eastern United States and summarize these reach-level simulations as 2002 nutrient budgets (specifically, loads delivered to the stream and loads delivered to coastal waters) and source shares for delivered loads. Nutrient budgets from the aligned specification models and comparisons with simulations from previously published models are illustrated in figure 4. Model-simulated

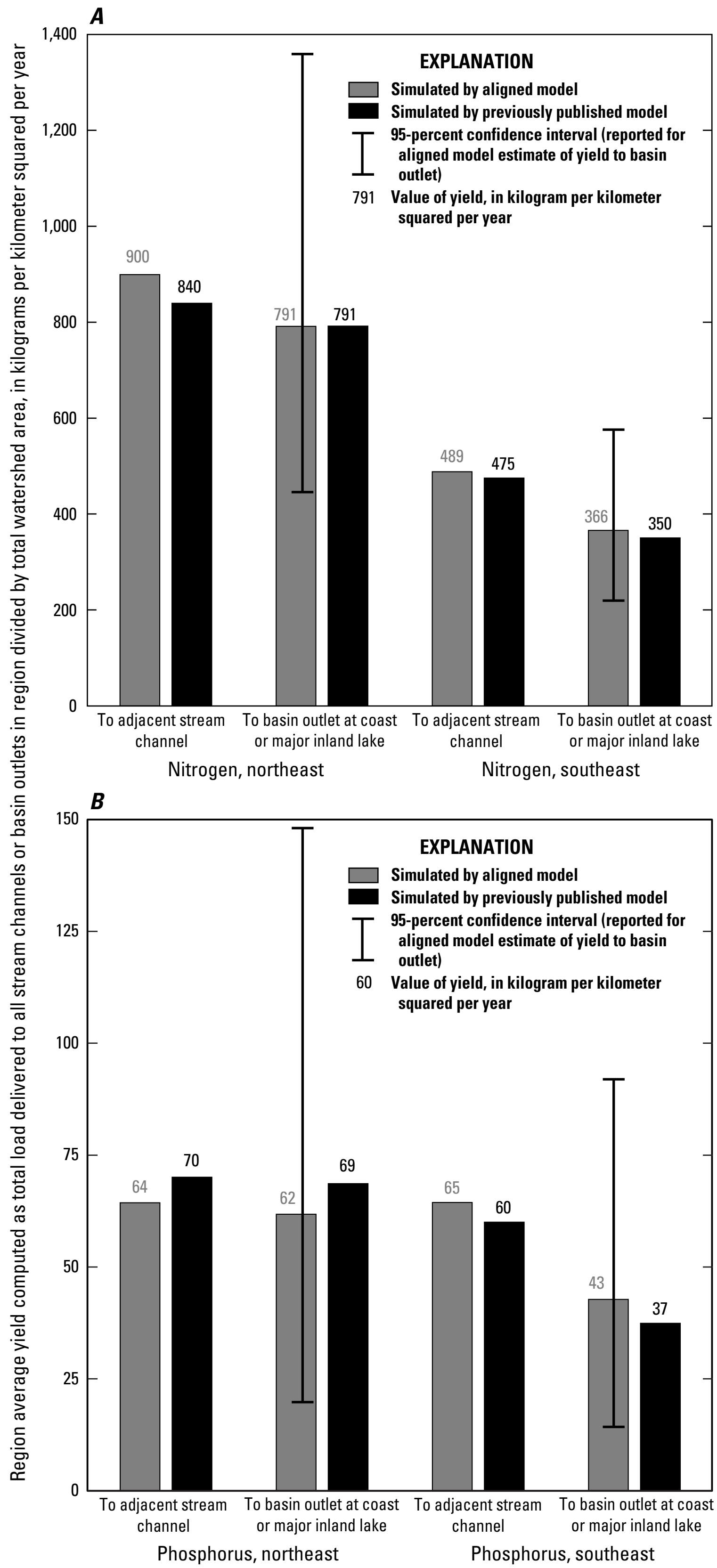


Figure 4. Region average yield of *A*, nitrogen and *B*, phosphorus delivered from catchment to stream channel and to basin outlet at coast or major inland lake, from aligned models compared to previously published models.

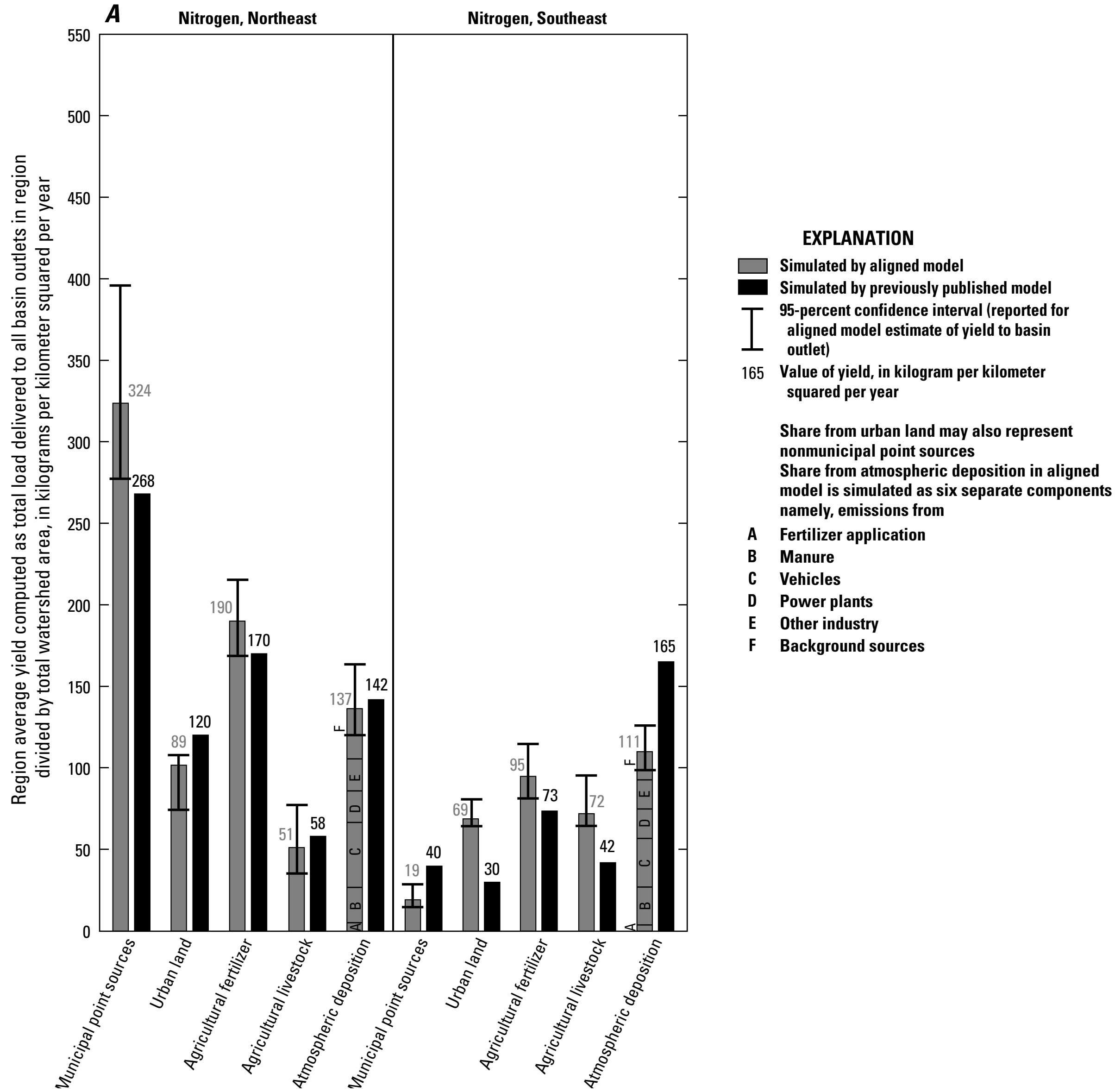


Figure 5*A*. Region average source shares of instream nitrogen yield at basin outlet, from aligned models compared to previously published models.

source shares for delivered loads are listed in table 8 and shown in figure 5. These summaries are for instream load and yield at the point of delivery to the coast or to the United States-Canada boundary.

Understanding Regional Differences in Simulations of the Aligned Models

Simulated nitrogen yield (load per unit area) delivered from a catchment to the adjacent stream channel is almost twice as high, on average, throughout the northeast region (900 kilograms per square kilometer per year (kg/km^2/yr)) compared to the southeast region (489 kg/km^2/yr; fig. 4*A*). This difference reflects not only the higher inputs in the northeast, particularly point sources and urban land, but also the model finding of more conservative land-phase transport of nitrogen (that is, higher land-phase delivery rate) for northeast watersheds, particularly New England and the northern part of the Mid-Atlantic region (fig. 2). Simulated nitrogen yield delivered to the basin outlets differs by approximately the same margin between northeast and southeast—791 versus 386 kg/km^2/yr, respectively—as the corresponding yield delivered to the adjacent stream channels. The aligned nitrogen model estimates the same rate coefficients of aqueous phase attenuation in rivers and streams in the southeast and northeast regions (table 6), but aqueous-phase processes are estimated to reduce nitrogen loading to coastal waters by a greater amount in the southeast compared to the northeast (25 percent compared to 12 percent), calculated from delivered yields

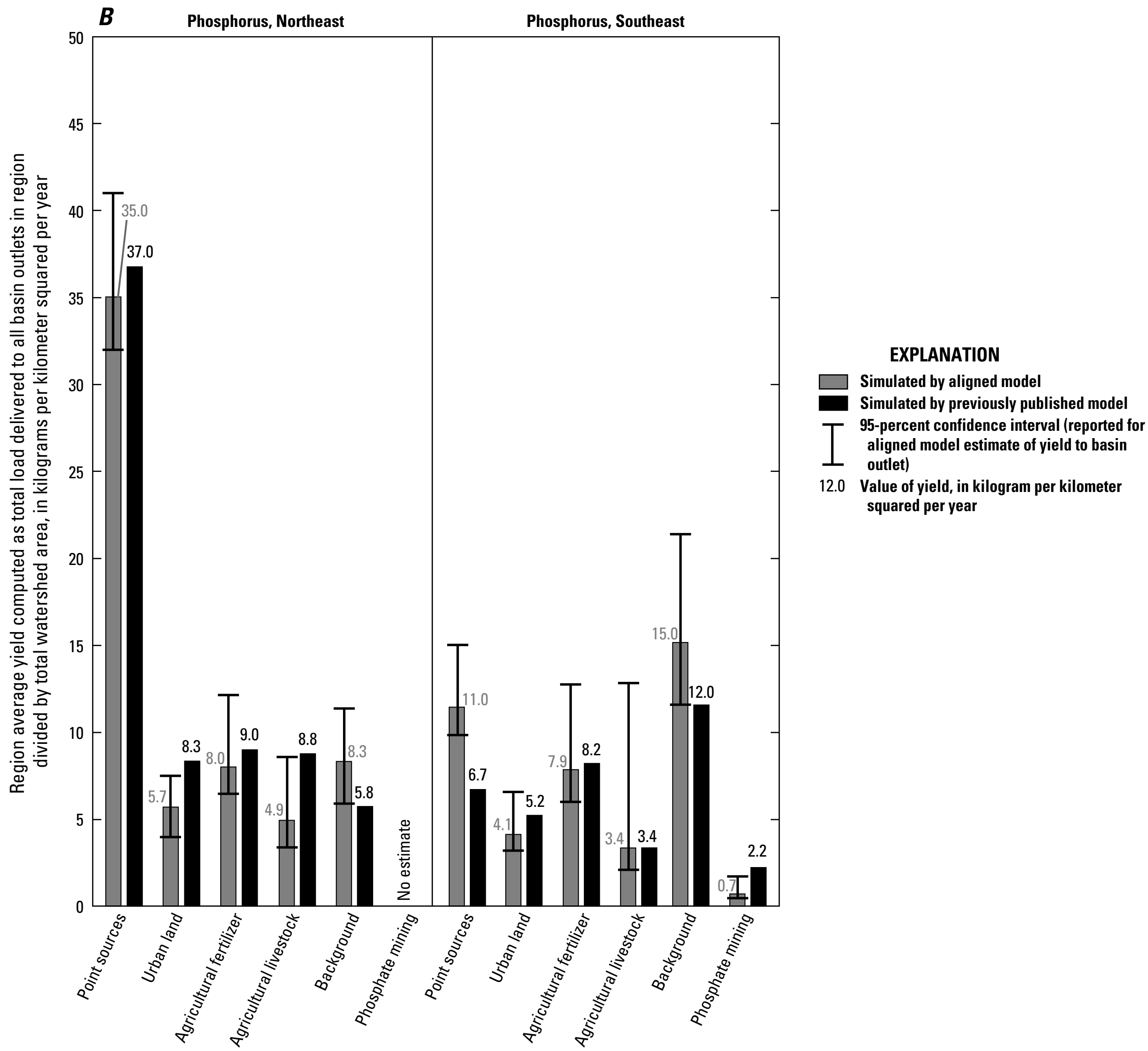


Figure 5*B*. Region average source shares of instream phosphorus yield at basin outlet, from aligned models compared to previously published models.—Continued

shown in figure 4*A*. This difference may be due to the greater number of high-retention reservoirs in the southeast and the greater presence of the riparian wetland systems interpreted to mitigate instream transport.

Simulated nitrogen yield delivered to the basin outlet is reported by river basin groups in table 8; the highest yields to the Atlantic Ocean are from rivers in the Mid-Atlantic region, and the lowest are from rivers in the South Atlantic region. Agriculture is the largest source of nitrogen delivered to the basin outlet for most southeast rivers, totaling 53 percent from both fertilizer and manure sources (table 8); however, it contributes less than 20 percent of the nitrogen for many rivers in the Mid-Atlantic region, where point sources constitute the primary source (table 8). The greater relative importance of agriculture as a nitrogen source for the southeast is not due to higher instream nitrogen yields from agricultural sources in southeast rivers compared to the northeast (194 $kg/km^2/yr$ in the southeast compared to 269 $kg/km^2/yr$ in the northeast). Rather, the greater importance is due to smaller inputs from other sources compared to most basins in the northeast.

Simulated phosphorus yield delivered from catchment to the adjacent stream channel, on average, is similar in the northeast region and southeast regions, totaling 64 and 65 $kg/km^2/yr$, respectively (fig. 4*B*). In contrast, simulated phosphorus yield delivered to the basin outlet differs widely between northeast and southeast regions, totaling 62 and 43 $kg/km^2/yr$, respectively. This difference reflects the model-based finding of more conservative aqueous-phase transport of phosphorus in northeast watersheds, as indicated by the higher model-fitted rate of in-reservoir attenuation in the southeast

Table 8. Estimated source shares of *A*, nitrogen and *B*, phosphorus yield at basin outlets for aligned models.

[Predicted instream yields are based on the SPARROW simulations—monitored values are not substituted for simulated values at monitored reaches; regions and basin groups are shown in figure 1; region yields are calculated as total load delivered to all outlets in the region, divided by total watershed area; region source shares are calculated by summing source-share loads delivered to all outlets in the region, divided by total load; km^2, square kilometer; $kg/km^2/yr$, kilogram per square kilometer per year]

***A.* Nitrogen**

Basin name	Basin area, based on NHDPlus network (km^2)	Nitrogen yield ($kg/km^2/yr$)	Standard error for nitrogen yield ($kg/km^2/yr$)	Nitrogen source shares (percent of total)							
								Emissions to atmosphere (and subsequent deposition)			
				Point sources	Urban land	Agricultural fertilizer[a]	Manure from livestock[b]	Power plant	Other industry	Vehicle	Background
Summary for northeast region	**447,518**	**791**	**315**	**40.9**	**11.3**	**24.0/0.7**	**6.5/2.8**	**2.4**	**4.2**	**5.0**	**2.1**
Basins draining to the St. Lawrence Seaway and the Gulf of Maine[c]	142,512	266	106	19.7	21.5	15.6/1.3	5.2/4.4	3.7	8.9	10.3	9.4
Basins draining to the Middle Atlantic[d] (Waquoit Bay to Maryland Coastal Bays)	134,470	1,389	564	61.0	10.6	13.9/0.5	2.5/1.6	1.5	3.2	3.9	1.2
Basins draining to Chesapeake Bay	170,536	759	304	18.2	9.2	41.0/0.8	12.6/4.0	3.4	4.4	5.1	1.3
Summary for southeast region	**761,030**	**366**	**145**	**5.2**	**18.8**	**26.0/1.1**	**19.7/6.4**	**4.9**	**8.1**	**8.2**	**1.5**
Basins draining to the South Atlantic (Albemarle Sound to Indian River)	332,904	260	103	6.9	18.7	29.6/0.9	17.5/7.0	4.3	6.4	7.4	1.2
Basins draining to the eastern Gulf of Mexico (Charlotte Harbor to Lake Borgne)	322,208	435	172	3.9	20.4	22.9/1.3	20.7/6.4	5.1	9.3	8.4	1.6
Tennessee River Basin	105,918	493	196	5.9	14.8	28.3/1.4	20.7/5.5	5.5	7.8	8.7	1.4

***B.* Phosphorus**

Basin name	Basin area, based on NHDPlus network (km^2)	Phosphorus yield ($kg/km^2/yr$)	Standard error for phosphorus yield ($kg/km^2/yr$)	Phosphorus source shares (percent of total)					
				Point sources	Urban land	Agricultural fertilizer	Manure from livestock	Background (parent-rock minerals)	Phosphate mining
Summary for northeast region	**447,518**	**62**	**46**	**56.5**	**9.2**	**12.9**	**8.0**	**13.4**	
Basins draining to the St. Lawrence Seaway and the Gulf of Maine[c]	142,512	19	14	27.7	14.1	18.4	4.2	35.6	
Basins draining to the Middle Atlantic[d] (Waquoit Bay to Maryland Coastal Bays)	134,470	127	97	75.2	7.0	6.3	2.5	9.0	
Basins draining to Chesapeake Bay	170,536	47	35	25.9	12.3	25.2	21.0	15.6	

Table 8. Estimated source shares of *A*, nitrogen and *B*, phosphorus yield at basin outlets for aligned models.—Continued

[Predicted instream yields are based on the SPARROW simulations—monitored values are not substituted for simulated values at monitored reaches; regions and basin groups are shown in figure 1; region yields are calculated as total load delivered to all outlets in the region, divided by total watershed area; region source shares are calculated by summing source-share loads delivered to all outlets in the region, divided by total load; km², square kilometer; kg/km²/yr, kilogram per square kilometer per year]

***B*. Phosphorus (continued)**

Basin name	Basin area, based on NHDPlus network (km²)	Phosphorus yield (kg/km²/yr)	Standard error for phosphorus yield (kg/km²/yr)	Phosphorus source shares (percent of total)					
				Point sources	Urban land	Agricultural fertilizer	Manure from livestock	Background (parent-rock minerals)	Phosphate mining
Summary for southeast region	**761,030**	**43**	**30**	**26.8**	**9.6**	**18.4**	**7.9**	**35.6**	**1.7**
Basins draining to the South Atlantic (Albemarle Sound to Indian River)	332,904	27	19	28.1	12.1	18.2	9.5	32.0	0.1
Basins draining to the eastern Gulf of Mexico (Charlotte Harbor to Lake Borgne)	322,208	54	39	30.4	10.0	18.3	7.5	30.8	3.0
Tennessee River Basin	105,918	57	42	14.6	4.9	19.1	6.6	54.4	0.5

[a]The estimate for nitrogen source share for "Agricultural fertilizer" is reported as two separate components: share from direct movement to stream from fertilizer applied in the watershed, and share from indirect transport from source through atmosphere to stream.

[b] The estimate of nitrogen source share for "Manure from livestock" is reported as two separate components: share from direct movement to stream of nitrogen from livestock manure in the watershed, and share from indirect transport from source through atmosphere to stream.

[c]For basins draining to the St. Lawrence Seaway and to the St. John and St. Croix Rivers, the outlet is defined as the United States-Canada border.

[d]Excluding Chesapeake Bay.

than northeast region (table 7) and the finding of no attenuation of phosphorus in streams in the northeast region. Reservoir attenuation is estimated to reduce phosphorus loading to coastal waters by 4 percent in the northeast, as indicated by comparing delivered yield in figure 4*B*. Attenuation in reservoirs and riparian wetlands is estimated to reduce phosphorus loading to coastal waters by 34 percent in the southeast.

Simulated phosphorus yield delivered to the basin outlet is reported by river basin group in table 8; the highest yields are from basins draining to the Mid-Atlantic coastline, the lowest yields are from the group of basins draining to the South Atlantic coastline. The background source *phosphorus from parent-rock minerals* is the largest contributor of phosphorus delivered to the basin outlet for most southeast rivers, averaging 35 percent for the region; the source contributes less than 15 percent of phosphorus on average for rivers in the northeast (table 8). Its greater relative importance for the southeast reflects higher instream phosphorus yields from this source in southeast rivers (15 kg/km²/yr compared to 8 kg/km²/yr in the northeast, fig. 5*B*).

Understanding Differences in Simulations of the Aligned Models Compared to the Previously Published Models

Simulated delivered yields and source shares from previously published models are also illustrated in figures 4 and 5 for comparison with results for the aligned model. The aligned nitrogen model in the northeast region simulates slightly higher loading to inland streams and equal loading to basin outlets compared to the previously published models. Specifically, the aligned nitrogen model parses overall removal of nitrogen between catchment and basin outlet in the northeast region differently than the previously published model, estimating less removal during land-phase transport (that is, transport from catchment to adjacent stream) and more removal during aqueous-phase transport, although the differences between aligned and previously published model are well within 95-percent confidence intervals (fig. 4*A*). Similarly, the aligned nitrogen and phosphorus models in the southeast estimate less removal during land-phase transport compared to the previously published model, although the shift is also within 95-percent confidence intervals (fig. 4*B*). For the southeast, the shift in how the aligned model parses nutrient removal between the catchment and basin outlet can be partly attributed to the inclusion in the calibration data set of sites on smaller streams, afforded by the shift to a finer hydrographic scale.

The aligned nitrogen model estimates higher source shares compared to the previously published models for the combination of agricultural sources, fertilizer and livestock (fig. 5*A*). The shares attributed to the combined agricultural sources in the aligned nitrogen model are 34 and 53 percent in northeast and southeast watersheds, respectively (table 8); compared to share attribution in the previously published models of 30 and 33 percent, respectively. The share attributed to the combination of point sources and urban land is about the same in the aligned nitrogen model and previously published models, but for the southeast, the aligned model assigns a much smaller share to point sources and much larger share to urban land (fig. 5*A*). The previously published nitrogen model in the southeast simulates point source contributions from all wastewater facilities, whereas the aligned nitrogen model simulates point source contributions from municipal wastewater sources only; the industrial wastewater inputs are probably assigned to the urban land term in the aligned model.

Compared to the previously published models, the share attributed to atmospheric deposition in the aligned nitrogen model decreased by an amount that balances the increased share from agricultural sources. These shifts may reflect additional information about dry deposition input used in the aligned model; the input estimates used in the aligned model are for total deposition, whereas previously published models used estimates of wet deposition only that served as a surrogate for both wet and dry deposition. Also in contrast to the previously published models, the share estimated for atmospheric deposition in the aligned models—137 $kg/km^2/yr$ on average for catchments in the northeast region and 111 $kg/km^2/yr$ on average for catchments in the southeast region—can be attributed to specific sectors of atmospheric input; namely, to atmospheric nitrogen deriving from emissions from agricultural fertilizer application, manure, vehicles, power plants, other industry, and background sources (fig. 5*A*). The shares shown on figure 5*A* for agricultural fertilizer and agricultural livestock—95 and 72 $kg/km^2/yr$, respectively, in the southeast—are assumed to only represent direct runoff of nitrogen from those components rather than also including the indirect transport from source through atmosphere to stream (appendix 1 provides additional explanation). The source shares for agricultural fertilizer and manure from livestock reported in table 8 are shown as two separate components: the share from the direct runoff of nitrogen and the share from the indirect transport from source through emission to atmosphere to stream.

Conclusions

The aligned models provide a uniform, consistent means of assessing nutrient transport in streams across the eastern United States. In contrast to the previously published models, the aligned models account explicitly for and quantify the influence of wetlands on regional- and basin-scale land-phase and aqueous-phase transport of nitrogen and phosphorus. In addition, in contrast with the previously published models, the aligned models assign the share estimated for atmospheric deposition to specific components of atmospheric nitrogen. These components are derived from emissions from agricultural manure, agricultural livestock, vehicles, power plants, other industry, and background sources. The assignment used in the aligned models makes it possible to simulate the effects of altering an individual component of atmospheric deposition, such as nitrate emissions from vehicles.

The alignment of model input and recalibration of model coefficients do not substantially improve model accuracy. For the southeast model, the aligned-specification models for both nitrogen and phosphorus actually give slightly less accurate results than the previously published models. Despite this slight decrease in overall accuracy, however, the aligned southeast models provide better-informed estimates of instream loads in smaller streams, afforded by the shift to a finer hydrographic scale and better representation in the calibration set of smaller streams. Compared to the previously published model, the aligned nitrogen and phosphorus models for the southeast estimates that less nutrient mass is removed during land-phase transport (that is, from catchment to adjacent stream); that is, more nutrient mass is delivered to the adjacent stream.

The aligned models were used to simulate transport region-wide and to compare source-share allocations between the regions and across individual river basins. Simulated yields of nitrogen delivered from catchments to adjacent stream channels are higher throughout the northeast region than the southeast region. This difference is due not only to higher nitrogen inputs in the northeast, particularly for point sources and urban land, but also to more conservative land-phase and aqueous-phase transport, simulated for nitrogen in for northeast watersheds. Removal of nitrogen and phosphorus through instream processes is greater for rivers and reservoirs in the southeast, estimated to reduce nitrogen loading to coastal waters by 25 percent, compared to 12 percent in the northeast, and reduce phosphorus loading to the coast by 34 percent in the southeast, compared to 4 percent in the northeast.

Agriculture contributes 53 percent (the largest source) of the nitrogen delivered to basin outlets for southeast rivers and 34 percent of the nitrogen delivered for northeast rivers. The greater relative contribution of agriculture to instream nitrogen loads in the southeast reflects smaller inputs from point sources and urban land rather than greater instream yields from this source compared to many river basins in the Mid-Atlantic region. The background source *phosphorus in parent-rock minerals* is the largest source of phosphorus delivered to the coast for rivers in the southeast and for rivers draining to the Gulf of Maine in New England, whereas point sources are the largest source of phosphorus delivered to the coast for many rivers in the Mid-Atlantic region.

The aligned nitrogen model simulates slightly higher loading to inland streams and equal loading to basin outlets in the northeast compared to the previously published model; specifically, the aligned nitrogen model estimates less removal during land-phase transport and more removal during aqueous-phase transport. Similarly, the aligned nitrogen and phosphorus models in the southeast estimate less removal during land-phase transport compared to the previously published model. These differences between aligned and previously published models are well within the 95-percent confidence intervals of the aligned models, however, and therefore do not represent substantial departures in aligned models compared to previous estimates.

The aligned models allow a comparison of the water-quality functions of different wetland systems over large spatial scales. Wetlands had both mitigating and enhancing effects on delivery of nutrients to streams. Several wetland systems (*Atlantic Coastal Plain Peatland Pocosin*, *Southern Coastal Plain Nonriverine Cypress Dome*, *Southern Coastal Plain Nonriverine Basin Swamp*, and *Southern Piedmont Small Floodplain and Riparian Forest*) were associated with mitigating land-phase delivery of either nitrogen or phosphorus, probably because of sedimentation, phosphate sorption, and ombrotrophic hydrology. More wetland systems, however, were associated with enhanced land-phase delivery of nutrients (lower than average removal efficiency). Possible mechanisms for a reduction in nutrient-removal efficiency include the export of dissolved organic nitrogen and bank erosion. Nutrient fractionation is not accounted for in the models, which only estimate total nitrogen or total phosphorus transport. It is possible that many of the wetland systems associated with enhanced delivery of total nitrogen and total phosphorus reduce bioavailable inorganic nutrient loading while increasing refractory organic nutrient loading and, therefore, overall total nutrient loading. The role of these systems in reducing inorganic nutrient loading may serve to limit downstream and estuarine eutrophication despite the increase in total nutrient loading.

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Appendix 1. Supplemental Description of Input Data and Model Specifications

Mapping Watershed Potential to Contribute Phosphorus from Geologic Materials to Receiving Streams in the Northeastern United States

Streambed-sediment phosphorus concentrations for streams in the northeast region were derived from the National Geochemical Survey (U.S. Geological Survey, 2004) following methods described in Terziotti and others (2009) and used as indirect measures of phosphorus in soil and parent rock. Bed-sediment samples collected at headwater streams in relatively undisturbed areas were aggregated by (1) geologic map units, delineated according to geologic age and ecoregion classifications, and a median concentration value (in parts per million of phosphorus) was assigned to each map unit. The spatial data set of median concentration varying by geologic map unit was then allocated to the catchment areas by spatial averaging; Terziotti and others (2009) provides a detailed description of this procedure. The concentration value, in parts per million (ppm), for each catchment was then scaled by catchment area, in square kilometers (km^2) to serve as a surrogate in the Spatially Referenced Regression on Watershed attributes (SPARROW) model for the mass of phosphorus in minerals derived from parent rock; the units for this surrogate variable are therefore ppm*km^2.

Estimating Relative Contributions of Individual Fractions of Atmospheric Nitrogen Deposition

The mass of reactive nitrogen from the source atmospheric deposition is in turn derived from several sources: emissions from industry and vehicles, volatilization of manure from livestock operations, volatilization of agricultural fertilizer, atmospheric fixation by lightning, and others. Thus, nitrogen is transported to the stream from sources such as manure and fertilizer along two separate pathways, a direct runoff pathway (source to land to stream) and an indirect pathway (source to atmosphere to land to stream). The manure and fertilizer sources are represented separately in the SPARROW models for the northeast and southeast by input measurements of agricultural activities that do not account for atmospheric deposition. Therefore, the SPARROW attribution of instream load into the respective source shares for atmospheric deposition, agricultural livestock, and agricultural fertilizer (and to some extent, urban land) is subject to ambiguity and, possibly, to double-counting between the atmospheric deposition share and the other shares.

Ambiguity in interpretation of source shares can be resolved by specifying a SPARROW model such that inputs for manure, fertilizer, and urban land are estimated as separate components of inputs to the separate pathways (direct and indirect) using separate sets of measurements (that is, separate measurements for *source to land* components of manure, fertilizer, and urban land, and separate measurements for *source to atmosphere to land* components of manure, fertilizer, and urban land). This model could attribute instream load for any stream reach to the following seven shares (in addition to point sources): manure, fertilizer, and urban land contribution through the direct runoff pathway; manure, fertilizer, and urban land contribution through the indirect runoff (via atmosphere) pathway; and other sources of atmospheric deposition.

Estimates of inputs for manure and fertilizer contribution through the indirect runoff (via atmosphere) pathway and for other sources of atmospheric deposition, are available from special simulations of the Community Multi-Scale Air Quality (CMAQ) Model using the decoupled direct method in three dimensions (DDM-3D) sensitivity option for source attribution (Napelenok, 2008). The CMAQ DDM-3D simulates the relative fraction of wet and dry deposition rates of nitrogen (oxidized versus reduced) for 10 sectors (unconfined operations for poultry, dairy, beef, swine, and other animals; confined livestock operations; commercial fertilizer; industrial and off-road sources; on-road sources; and other sources) (Dennis, 2010) by combining national emissions inventory subdivisions and special tracking equations added to the atmospheric transport, dispersion, and transformation algorithms. The standard CMAQ (Byun and Schere, 2006) estimates of wet deposition rates used in the SPARROW modeling have been corrected to best match (minimize error and eliminate average bias) measured and contoured estimates of wet deposition from the National Atmospheric Deposition Program (NADP) (Dennis and Foley, 2009).

We tested the CMAQ estimates of wet deposition of reduced and oxidized inorganic nitrogen (all sectors combined) and dry deposition of reduced and oxidized inorganic nitrogen (all sectors combined) as predictor variables in the aligned SPARROW models for the northeast and southeast. Wet deposition and dry deposition could not be specified as separate predictor variables in the models because of collinearity. Likewise, the CMAQ estimates of individual sectors could not be specified as separate predictor variables because of collinearity; however, the sector information is used herein to interpret output from the model as follows:

1. Interpret SPARROW-model estimate of instream load contributed from atmospheric deposition as comprising the six components manure, fertilizer,

vehicle emissions, power plant emissions, other industrial emissions, and background sources, and use the sector information from CMAQ to estimate the instream load source shares from each of those components.

2. Interpret SPARROW-model estimate of instream load contributed from manure from agricultural livestock as constituting the direct runoff pathway.

3. Interpret SPARROW-model estimate of instream load contributed from agricultural fertilizer as constituting the direct runoff pathway.

The total (direct plus indirect) contribution from manure (from livestock operations) to instream load is, therefore, estimated from the SPARROW results (table 8) by summing both the SPARROW-model estimate of instream load contributed from agricultural livestock, as well as the portion of atmospheric deposition from manure. A similar process is used to estimate total contribution from fertilizer.

Freshwater Wetlands Classified by Inundation Duration and Proximity to Stream

The mapped wetland land-cover classes from the National Land Cover Gap Analysis Project (U.S. Geological Survey, 2010) were narrowed to dominant freshwater nontidal wetland classes, 12 in the northeast and 20 in the southeast (tables 1-1 and 1-2), that each had a total area exceeding 1 percent of the total mapped wetland area in their respective regions. Cumulatively, these dominant wetland classes covered 96 and 85 percent of the total wetland area of the northeast and southeast, respectively. Tidal and estuarine wetlands were excluded from consideration because they are downstream of the modeled reaches. The hydrology of each dominant wetland class was determined from the NatureServe descriptions of terrestrial ecological systems (NatureServe, 2010) that are the basis of the mapping units. Specifically, wetland classes were identified as riparian or nonriparian, based on geomorphology, hydrology, and the dominant vegetation listed in the description of each wetland class.

Table 1–1. Description of wetland classes for the northeastern United States and assigned riparian versus nonriparian status.

[Wetland information is derived from NatureServe (2010)]

Code (GAP analysis)	Name	Dominant vegetation	Riparian[a]	Percent of total freshwater wetland area in the northeast	Percent of total area in the northeast
9214	Laurentian-Acadian Swamp Systems	*Taxodium distichum*, *Quercus laurifolia*	No	26.9	1.9
9212	Central Interior and Appalachian Swamp Systems	*Pinus elliottii* var. *densa*	No	14.2	1.0
9224	Laurentian-Acadian Shrub-Herbaceous Wetland Systems	*Taxodium distichum*, *Nyssa aquatica*, *Nyssa biflora*	Variable	13.8	1.0
9240	Northern Atlantic Coastal Plain Basin Swamp and Wet Hardwood Forest	*Taxodium distichum*/*Nyssa aquatica*, *Platanus occidentalis*, *Quercus laurifolia*	No	10.6	0.8
9843	Atlantic Coastal Plain Small Blackwater River Floodplain Forest	*Taxodium distichum*, *Nyssa biflora*, *Pinus serotina*	Yes	6.9	0.5
9501	Boreal Acidic Peatland Systems	*Taxodium* spp.	No	4.3	0.3
9818	Central Interior and Appalachian Floodplain Systems	*Taxodium distichum* and *Nyssa biflora*, *Quercus* spp.	Yes	4.1	0.3
9820	Laurentian-Acadian Floodplain Systems	*Quercus michauxii*, *Quercus laurifolia*, *Quercus pagoda*, *Quercus phellos*	Yes	4.1	0.3
9801	Atlantic Coastal Plain Blackwater Stream Floodplain Forest—Forest Modifier	*Taxodium ascendens*	Yes	3.2	0.2
9213	Gulf and Atlantic Coastal Plain Swamp Systems	*Taxodium distichum*, *Nyssa aquatica*, and *Chamaecyparis thyoides*, *Pinus elliotti*	No	2.8	0.2
9819	Central Interior and Appalachian Riparian Systems	*Typha latifolia*, *Panicum hemitomon*	Yes	2.8	0.2
9841	Southern Piedmont Small Floodplain and Riparian Forest	*Ilex glabra*, *Pinus serotina*	Yes	2.8	0.2

[a]As inferred from NatureServe (2010).

Table 1–2. Description of wetland classes for the southeastern United States and assigned riparian versus nonriparian status.

[Wetland information is derived from NatureServe (2010)]

Code (GAP analysis)	Name	Dominant vegetation	Riparian[a]	Percent of total freshwater wetland area in the southeast	Percent of total area in the southeast
CES203.304a, CES203.304b (combined)	Atlantic Coastal Plain Nonriverine Swamp and Wet Hardwood Forest—*Taxodium*/*Nyssa* and Oak Dominated Modifier	*Taxodium distichum*, *Nyssa aquatica*, *Nyssa biflora*	No	4.2	0.6
CES203.384, CES203.384a (combined)	Southern Coastal Plain Nonriverine Basin Swamp, including Okefenokee *Taxodium* Modifier	*Taxodium distichum*, *Nyssa biflora*, *Pinus serotina*	No	5.1	0.8
CES203.251	Southern Coastal Plain Nonriverine Cypress Dome	*Taxodium ascendens*	No	4.0	0.6
CES203.493	Southern Coastal Plain Blackwater River Floodplain Forest	*Taxodium distichum*, *Nyssa aquatica*, and *Chamaecyparis thyoides*, *Pinus ellioti*	Yes	10.2	1.6
CES203.247a	Atlantic Coastal Plain Blackwater Stream Floodplain Forest—Forest Modifier	*Taxodium distichum* and *Nyssa biflora*, *Quercus* spp.	Yes	5.9	0.9
CES203.250	Atlantic Coastal Plain Small Brownwater River Floodplain Forest	*Taxodium distichum*/*Nyssa aquatica*, *Platanus occidentalis*, *Quercus laurifolia*	Yes	4.2	0.6
CES203.249	Atlantic Coastal Plain Small Blackwater River Floodplain Forest	*Taxodium distichum*, *Quercus laurifolia*	Yes	7.5	1.1
CES203.077	Floridian Highlands Freshwater Marsh	*Typha latifolia*, *Panicum hemitomon*	No	2.0	0.3
CES411.381	South Florida Pine Flatwoods	*Pinus elliottii* var. *densa*	No	2.2	0.3
CES203.267	Atlantic Coastal Plain Peatland Pocosin	*Ilex glabra*, *Pinus serotina*	No	5.1	0.8
CES203.489a	East Gulf Coastal Plain Large River Floodplain Forest—Forest Modifier	Varied	Yes	6.6	1.0
CES203.559	East Gulf Coastal Plain Small Stream and River Floodplain Forest	*Quercus phellos* or *Quercus nigra*	Yes	11.4	1.7
CES202.706	South-Central Interior Small Stream and Riparian	*Platanus occidentalis*, *Acer rubrum* var. *trilobum*, *Betula nigra*, *Liquidambar styraciflua*, *Quercus* spp.	Yes	1.5	0.2
CES202.323	Southern Piedmont Small Floodplain and Riparian Forest	*Liquidambar styraciflua*, *Liriodendron tulipifera*	Yes	3.4	0.5
CES203.501	Southern Coastal Plain Hydric Hammock	*Sabal palmetto*	Yes	5.0	0.8
CES203.265	Atlantic Coastal Plain Northern Wet Longleaf Pine Savanna and Flatwoods	*Pinus palustris*	No	1.2	0.2
CES203.375a, CES203.375c (combined)	East Gulf Coastal Plain Near-Coast Pine Flatwoods—Open Understory Modifier and Offsite Hardwood Modifier	*Pinus palustris*	No	5.5	0.8

[a]As inferred from NatureServe (2010).

Specification of Aqueous-Phase Attenuation in Stream Reaches

Removal of mass moving in a stream by means of denitrification, uptake, or settling is specified, as in the previously published regional models, as a first-order decay function of stream reach attributes:

$$L_i = Linstream_{i-1} \exp\left(-\sum_{c=1}^{C_s} Z_{c\,i}^{S} \theta_{Sc}\right), \quad (1\text{-}1)$$

where

L_i is the mass transported to the downstream node from the upstream node for reach *i* ,

$Linstream_{i-1}$ is the load instream at the *upstream* node for reach *i*, and

$\exp\left(-\sum_{c=1}^{C_s} Z_{c\,i}^{S} \theta_{Sc}\right)$ (aqueous-phase delivery rate) is the term specifying fraction (from 0 to 1) of mass *remaining* after decay by instream processes between the upstream node and the downstream node of the reach i. The fraction (from 0 to 1) of mass *removed* by instream processes between the upstream and downstream node of reach is therefore 1 - $\exp\left(-\sum_{c=1}^{C_s} Z_{c\,i}^{S} \theta_{Sc}\right)$. exp is the natural (base e) exponential function. The terms in the exponential function argument (C_s, θ_{Sc}, and Z^S_c) are described in appendix 2.

Unlike previous models, we include in Z^S not only the variables (time of travel and stream size) that represent in-channel processing of nitrogen (in the main channel water column or hyporheic zone), but also variables that represent out-of-bank processing in riparian wetlands. For the eastern U.S. nitrogen model, the vectors Z^S and θ_S are defined as

$$Z^S = [TOT(Q<=1.98), TOT(Q>1.98), TOT*R1, TOT*R2], \text{ and} \quad (1\text{-}2)$$

$$\theta_S = [B1, B2, BR1, \text{ and } BR2], \quad (1\text{-}3)$$

where

TOT(Q<=1.98) is time of travel (TOT) in the stream segment when mean annual streamflow (Q) is <= 1.98 m^3/s;

TOT(Q>1.98) is time of travel in the stream segment when mean annual streamflow is > 1.98 m^3/s;

R1 is the width of the riparian wetland corridor along the stream, in meters, of the variable *Atlantic Coastal Plain Blackwater Stream Floodplain Forest*, computed as the quotient area of this wetland class in the catchment divided by length of flowline in reach segment;

R2 is the width of the riparian wetland corridor along the stream (meters) of the variable *Southern Piedmont Small Floodplain and Riparian Forest*, computed similarly as above; and

B1, B2, BR1, and BR2 are the coefficients associated with the variables in vector Z^S.

This yields the expression for fraction of mass removed by instream processing as

1 - exp(-(B1*(TOT(Q<=1.98)) +
B2*(TOT(Q>1.98)) +
BR1(TOT*R1) + BR2(TOT*R2))) . (1-4)

This is equivalent mathematically to

1 - exp(-((TOT(Q<=1.98))*
(B1 + BR1*R1 +BR2*R2) +
(TOT(Q>1.98))*
(B2 + BR1*R1 + BR2*R2))). (1-5)

This last expression clarifies that the first-order decay coefficient for each TOT variable is modified by BR*R; that is, the first-order decay coefficient is modified proportional to the width of the riparian wetland corridor in the reach segment. We interpret a SPARROW model-analysis finding that both B1, and BR1 and (or) BR2, and so forth, are statistically significant as predictors of instream load to mean that both in-channel and out-of-bank processing influences aqueous-phase decay for stream class 1. Conversely, a finding that BR1 or BR2 is statistically significant and either B1, B2, or both, is not is interpreted to mean that for that stream class (1 or 2), out-of-bank processing is primarily responsible for aqueous-phase decay.

Appendix 2. Supplemental Description of the SPARROW Model Equation and Coefficients

SPARROW Model Equation

For each reach in a hydrologic network, SPARROW predicts long-term mean-annual instream nutrient load as a function of nutrient sources, land-phase attenuation rate, and aqueous-phase attenuation rates. Conceptually, the instream nutrient load or flux at the downstream node of a reach can be expressed as the sum of two components:

$$Linstream_i = Lcatchment_i + Lupstream_i \,, \qquad (2\text{-}1)$$

where

$Linstream_i$ is the instream load at the downstream node of reach i;

$Lcatchment_i$ is the load originating within the catchment for reach i and delivered to the downstream node of reach i; and

$Lupstream_i$ is the load generated within catchments for upstream reaches and transported to the downstream node of reach i via the stream network.

The load originating within the catchment for reach i ($Lcatchment_i$) is determined by

$$Lcatchment_i = \sum_{n=1}^{N_S} S_{n,i}\alpha_n D_n\left(Z_i^D;\theta_D\right)A\left(Z_i^S, Z_i^R;\theta_S,\theta_R\right), \qquad (2\text{-}2)$$

where

n, N_s is the source index (N_s is the total number of individual sources);

$\sum$ represents summation across all individual sources

S_{ni} is the vector of source variables for reach i (for example, a measurement of mass placed in the watershed, or the area of a particular land cover);

α_n is the vector of coefficients, *estimated by the model*, in units that convert source variable units to flux units. For land-applied sources, α_n is the model estimate of the average land-phase delivery ratio across all catchments in the model area. For land- applied sources represented by characteristics other than mass input (for example, area of developed land), α expresses the conversion of source units to mass applied to the watershed, as well as the average land-phase delivery ratio for the source;

$D_n(\cdot)$ is the delivery variation factor, defining the variation among catchments in land-phase attenuation processes and, therefore, in land-phase delivery ratio. The delivery variation factor is modeled as a series of exponential functions of physical landscape characteristics that influence nutrient attenuation;

Z_i^D is the vector of physical landscape variables for reach i (for example, measured landform or soil characteristics, area of long-hydroperiod wetlands, and so forth);

θ_D is the vector of coefficients, *estimated by the model*, for the physical landscape variables;

$A(\cdot)$ is the aqueous-phase delivery function, representing the result of attenuation processes acting on flux as it travels along the stream channel. Modeled as first-order decay, the aqueous-phase delivery function defines the fraction of flux originating in, and delivered to, reach i that is transported to the reach's downstream node;

Z_i^S, Z_i^R are vectors of measured stream and reservoir variables, respectively, for reach i (examples include stream-water depth or velocity, width of riparian corridor, and reservoir areal hydraulic loading); and

θ_S, θ_R are vectors of coefficients, *estimated by the model*, for the stream and reservoir variables, respectively.

The delivery variation factor $D_n(\cdot)$ allows the model to estimate variation in land-phase transport rates among catchments. Values of $D_n(\cdot)$ greater than 1 for a catchment indicate a larger fraction of nutrient reaching streams than the median for the model area, values of $D_n(\cdot)$ less than 1 indicate a smaller fraction of nutrient reaching streams than the median for the model area.

The second component in equation 2-1, the flux entering reach i from upstream reaches, is the sum of the flux from any upstream catchment ($Lcatchment_{i-1}$, $Lcatchment_{i-2}$, and so forth) adjusted for losses caused by stream and reservoir attenuation processes acting on flux along the reach pathway to and including reach i. For headwater reaches, equation 2-1 is simplified to include only the $Lcatchment_i$ term. More information about the model form and assumptions is available in Schwarz and others (2006).

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