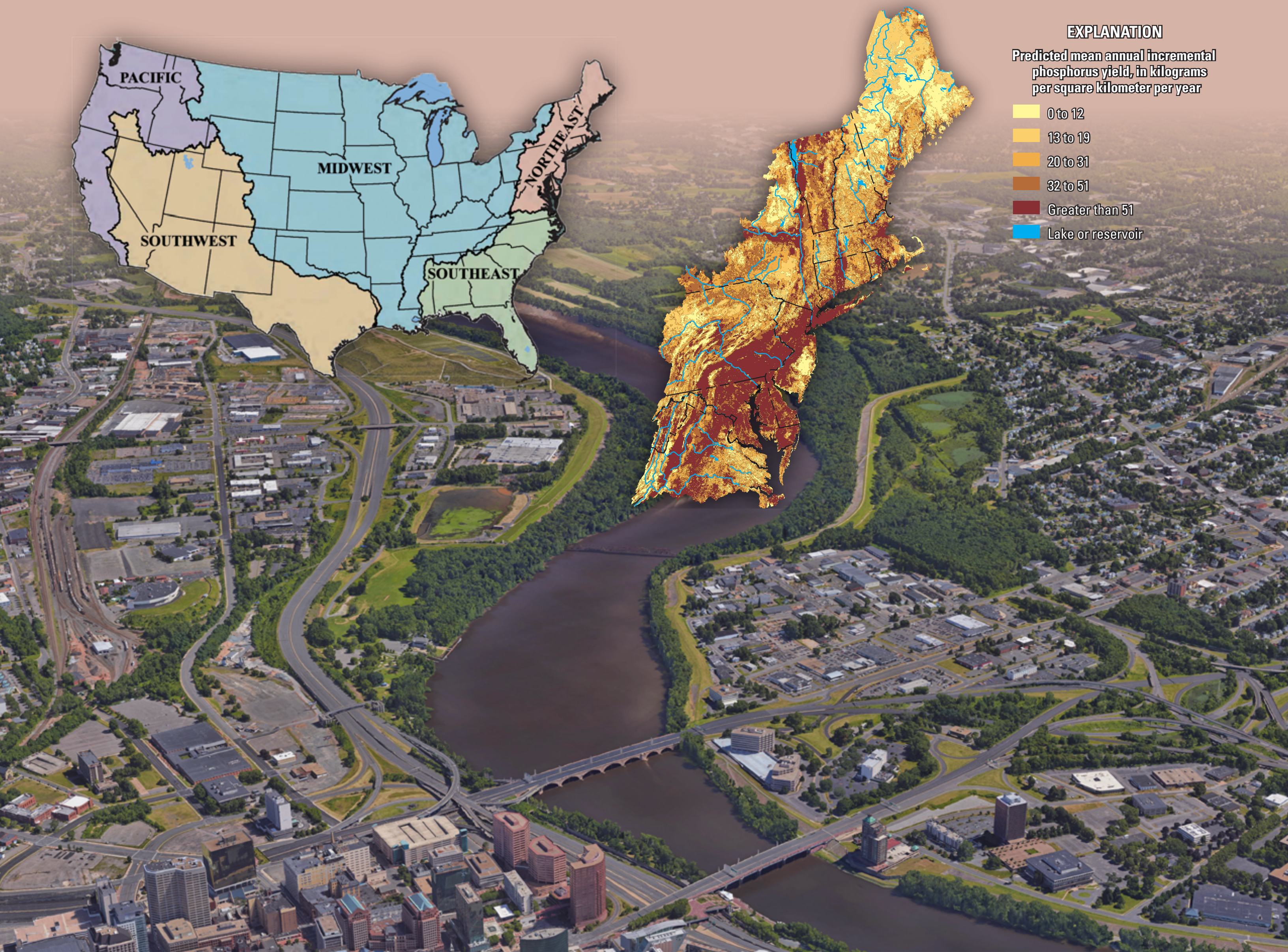
National Water-Quality Program

Spatially Referenced Models of Streamflow and Nitrogen, Phosphorus, and Suspended-Sediment Loads in Streams of the Northeastern United States



Scientific Investigations Report 2019–5118

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

Cover: Upper left: SPAtially Referenced Regression On Watershed attritutes (SPARROW) modeling regions of the conterminous United States.
Upper right: SPARROW simulated total phosphorus incremental yield, in kilograms per square kilometer per year.
Lower center: Connecticut River looking north-northeast, Hartford, Connecticut. Credit: Satellite image courtesy of Google Earth.

Spatially Referenced Models of Streamflow and Nitrogen, Phosphorus, and Suspended-Sediment Loads in Streams of the Northeastern United States

By Scott W. Ator

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U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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Foreword

Sustaining the quality of the Nation's water resources and the health of our diverse ecosystems depends on the availability of sound water-resources data and information to develop effective, science-based policies. Effective management of water resources also brings more certainty and efficiency to important economic sectors. Taken together, these actions lead to immediate and long-term economic, social, and environmental benefits that make a difference to the lives of the almost 400 million people projected to live in the United States by 2050.

In 1991, Congress established the National Water-Quality Assessment (NAWQA) to address where, when, why, and how the Nation's water quality has changed, or is likely to change in the future, in response to human activities and natural factors. Since then, NAWQA has been a leading source of scientific data and knowledge used by national, regional, state, and local agencies to develop science-based policies and management strategies to improve and protect water resources used for drinking water, recreation, irrigation, energy development, and ecosystem needs (https://water.usgs.gov/nawqa/applications/). Plans for the third decade of NAWQA (2013–21) address priority water-quality issues and science needs identified by NAWQA stakeholders, such as the Advisory Committee on Water Information and the National Research Council, and are designed to meet increasing challenges related to population growth, increasing needs for clean water, and changing land-use and weather patterns.

Federal, State, and local agencies have invested billions of dollars to reduce the amount of pollution entering rivers and streams that millions of Americans rely on for a variety of water needs and biota rely on for habitat. Understanding the sources and transport of pollution is crucial for designing strategies to improve water quality. The United States Geological Survey's (USGS) SPAtially Referenced Regression On Watershed attributes (SPARROW) model was developed to aid in the understanding of sources and transport of pollution across large spatial scales. The SPARROW model is calibrated by statistically relating watershed sources and transport-related properties to monitoring-based water-quality load estimates. This report describes the methods and results of SPARROW models recently developed to estimate streamflow, and total nitrogen, total phosphorus and suspended-sediment transport in streams of the Northeastern Region of the United States. The model results are expected to provide useful information for understanding the hydrology and water quality of streams in the Northeastern Region. They are also expected to provide useful information for understanding anthropogenic influences on surface-water resources and for managing those resources to ensure adequate water supply for human needs and to ensure ecological integrity for fish and other aquatic life.

We hope this publication will provide you with insights and information to meet your water-resource needs and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters. The information in this report is intended primarily for those interested or involved in resource management and protection, conservation, regulation, and policymaking at the regional and national levels.

Dr. Donald W. Cline
Associate Director for Water
U.S. Geological Survey

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
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)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Application rate	
kilogram per square kilometer per year ([kg/km^2]/yr)	0.008921	pound per acre per year ([lb/acre]/yr)
kilogram per square kilometer per year ([kg/km^2]/yr)	0.01	kilogram per hectare per year ([kg/ha]/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Inputs and outputs of the Northeast SPARROW models are available at https://doi.org/10.5066/P9NKNVQO.

Abbreviations

EVI	enhanced-vegetative index
EPA	U.S. Environmental Protection Agency
NLLS	nonlinear least squares
SPARROW	SPAtially Referenced Regression On Watershed attributes
SSC	suspended-sediment concentration
TSS	total suspended solids
USGS	U.S. Geological Survey

Spatially Referenced Models of Streamflow and Nitrogen, Phosphorus, and Suspended-Sediment Loads in Streams of the Northeastern United States

By Scott W. Ator

Abstract

SPAtially Referenced Regression On Watershed attributes (SPARROW) models were developed to quantify and improve the understanding of the sources, fate, and transport of nitrogen, phosphorus, and suspended sediment in the northeastern United States. Excessive nutrients and suspended sediment from upland watersheds and tributary streams have contributed to ecological and economic degradation of northeastern surface waters. Recent efforts to reduce the flux of nutrients and suspended sediment in northeastern streams and to downstream estuaries have met with mixed results, and expected ecological improvements have been observed in some areas but not in others. Effective watershed management and restoration to improve surface-water quality are complicated by the multitude of nutrient sources in the Northeast and the multitude of natural and human landscape processes affecting the delivery of nutrients and suspended sediment from upland areas to and within surface waters. Individual models were constructed representing streamflow and the loads of total nitrogen, total phosphorus, and suspended sediment from watersheds draining to the Atlantic Ocean from southern Virginia through Maine.

Northeastern streams contribute 303,000 metric tons (t) of nitrogen, 25,300 t of phosphorus, and 14,700,000 t of suspended sediment, annually (on average), to waters along the Atlantic Coast of North America. Although atmospheric deposition and natural mineral erosion contribute to nitrogen and phosphorus loads, respectively, in northeastern streams, most of the contributions are attributable to urban or agricultural sources. Within the Northeast, average yields of nutrients are therefore generally greater from densely populated or intensively cultivated areas of the mid-Atlantic region, the Hudson, Mohawk, and Connecticut River valleys, and the coastal areas of southern New England than in predominantly forested areas such as northern New England. Average upland sediment yields are similarly greater from agricultural areas than from urban or forested areas and are therefore generally greatest in areas yielding the greatest nutrients. Landscape conditions that are significant to nitrogen delivery from uplands to streams likely reflect the importance of groundwater transport in carbonate settings and of denitrification for removing nitrogen from uplands. Nitrogen losses to streams in agricultural areas are apparently mitigated by the use of cover crops but are exacerbated by the use of conservation tillage or no-till practices. The transport of phosphorus and suspended sediment from uplands to streams is greater in areas of more erodible soils but mitigated in agricultural areas with greater use of conservation tillage or no-till practices. Loads of nutrients and suspended sediment are significantly reduced within the stream network in impounded reaches, and nitrogen load is also significantly reduced in small flowing reaches.

Introduction

Nitrogen, phosphorus, and suspended sediment are among the most pervasive and damaging contaminants in surface waters (Howarth and others, 1991; Bricker and others, 2007; Diaz and Rosenberg, 2008). Ecological and economic consequences of excessive nutrients or suspended sediment in streams and estuaries include algal blooms; increased cost of drinking-water treatment; and declines in dissolved oxygen, water clarity, submerged-aquatic vegetation, and fisheries (Carpenter and others, 1998; Langland and Cronin, 2003; Hagy and others, 2004; Bilotta and Brazier, 2008; Hanson and others, 2016). Excessive phosphorus is the most common cause of eutrophication in freshwater systems (Correll, 1998). In contrast, primary production in temperate estuaries is often nitrogen limited (Vitousek and others, 1997) but also may be limited seasonally by phosphorus concentrations (Prasad and others, 2010). Davidson and others (2012) estimate that excessive nutrients affect 67 percent of coastal waters, 33 percent of streams, and 40 percent of lakes in the United States.

The U.S. Geological Survey has used a SPAtially Referenced Regression On Watershed attributes (SPARROW) technique to develop watershed models for large regions of the conterminous United States (fig. 1). The models were developed to improve the understanding of source, fate, and transport of nitrogen, phosphorus, and suspended sediment in local streams and downstream receiving waters in support of watershed management and restoration.

Figure 1. Spatial extent of the Northeast SPARROW (SPAtially Referenced Regression On Watershad attributes) model region.

Effects of excessive nutrient and sediment inputs from contributing watersheds on streams and coastal estuaries of the Northeastern United States (fig. 2) are particularly extensive and pronounced (Bricker and others, 2007). Terrestrial and atmospheric nutrient inputs to Atlantic coastal watersheds in the Northeastern United States by the 1990s exceeded natural levels by as much as a factor of 8 for nitrogen and 24 for phosphorus (Boynton and others, 1995; Howarth and others, 2002). Human disturbance of the land surface has also substantially increased sediment losses from terrestrial uplands to surface waters (Langland and Cronin, 2003; Brakebill and others, 2010). Consequent declines in water quality or ecological conditions attributable to excessive nutrients or sediment have been observed in recent decades in many New England and mid-Atlantic surface waters (Bricker and others, 2007), including Chesapeake Bay (Kemp and others, 2005), Long Island Sound (Suter and others, 2014), and Buzzards Bay (Pospelova and others, 2005). Bricker and others (2007) review the effects of excessive nutrients on estuaries throughout the United States and report those effects along the Atlantic Coast from Chesapeake Bay through Cape Cod to be the most prevalent and severe.

Recent efforts to reduce the flux of nutrients and suspended sediment in streams and to estuaries of the Northeastern United States have met with mixed results. As required by the Clean Water Act, total maximum daily loads (TMDLs) have been established by watershed communities to direct reductions in nitrogen, phosphorus, and (or) sediment inputs to numerous northeastern surface waters (Stahl and Bolton, 2005; Volk, 2010; Yagow and others, 2012), including Long Island Sound (U.S. Environmental Protection Agency, 2009b), Lake Champlain (U.S. Environmental Protection Agency, 2016),

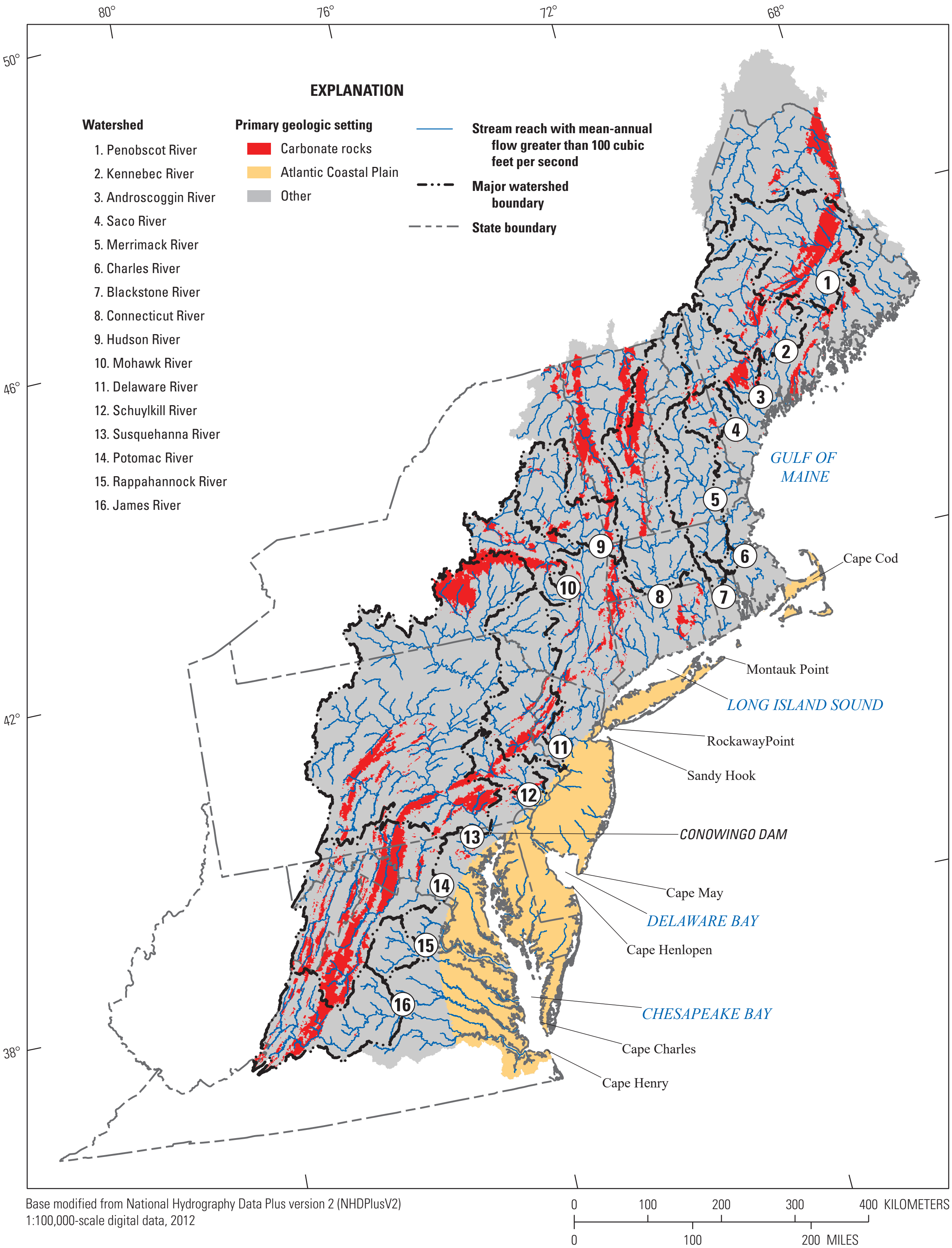

Figure 2. Watersheds above the head of tide on major streams and a summary of geology in the Northeastern United States (Anning and Ator, 2017; Wieczorek and others, 2019).

and Chesapeake Bay (U.S. Environmental Protection Agency, 2011) (figs. 2, 3). Requirements of these TMDLs include a 58.5-percent decline in nitrogen inputs to Long Island Sound (U.S. Environmental Protection Agency, 2009a) and reductions of 25, 24, and 20 percent in nitrogen, phosphorus, and sediment loads, respectively, to Chesapeake Bay (Linker and others, 2013a). Although water-quality improvements likely attributable to upstream input reductions or other restoration or management practices implemented as part of TMDL requirements or other programs have been observed recently in surface waters in some areas of the Northeast (Monti and Scorca, 2003; Weller and others, 2011; Boynton and others, 2013; Eshleman and others, 2013), nutrient and (or) suspended-sediment concentrations (SSCs) and loads in other streams and estuaries have remained stable or increased (Hirsch and others, 2010; Trench and others, 2012; Zhang and others, 2015; Chanat and others, 2016). Similarly, ecological improvements expected from nutrient and sediment reductions have been observed in some northeastern streams and coastal estuaries (Sharp and others, 2009; Murphy and others, 2011; Boynton and others, 2013; Lefcheck and others, 2018) but remain elusive in others (Kemp and others, 2005; Lee and Lwiza, 2008; Suter and others, 2014; Chesapeake Bay Program, 2018).

Effective watershed management and restoration to improve surface-water quality is complicated by the multitude of nutrient sources in the Northeastern United States. Nutrient and sediment reductions often represent a substantial investment for affected communities; such reductions mandated by the TMDL in the Chesapeake Bay watershed will cost an estimated $3.6 billion from the agricultural sector by 2025 and $900 million annually thereafter (Shortle and others, 2013). Maximizing ecological returns on such investments requires understanding of the multiple sources of nutrients or processes that affect sediment erosion, which often vary substantially over space and time. The Northeastern United States is mostly forested but includes areas of intensive agriculture and densely populated urban centers (fig. 3). States in the region hosted a 2010 human population of more than 72 million and supported a 2009 gross-domestic product estimated at $3.8 trillion (U.S. Census Bureau, 2012). Sources of nitrogen and phosphorus to surface waters and terrestrial uplands include disposal of human wastes, fertilizer and animal manure applications, and (for nitrogen) direct deposition or fixation from the atmosphere (Boyer and others, 2002; Moore and others, 2004; Ator and others, 2011; Moore and others, 2011; Moorman and others, 2014). Phosphorus in natural mineral deposits also may be mobilized through erosion (Likens and others, 1977; Ator and others, 2011), which occurs naturally in uplands and stream channels but is often exacerbated in areas of agricultural or urban land disturbance (Brakebill and others, 2010). Nutrient applications per area are generally smaller in New England than to the south in the mid-Atlantic region, where agriculture and densely populated urban centers are more common (Boyer and others, 2002).

Watershed restoration and management in the Northeast are complicated by variable interacting natural and anthropogenic landscape conditions that control the fate and transport of nutrients and sediment from source areas to and within steams. The Northeastern United States stretches over more than 1,200 kilometers (km) along the Atlantic Coast from southern Virginia through northern Maine and encompasses variable soil, hydrologic, geologic, and climate conditions that control erosion and nutrient and sediment transport from uplands to surface waters (figs. 2, 4, 5). Approximately 25 percent of nitrogen inputs to the landscape, on average, is transported to surface waters (Howarth and others, 1996; Boyer and others, 2002), often through groundwater in the form of nitrate (Böhlke and Denver, 1995; Bachman and others, 1998; Scorca and Monti, 2001; Ator and Denver, 2012). Most of the remaining nitrogen is returned to the atmosphere through terrestrial denitrification (Van Breemen and others, 2002; Ator and García, 2016), which has been observed in numerous upland areas in the Northeastern United States, including depressional wetlands (Denver and others, 2014) and along groundwater flowpaths (Böhlke and Denver, 1995; Ator and Denis, 1997). Soil denitrification is difficult to measure (Groffman, 2012) but also likely substantial (Van Breemen and others, 2002; Ator and García, 2016). Remaining nitrogen inputs may be volatilized as ammonia or stored in soils or biomass, a portion of which (typically around 20 percent of total applications) may be removed through the harvest of agricultural or forest products (Boyer and others, 2002; Van Breemen and others, 2002; Ator and García, 2016). The net annual increase in landscape storage of nitrogen averages around 620 kilograms per square kilometer (kg km^{-2}) across the northeast (Van Breemen and others, 2002) but varies spatially and exceeds 1,000 kg km^{-2} in some areas (Ator and García, 2016). As with nitrogen, agricultural phosphorus applications in recent decades often have far exceeded removal in harvested crops, particularly in areas that also support concentrated animal production (Staver and Brinsfield, 2001). Unlike nitrogen, however, which is often lost to the atmosphere through volatilization or denitrification, phosphorus is relatively insoluble and immobile and remains sequestered in soils and sediment. Phosphorus has consequently accumulated in agricultural soils in some areas at levels that exceed agronomic demand and that likely promote losses to streams in dissolved form (Staver and Brinsfield, 2001). The movement of suspended sediment and associated particulate nutrient compounds typically is episodic; once mobilized through erosion, individual particles may remain in storage in watershed uplands, streambanks, or flood plains for decades or even centuries between short periods of movement during high streamflows.

Monitoring and modeling in recent years have substantially improved our understanding of the sources, fate, and transport of nutrients and sediment in the Northeastern United States in support of water-quality management and restoration. Water-quality and stream-discharge records now exceed multiple decades for many northeastern streams (Sprague and others, 2009; Zhang and others, 2015; Chanat and others, 2016), and numerical techniques have been developed to

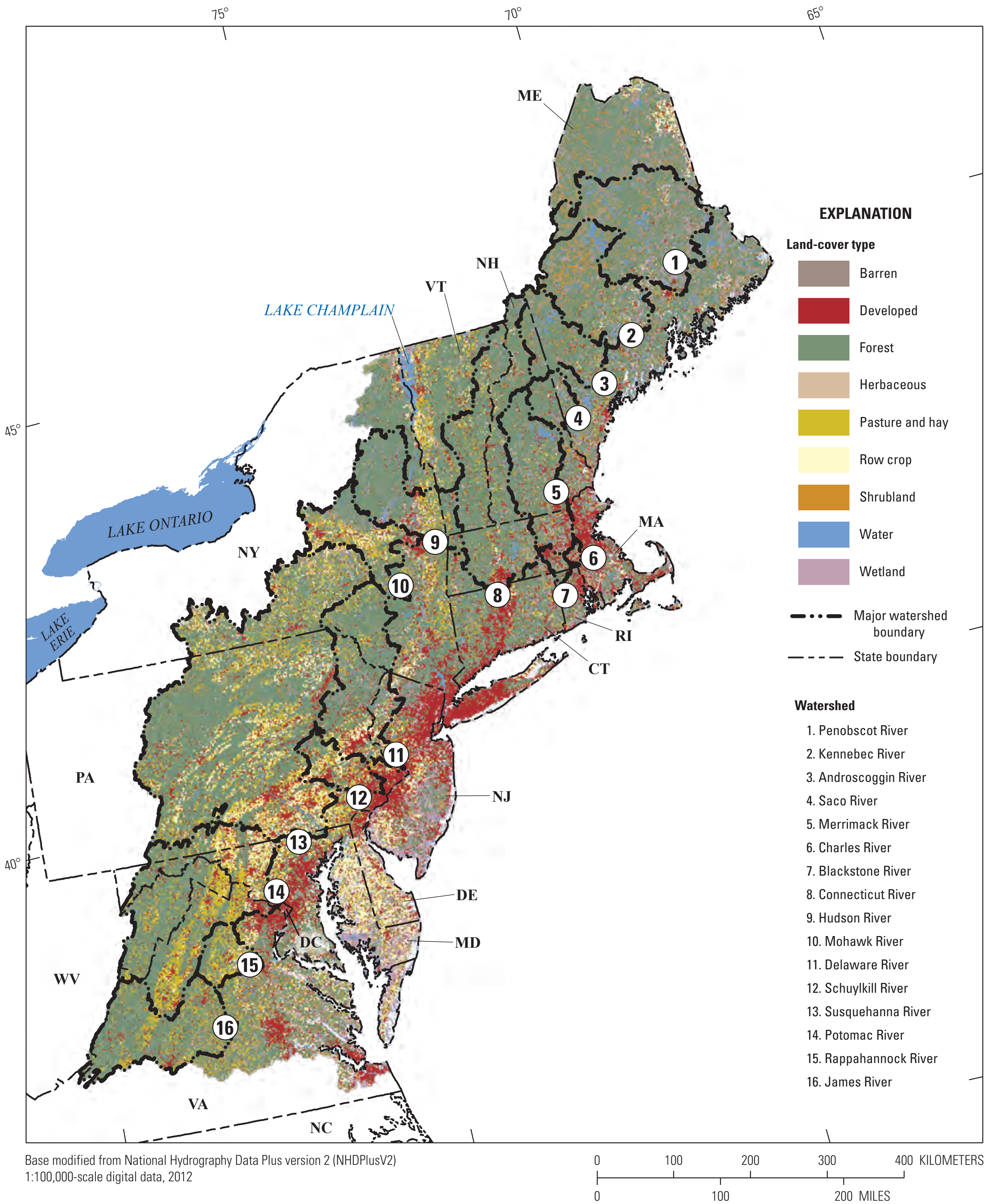

Figure 3. Land cover in the Northeastern United States, 2011. (Adapted from Homer and others (2015) and Wieczorek and others (2019)).

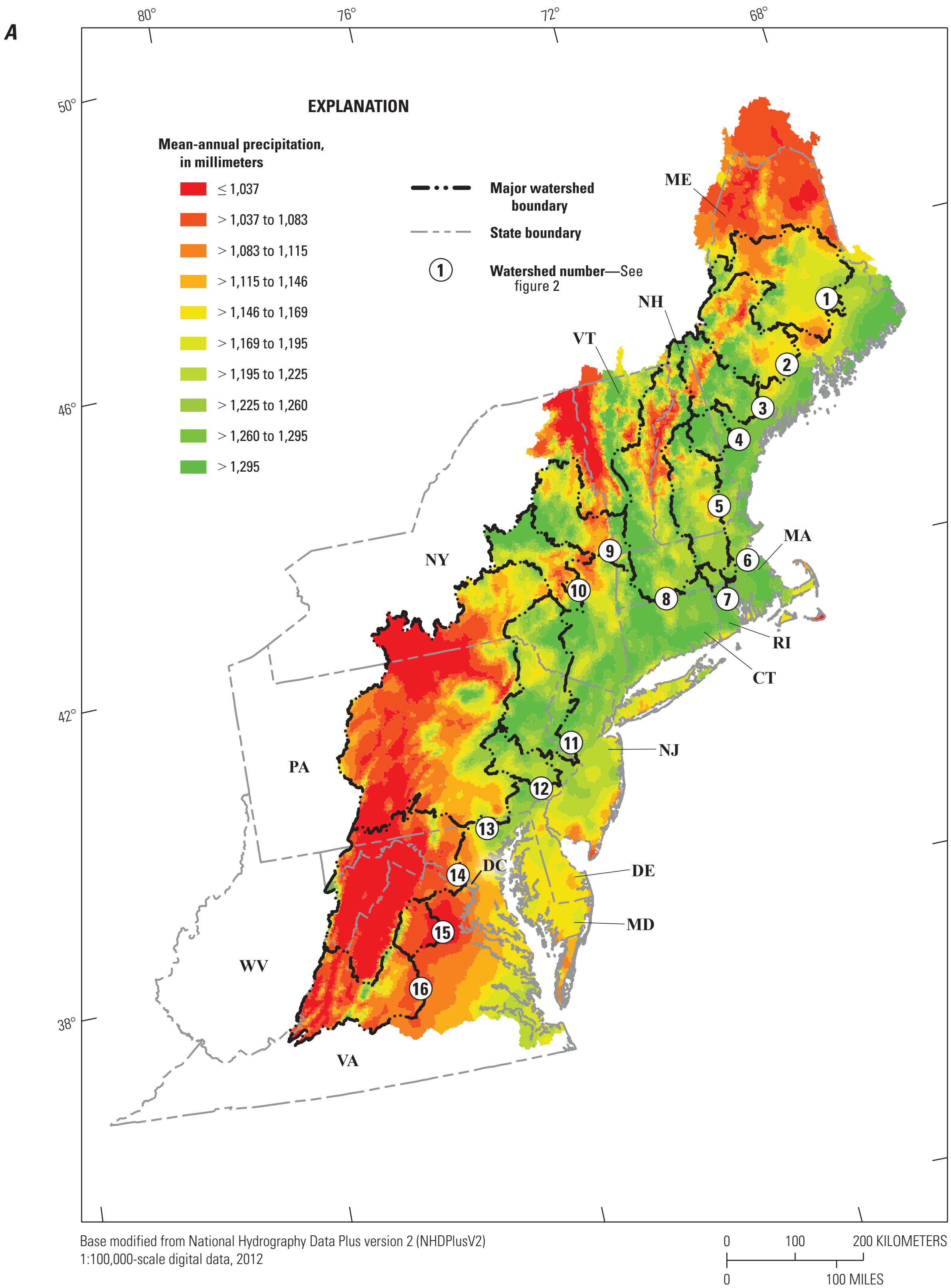

Figure 4. Mean-annual *A*, precipitation and *B*, precipitation in excess of actual evapotranspiration, or surplus precipitation, during 2000 through 2014 in the Northeastern United States. Adapted from Wolock and McCabe (2018) and Wieczorek and others (2019).

B

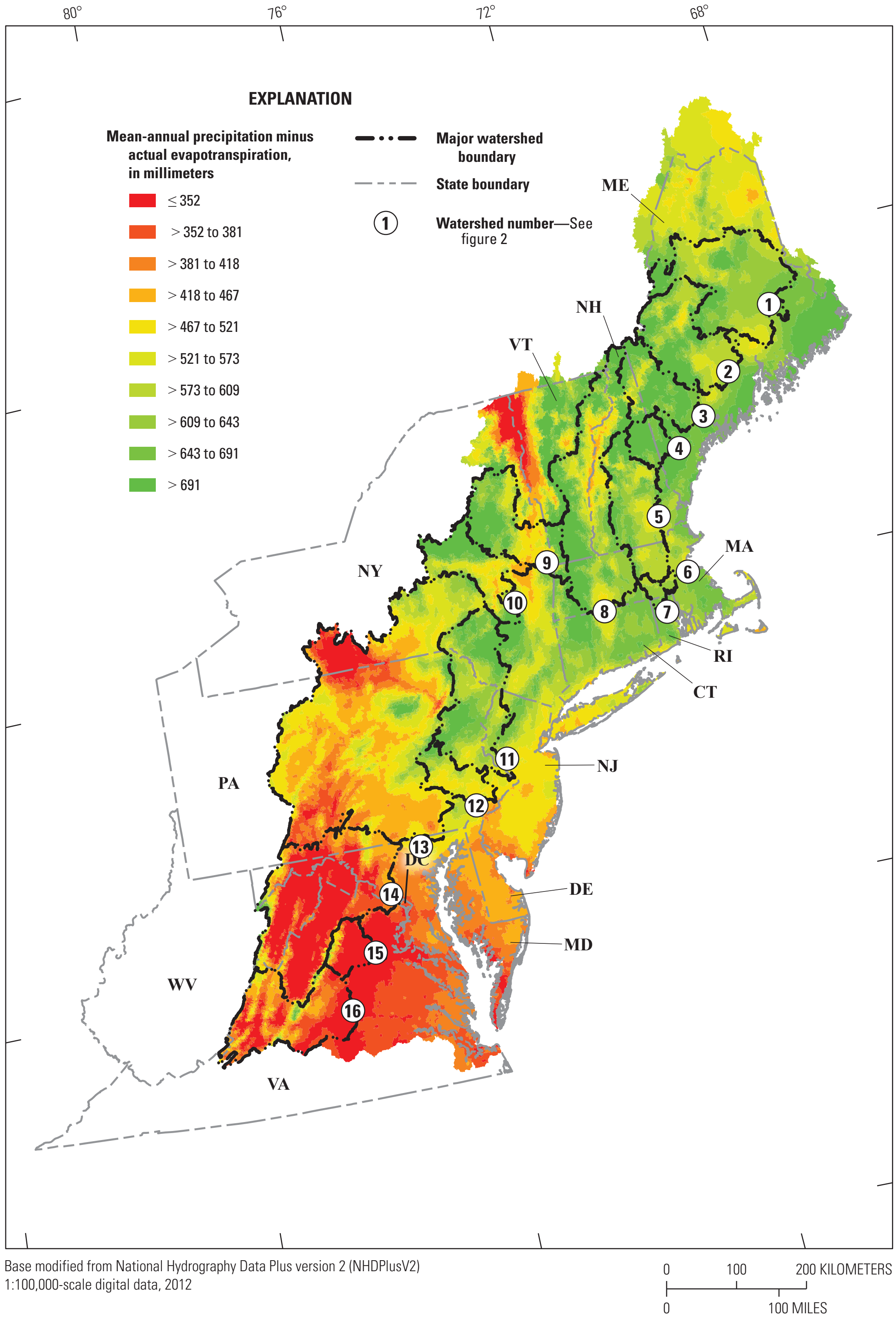

Figure 4. Mean-annual *A*, precipitation and *B*, precipitation in excess of actual evapotranspiration, or surplus precipitation, during 2000 through 2014 in the Northeastern United States.—Continued Adapted from Wolock and McCabe (2018) and Wieczorek and others (2019).

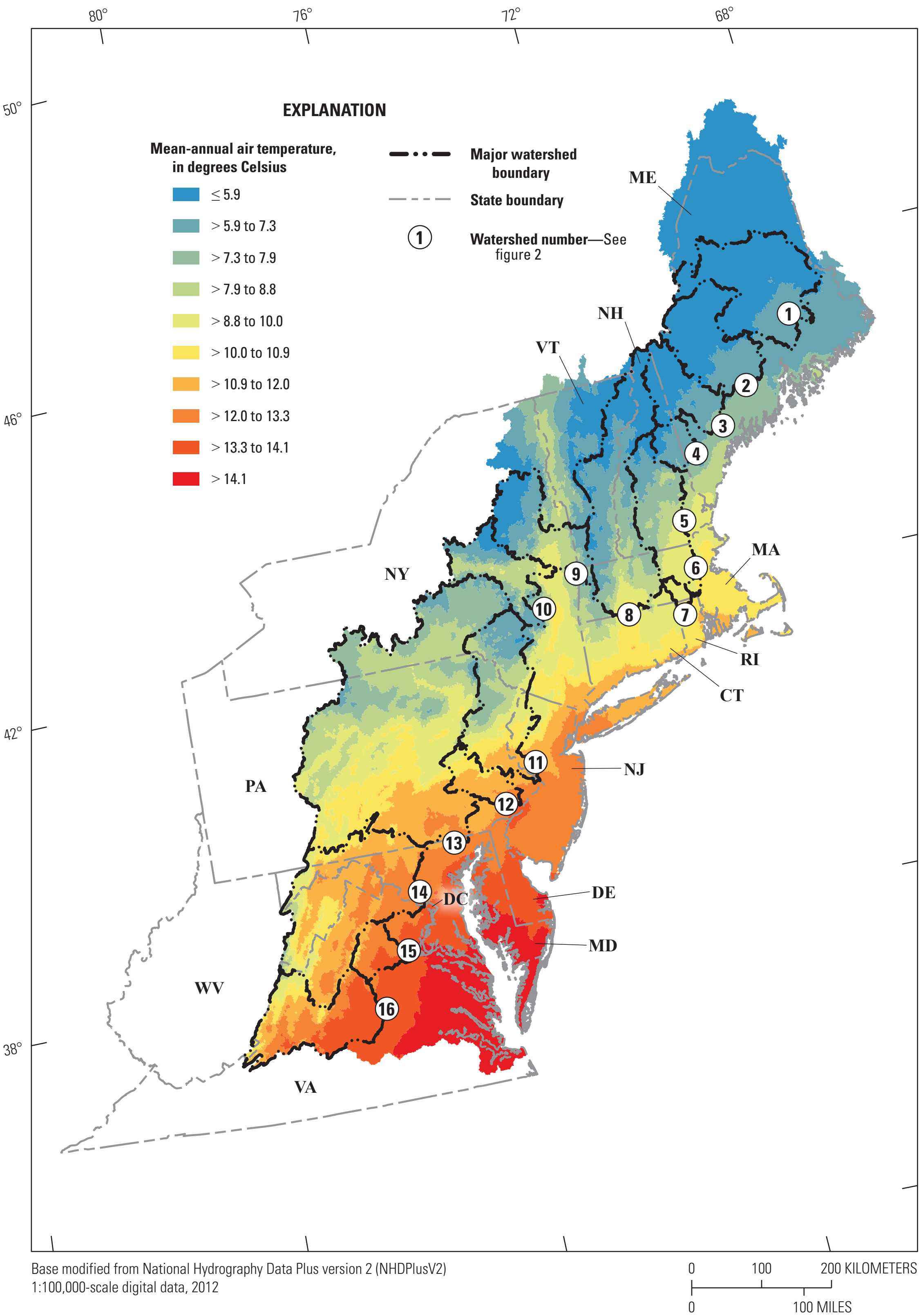

Figure 5. Mean-annual air temperature during 2000 through 2014 in the Northeastern United States. Adapted from Wolock and McCabe (2018) and Wieczorek and others (2019).

leverage these data to estimate instream loads and to identify and quantify temporal trends in constituent loads and concentrations in monitored streams (Hirsch and others, 1982; Cohn and others, 1992; Turpin and others, 1998; Cohn, 2005; Helsel and Frans, 2006; Hirsch and others, 2010). Improved and expanded remote sensing and other data-gathering techniques have supported improved estimates and mapping of ancillary factors such as land use (Falcone, 2015), land cover (Homer and others, 2015), nutrient inputs (Maizel and others, 1997; National Atmospheric Deposition Program, 2018), and management practices (Sekellick and others, 2019). Watershed models (Preston and Brakebill, 1999; Moore and others, 2004; Brakebill and others, 2010; Roberts and Prince, 2010; Ator and others, 2011; Moore and others, 2011; Shenk and Linker, 2013) and nutrient budgets (Howarth and others, 1996; Boyer and others, 2002; Van Breemen and others, 2002) have capitalized on this information to identify and quantify sources, evaluate natural and human factors affecting nutrient fate in uplands and stream channels, and estimate concentrations and loads in unmonitored streams. Models of groundwater hydrology (Buxton and Modica, 1992; Kauffman and others, 2001; Scorca and Monti, 2001; Sanford and Pope, 2007; Sanford and others, 2012) and geochemistry (Böhlke and Denver, 1995; Greene and others, 2005; Denver and others, 2011; Tesoriero and others, 2015) have been developed to improve our understanding of nutrient delivery from upland application areas to surface waters.

Watershed models illustrating and quantifying the sources, fate, and transport of water, nitrogen, phosphorus, and suspended sediment in streams of the Northeastern United States are described and discussed in this report. The models were developed using SPARROW modeling, which uses nonlinear regression to relate the mean-annual load of contaminants (such as nitrogen or phosphorus) in streams (the dependent variable) to watershed sources and landscape conditions describing contaminant fate and transport in contributing watersheds (the explanatory variables) (Smith and others, 1997; Schwarz and others, 2006). Individual models were developed for mean-annual nitrogen, phosphorus, and suspended-sediment loads as well as streamflow in the Northeastern United States (fig. 2). The models are focused on 2012 but are designed to represent steady-state conditions over a multiyear period. The models include multiple improvements over past models developed for the Northeast. Along with an updated (2012) timeframe, such innovations include updates and improvements to the stream hydrography (Schwarz and Wieczorek, 2018; Schwarz, 2019; Brakebill and others, in press) and development of extensive and comprehensive calibration data (Saad and others, 2019) and explanatory data. The annual loads of nitrogen, phosphorus, and suspended sediment from the Northeastern United States to the northern Atlantic Ocean and major coastal estuaries are presented. Limitations of the model predictions are discussed along with implications of model estimates and results for watershed restoration and management and for future research. Inputs and outputs from the 2012 Northeast SPARROW models are available in an associated U.S. Geological Survey data release (Ator, 2019).

Methods

The SPARROW modeling tool was used to develop watershed models representing streamflow and loads of nitrogen, phosphorus, and suspended sediment in northeastern streams. The models were calibrated to water, nutrient, and suspended-sediment loads estimated from available water-quality and streamflow monitoring data, and explanatory data for the models were compiled from available geographic information. The calibrated models quantify important sources and environmental factors affecting upland and aquatic fate and transport in the Northeast and are used to predict water-quality conditions in unsampled streams.

The SPARROW Modeling Tool

SPARROW is a hybrid statistical and mechanistic model for estimating the load of a target constituent (such as water, nitrogen, phosphorus, or suspended sediment) moving through the landscape under long-term, steady-state conditions (Schwarz and others, 2006). The model typically uses catchment (watershed) attributes (such as sources of the constituent, land cover, climate, soil properties, geology, hydrology, and stream and waterbody properties) to explain spatial variation in the measured (observed) mean-annual load of the target constituent in streams at monitoring stations. SPARROW simulates the net effect of such landscape properties on the delivery of the target constituent from uplands to surface waters as well as permanent or long-term constituent loss within free-flowing streams and impoundments. Calibrated models can be used to predict constituent concentration and load in unsampled areas.

SPARROW offers several advantages for evaluating, explaining, and mapping surface-water quality and related upstream causal factors at relatively fine spatial scales over large regions. Models are developed using statistical algorithms that optimize the fit of model coefficients to objectively identify environmental factors correlated with water quality. The statistical framework supports estimates of uncertainty in model predictions and objective evaluation of the significance of observed relations between stream chemistry and possible explanatory factors. Additionally, SPARROW models synthesize geographic information at multiple scales in a way that can be related to the often larger spatial scale of available monitoring data while also supporting finer scale predictions. In that way, SPARROW models provide a framework for integrating a wide range of different types of data to provide spatially detailed estimates of water quality. SPARROW models also provide spatially explicit water-quality estimates through which upstream environmental factors are directly related to downstream water quality.

Model Inputs

SPARROW requires three types of input data, including (1) a spatially explicit digital representation of the surface-water drainage network and associated upland catchments (watersheds) covering the model domain, (2) measured or estimated mean-annual loads of the target constituent at monitoring stations on the drainage network for use in model calibration, and (3) spatially explicit geographic information (explanatory data) for each network reach or associated catchment representing constituent sources and physical and chemical landscape properties that affect delivery to streams and loss within free-flowing streams and impoundments.

The Surface-Water Drainage Network

The surface-water drainage network for use in SPARROW modeling in the Northeast (fig. 2) was modified from NHDPlus Version 2 (Horizon Systems, 2013; U.S. Environmental Protection Agency, 2017; Schwarz and Wieczorek, 2018; Schwarz, 2019; Brakebill and others, in press), a comprehensive set of digital spatial data that includes attributes for surface-water features, such as streams, lakes, ponds, and artificial reservoirs, and contributing upland watersheds (Simley and Carswell, 2009). Particularly important hydrologic features represented in NHDPlus for use in SPARROW include reaches (individual segments of streams, coastlines, or flowlines within impoundments) and the delineation of upland catchments contributing to those reaches. Such features represented in NHDPlus largely correspond to those on 1:100,000 scale U.S. Geological Survey topographic maps; in the Northeastern United States model domain, such features include 197,596 stream, impoundment, or coastline reaches averaging 1.5 km in length and draining adjacent upland catchments averaging 2.3 square kilometers (km^2) in area. NHDPlus attributes used for the SPARROW modeling include the estimated mean-annual discharge and velocity in each stream reach and the morphometry and hydraulic properties of impoundments such as ponds, lakes, and reservoirs. Most NHDPlus reaches represent streams or inland waterbodies (such as lakes, ponds, and reservoirs), although some represent coastlines or closed basins, which do not have a surface-water connection to other reaches in NHDPlus. Impounded reaches in the stream network were identified on the basis of NHDPlus and additional information from the National Inventory of Dams (Wieczorek and others, 2019).

Calibration Data

Available water-quality data collected by the USGS and other Federal, State, and local agencies on northeastern streams (table 1) were compiled to support estimation of the mean-annual loads of total nitrogen, total phosphorus, and suspended sediment at monitoring stations for use in SPARROW model calibration (Saad and others, 2019). Concentrations of total nitrogen, total phosphorus, total suspended solids (TSS), and suspended sediment measured in samples collected during water years 2000 through 2014 (from October 1, 1999, through September 30, 2014) were compiled for consideration. Where not reported, total nitrogen concentration was estimated as the sum of reported concentrations of dissolved and particulate nitrogen or of individual nitrogen compounds, if available. In cases of multiple available observations of the same constituent at the same monitoring station on the same date, one observation was retained at random. Water-quality records covering a minimum of 3 years through as late as at least September 30, 2009, and including at least 24 observations with 3 observations in each season were considered for use in load estimation. Water-quality observations collected from multiple stations on the same NHDPlus stream reach were considered to represent a single water-quality record in selected cases where available location information suggests the multiple stations are at the same location or in close proximity. Where such merging of water-quality records resulted in multiple observations for the same constituent on the same date, one observation was retained at random.

Water-quality records were matched with appropriate streamflow records to support estimation of nutrient and sediment loads. Streamflow data for northeastern streams were compiled from USGS records for streamgages with a minimum of 10 or (for use in computing water loads) 13 consecutive years of complete data, including 2012. Water-quality data of the Chesapeake Bay Nontidal Network (U.S. Geological Survey, 2016) are deliberately collected near streamgages to support load estimation. Water-quality data from other monitoring stations were matched with streamflow records from nested (upstream or downstream) stations using an algorithm to maximize (in order of decreasing importance) (1) the proximity of the water-quality and streamflow monitoring stations, (2) the period of overlap between water-quality and streamflow records, and (3) the length of the streamflow records. Water-quality records for relatively small streams (draining less than 259 km^2) were matched with streamflow records from non-nested streamgages if located within 40 km.

Streamflow and mean-annual loads of nutrients and sediment at monitoring stations were estimated for use in SPARROW model calibration. The mean daily streamflow for the period of record at each station was selected to calibrate

Table 1. Source agencies of selected data compiled to estimate calibration loads.

Agency
Brick Township, New Jersey, Municipal Utilities Authority
Connecticut Department of Energy and Environmental Protection
Delaware Department of Natural Resources and Environmental Control
Delaware Geological Survey
Delaware River Basin Commission
District of Columbia Department of the Environment
Maryland Department of Natural Resources
Maryland Department of the Environment
Massachusetts Department of Environmental Protection
Massachusetts Rural Water Association
Monmouth County, New Jersey, Health Department
National Park Service
New Hampshire Department of Environmental Services
New Jersey Department of Environmental Protection
New York Department of Environmental Conservation
Pennsylvania Department of Environmental Protection
Rutgers University Cooperative Extension
Susquehanna River Basin Commission
US Army Corps of Engineers
US Environmental Protection Agency
US Geological Survey
Virginia Department of Environmental Quality
Vermont Department of Environmental Conservation
West Virginia Department of Environmental Protection

the streamflow model. Because water-quality records are more sparse and represent various periods of record, however, regression methods were used to estimate the mean-annual load of nutrients or sediment at monitoring stations during 2012 for use in the nitrogen, phosphorus, and suspended-sediment model calibration (Saad and others, 2019). The Beale's Ratio Estimator is relatively unbiased and particularly suitable for estimating long-term mean-annual load in streams (Lee and others, 2016a) and was used for such estimates in cases where temporal trends in load are statistically insignificant. For cases with significant trends in load, however, a five-parameter model (based on time and streamflow) with Kalman-smoothing was used to estimate mean-annual load detrended to 2012 (Preston and others, 2009; Saad and others, 2019). Such load estimates with a standard error less than 50 percent were considered for use in SPARROW calibration. Details of load estimation for use in SPARROW calibration are available in Saad and others (2019).

Explanatory Data

Available data representing sources and landscape conditions affecting the fate and transport of water, nutrients, and suspended sediment to and within streams of the northeastern United States (Wieczorek and others, 2019) were compiled for consideration as explanatory variables in the SPARROW models. This compilation was guided in general by information in the literature about surface-water hydrology and nitrogen, phosphorus, and suspended sediment in the Northeast (Howarth and others, 1996; Preston and Brakebill, 1999; Boyer and others, 2002; Moore and others, 2004; Brakebill and others, 2010; Ator and others, 2011; Moore and others, 2011) and, in particular, by the need for spatially explicit data covering the entire study area (fig. 2) to support the modeling (Schwarz and others, 2006). The chosen data are generally available for the entire conterminous United States and include point sources (Skinner and Maupin, 2019), agricultural fertilizer and manure applications (Stewart and others, 2019), septic effluent, water use (Maupin and others, 2014; Roland and Hoos, 2019), land cover (Homer and others, 2015), soil conditions (Wolock, 1997), geology (Soller and others, 2009; Anning and Ator, 2017), atmospheric deposition, climate and hydrology (Wolock and McCabe, 2018), crop acreage (U.S. Department of Agriculture, 2015), and land management practices (Wieczorek and others, 2019).

Model Specification

The SPARROW models were specified to estimate coefficients and make predictions useful for quantifying and understanding the sources, fate, and transport of water, nutrients, and suspended sediment in northeastern streams. Numerous explanatory variables were considered for each model on the basis of previous knowledge or conceptual models of source, fate, and transport of constituents, and the final specification was selected through consideration of the overall model fit and the statistical significance of model coefficients. Sources are generally specified as intensive estimates of mass inputs (such as through point sources, fertilizer applications, or atmospheric deposition) or as extensive measurements of catchment areas in a particular land-use or geologic setting (Schwarz and others, 2006). Land-to-water terms are generally log-transformed and were mean-adjusted to improve the interpretability of the source coefficients (Schwarz and others, 2006). Nutrient and sediment losses within the stream network were specified as a function of estimated traveltime in flowing streams and a hypothetical apparent settling velocity in impoundments. Because the models are specified to represent mean-annual conditions, these loss terms likely represent effects of long-term or permanent removal processes, such as particle settling or denitrification, rather than short-term or seasonal removal processes (Schwarz and others, 2006). Traveltimes in flowing reaches were estimated as a function of reach length and average velocity (Schwarz and Wieczorek, 2018; Schwarz, 2019; Brakebill and others, in press). Apparent settling velocity was estimated as a function of streamflow and impounded area (Simley and Carswell, 2009; Wieczorek and others, 2019). Estimates of streamflow in each reach were taken from NHDPlus for use in the streamflow SPARROW model and from that streamflow model for use in the nitrogen, phosphorus, and suspended-sediment models.

The specification of the nutrient and sediment models was customized to represent evolving conditions on the lower reaches of the Susquehanna River, the largest river on the east coast of the United States. Three hydroelectric dams were constructed on the lower Susquehanna River by 1931 (Langland, 2009). Reservoirs behind the two upper dams have been in dynamic equilibrium since the mid-20th century and no longer serve as net sinks for suspended particulates in the river (Langland, 2009); recent observations suggest similar conditions are evolving behind the lower-most dam, Conowingo Dam (Langland and Hainly, 1997; Langland, 2009; Hirsch, 2012; Zhang and others, 2013; Zhang and others, 2015; Zhang and others, 2016). Reaches behind all three dams were therefore specified as flowing rather than impounded in the nitrogen, phosphorus, and suspended-sediment models; recent SPARROW modeling for the Chesapeake Bay watershed suggests that phosphorus load leaving the reservoir system at the lower dam in 2012 is best approximated using this approach (Ator and others, 2019).

Streamflow

The streamflow model for the Northeast was specified to represent the dominant sources of water to streams in the Northeast. Streamflow diversions and groundwater pumping from deep aquifers that might naturally be relatively isolated from surficial hydrology occur in some areas of the Northeastern United States (Buxton and Smolensky, 1999; dePaul and others, 2008), and water returned to streams from such extractions for municipal supply is represented by the inclusion of wastewater point-source discharges in the streamflow SPARROW model. Owing to the humid and temperate climate, however, the surplus of precipitation over evapotranspiration generally substantially exceeds any such additions or removals of water in most areas, and natural runoff is the dominant source of flow in most streams (Leahy and Martin, 1993; Scorca and Monti, 2001; Sloto and Buxton, 2005; Masterson and others, 2009). Natural runoff is represented in the streamflow SPARROW model by the surplus of mean-annual precipitation over actual evapotranspiration estimated for 2000 through 2014 by Wolock and McCabe (2018) and attributed to NHDPlus catchments by Wieczorek and others (2019). This runoff would include streamflow generated by overland runoff as well as through groundwater discharge. Most groundwater discharge in the Northeast occurs from relatively shallow surficial or near-surface aquifers within a few decades; the small fraction of groundwater recharge reaching deeper aquifers may travel along groundwater flow paths for centuries or longer before discharging to surface waters (Buxton and Modica, 1992; Sanford and others, 2012).

Additional explanatory terms for the streamflow SPARROW model were considered and selected to represent removal or retention of water in terrestrial uplands and evaporation and withdrawal from model stream reaches. Land-to-water terms considered to interact with the surplus precipitation source term in the SPARROW model were chosen to represent spatial variability in the retention or removal of water from uplands. The mean satellite-observed enhanced-vegetative index (EVI) (Wieczorek and others, 2019) represents the health or “greenness” of vegetation and was chosen to represent spatial variability in vegetative transpiration. Similarly, the average soil moisture storage during 2000 through 2014 estimated by Wolock and McCabe (2018) and attributed to NHDPlus by Wieczorek and others (2019) was selected to represent upland water storage in soils. Upland losses to the atmosphere through either evaporation or transpiration are likely greater in warmer areas, as represented by the mean-annual air temperature during 2000 through 2014 (Wolock and McCabe, 2018; Wieczorek and others, 2019). Evaporative losses from impounded waters such as lakes, ponds, and reservoirs were modeled as a function of the impounded surface area (Schwarz and Wieczorek, 2018; Schwarz, 2019; Wieczorek and others, 2019; Brakebill and others, in press), the mean-annual potential evapotranspiration during 2000 through 2014, and the total flow in each impounded reach (Schwarz and Wieczorek, 2018; Wolock and McCabe, 2018; Schwarz, 2019; Wieczorek and others, 2019; Brakebill and others, in press). Surface-water withdrawals for public supply were estimated as a function of population served and modeled as a fraction of flow (Maupin and others, 2014; Roland and Hoos, 2019; Wieczorek and others, 2019).

Total Nitrogen and Total Phosphorus

The nutrient SPARROW models were specified to represent the major sources of nitrogen and phosphorus to northeastern streams. Nitrogen and phosphorus in surface waters may originate from natural sources but in the Northeast are primarily anthropogenic (Boyer and others, 2002; Moore and others, 2004; Ator and others, 2011; Moore and others, 2011). Nutrients in human waste are represented in the models by municipal wastewater discharges (Skinner and Maupin, 2019) and (for nitrogen) estimated effluent from septic systems (Wieczorek and others, 2019). Because other nonpoint nutrient sources in urban areas (such as lawn fertilizers, pet waste, and leaking sewer lines) are particularly difficult to estimate, these are often (and are herein) represented in SPARROW models by the area of urban land (Homer and others, 2015; Wieczorek and others, 2019). Agriculture is a substantial source of both nitrogen (Howarth and others, 1996; Boyer and others, 2002) and phosphorus (Staver and Brinsfield, 2001) to northeastern watersheds; these sources are represented by estimated agricultural fertilizer and manure applications (Stewart and others, 2019; Wieczorek and others, 2019) and the area of each catchment planted in crops that fix nitrogen directly from the atmosphere (U.S. Department of Agriculture, 2015; Wieczorek and others, 2019). Atmospheric deposition is an important source of nitrogen to the landscape throughout the Northeast (Eshleman and others, 2013; Linker and others, 2013b) and was estimated from the Community Multiscale Air Quality (CMAQ) model for use in the nitrogen model (Wieczorek and others, 2019). Although carbonate rocks (fig. 2) do not generally contain mineral phosphorus, erosion of minerals in crystalline and siliciclastic rocks represents a natural source of phosphorus to groundwater (Denver and others, 2011) and streams (Dillon and Kirchner, 1975; Likens and others, 1977) in areas of the Northeast and vicinity and may explain net phosphorus yields from forested areas estimated by previous SPARROW models (Moore and others, 2004; Alexander and others, 2008; Moore and others, 2011). Areas underlain by such rocks or by unconsolidated siliciclastic sediments of the Coastal Plain (Anning and Ator, 2017; Wieczorek and others, 2019) were considered for the phosphorus model to represent natural sources; this includes all areas of the model domain except those underlain by carbonate rocks (fig. 2). Ator and others (2011) used a similar approach in a previous SPARROW model for the Chesapeake Bay watershed.

Explanatory terms representing land-to-water delivery of nutrients were specified to interact with upland (nonpoint) sources in the models to represent natural landscape conditions and human management practices likely affecting the fate and transport of nitrogen or phosphorus to surface waters. Nitrogen transport to streams (primarily as nitrate through groundwater) can be particularly conservative and efficient in carbonate terranes, and nitrogen concentrations and (or) yields are often greater in groundwater and streams in such areas (Cady, 1936; Trainer and Watkins, 1975; Ator and Denis, 1997; Ator and Ferrari, 1997; Lizarraga, 1997; Miller and others, 1997; Ator and others, 2011). The fraction of each catchment underlain by carbonate rocks (Anning and Ator, 2017; Wieczorek and others, 2019) was therefore considered as a land-to-water term in the nitrogen model, along with the average annual runoff in each catchment during 2000 through 2014 (Wolock and McCabe, 2018; Wieczorek and others, 2019). Soil thickness (Wolock, 1997; Wieczorek and others, 2019), average air temperature (Wolock and McCabe, 2018; Wieczorek and others, 2019), and the presence of forest or wetlands (Homer and others, 2015; Wieczorek and others, 2019) were also considered for the nitrogen model to represent conditions likely conducive to the removal of nitrogen to the atmosphere through terrestrial denitrification. Conservation practices (such as conservation tillage and cover crops) have been increasingly implemented in agricultural areas in recent years to mitigate sediment and nutrient losses to surface waters (Staver and Brinsfield, 1998, 2001; Hively and others, 2009; Hively and others, 2013; Sekellick and others, 2019) and were therefore considered to interact with agricultural source terms in the nitrogen and phosphorus models. Because phosphorus transport from uplands to surface waters occurs primarily in the particulate phase attached to sediment, soil erodibility (Wolock, 1997; Wieczorek and others, 2019) was considered as a land-to-water term in the phosphorus model. To better refine estimates of phosphorus from mineral sources, the average natural phosphorus content in soils (Wieczorek and others, 2019) was specified to interact with the geologic phosphorus source.

A substantial portion of nutrient inputs to northeastern streams may be removed during instream transport (Seitzinger and others, 2002; Moore and others, 2004; Ator and others, 2011; Moore and others, 2011); therefore, the models were specified to estimate nutrient losses in free-flowing and impounded streams. Permanent or long-term loss of nitrogen in free-flowing streams was evaluated by estimating a first-order decay rate (inverse days) that, when multiplied by the reach time of travel (days), represents the fraction of the load that either settles to the bottom of the reach or is taken up by benthic bacteria. Because nitrogen decay rates are often greater in small streams (Alexander and others, 2000; Schwarz and others, 2006), stream decay in the nitrogen model was considered for three classes of stream sizes. Permanent or long-term loss of nitrogen and phosphorus in impoundments was evaluated by estimating a hypothetical settling velocity that, when multiplied by reciprocal areal hydraulic load, represents the fraction of incoming load that either settles to the bottom of the impoundment or is taken up by benthic bacteria (Schwarz and others, 2006).

Suspended Sediment

The suspended-sediment model was specified to represent upland and stream-channel erosion. Sediment may be mobilized in uplands (such as through surface erosion, soil creep, or mass wasting) or within stream corridors through bank erosion or resuspension (Gellis and others, 2016). Sediment eroded from headwater areas is often quickly delivered to stream channels and transported to moderate and lower elevations, which are generally depositional and favor storage of sediment in channels and flood plains over sediment generation (Gellis and others, 2016). Although erosion occurs naturally, it is often greatly enhanced by human activities on the landscape, particularly agriculture and urban development (Wark and Keller, 1963; Wolman, 1964; Guy, 1965; Wolman and Schick, 1967; Vice and others, 1969). Erosion vulnerability varies substantially with variations in topography and lithology among geologic settings. Uplands in the Northeast were therefore classified as sources for the sediment model based on a two-way classification of surficial geology (Soller and others, 2009) and land cover (Homer and others, 2015; Wieczorek and others, 2019). Land-to-water terms considered to interact with upland sources in the model include soil erosion vulnerability and (for agricultural source areas) conservation tillage or no-till agriculture (Wolock, 1997; Wieczorek and others, 2019). The length of free-flowing stream reaches was included in the model to estimate net sources of suspended sediment in stream channels (as specified by Brakebill and others (2010) in a previous suspended-sediment SPARROW model), and streamflow velocity was specified as a land-to-water term interacting only with this source. Large streams (with average annual flow of at least 100 cubic feet per second [ft^3/s]) in the Atlantic Coastal Plain (Fenneman and Johnson, 1946; Wieczorek and others, 2019) were excluded from consideration as possible stream channel sources on the assumption that they likely represent net depositional areas. In the Chesapeake Bay watershed, net sediment deposition and resulting aggradation are typical along lowland streams, particularly in the Coastal Plain (Langland and Cronin, 2003).

The suspended-sediment model accounts for the loss of sediment in free-flowing streams and impoundments. Losses of suspended sediment in impoundments were estimated as an apparent settlement velocity in the same manner as for the nitrogen and phosphorus models. Losses in free-flowing streams were similarly estimated on the basis of reach time of travel, as in the nitrogen model, but were restricted to large streams in the Coastal Plain that were not considered as possible net sources.

Model Calibration

The SPARROW models were calibrated to the mean-annual load of water, nitrogen, phosphorus, suspended sediment, or TSS estimated at monitoring stations on nontidal northeastern streams (Saad and others, 2019). On stream reaches with suitable potential calibration data from multiple monitoring stations (calibration stations), data from only the downstream-most station (draining the largest area) were retained for SPARROW calibration. In such cases with identical drainage areas, data from one station were retained at random or (for the case of one set of stations in the streamflow model) for the station with calibration data generated from the longest streamflow record. For calibrating the suspended-sediment model, estimated suspended-sediment loads were used preferentially over total suspended solid loads on the same stream reach. Because SPARROW assumes calibration values represent loads at the bottom end of calibration reaches, estimated water loads at a few calibration stations located relatively high on small (draining less than 100 km^2) headwater or second-order streams were adjusted on the basis of drainage area to better approximate flow at the bottom of the reach for use in calibrating the streamflow model. The particularly large estimated suspended-sediment load at one station on the Connecticut River and phosphorus load at one station on the Mohawk River likely affected by sampling under extreme hydrologic conditions related to Hurricane Irene in 2011 were omitted from calibration of the suspended-sediment and phosphorus SPARROW models, respectively. Selected calibration stations were dropped from the streamflow model after investigation suggested that particularly large overpredictions or underpredictions in preliminary SPARROW runs may be due to nearby diversions, withdrawals, extractions, or other conditions that are not well represented in the model stream network.

SPARROW uses an iterative process to calibrate the models and estimate coefficients for specified model variables (Schwarz and others, 2006). Beginning in headwater reaches, SPARROW uses initial coefficient values to estimate the constituent load generated within the incremental catchment for each stream reach and transmitted through the stream network. These loads are accumulated downstream through the network until a calibration station is reached, at which point the accumulated load is adjusted to match the measured value at the calibration station. This accumulation process continues downstream until a terminal reach (such as an estuary or internal drainage) is encountered. Nonlinear least squares (NLLS) regression is then used iteratively to adjust the coefficients to minimize the differences between the estimated and measured loads at the model calibration stations.

The model fit was evaluated through the significance of the model coefficients, the load and yield coefficient of determination (R^2), the conditioned and unconditioned root mean square error (RMSE), and the distribution of unconditioned residuals. Because the correlation of both sources and constituent loads with the upstream drainage area typical of many watersheds often contributes to relatively large load-R^2 values in SPARROW models, the yield-R^2 (the R^2 of the logarithm of contaminant yield) may better represent model fit in small watersheds (Schwarz and others, 2006). The significance of model coefficients was evaluated ($\alpha = 0.10$) using a two-sided t-test for land-to-water terms or (because they were constrained to be positive) a one-sided test for sources and aquatic decay terms. Insignificant terms were retained in the models in a few cases, particularly where computed variance-inflation factors suggest estimated standard errors may be inflated by correlation among explanatory terms (Schwarz and others, 2006). Because SPARROW models often contain nested calibration stations, residuals are generally conditioned by first setting loads at any upstream stations equal to calibration values to avoid the downstream propagation of errors (Schwarz and others, 2006). Because such conditioned residuals (and the associated RMSE) may underestimate true model error, unconditioned residuals and RMSE also were computed. Estimated standard errors and quantiles from the standard t distribution were used to estimate 90-percent confidence intervals for each model coefficient (Schwarz and others, 2006).

Conversions Between Different Types of Calibration Data

Binary explanatory terms were included in the phosphorus and suspended-sediment models to account for systemic differences between groups of calibration loads. Because the distribution of residuals from preliminary models suggested possible bias stemming from the use of non-nested streamflow and water-quality data for estimating calibration loads, a binary term defining calibration loads generated using such non-nested rather than nested data was included in both models. A similar term was included in the suspended-sediment model to identify TSS rather than SSC, both of which were used in order to maximize the number of calibration stations. Standard SSC is the mass of all the sediment within a known volume of a water-sediment mixture collected directly from a waterbody (Guy, 1969). In contrast, TSS is the mass of suspended material within a subsample of a water-sediment mixture and tends to underestimate SSC, particularly at large values of SSC and for coarse sediment (Glysson and others, 2000; Gray and others, 2000). Glysson and others (2000) note, however, that TSS and SSC at individual monitoring stations could be related only through local paired observations.

Interpreting SPARROW Model Coefficients

Coefficients estimated for the SPARROW models provide insight into important properties and processes that control the manner in which water, sediment, and nutrients move through northeastern watersheds (Schwarz and others, 2006).

Coefficients corresponding to source terms have a physical interpretation that depends upon the form by which each source is expressed (Schwarz and others, 2006). Coefficients estimated for intensive source terms (with units of volume or mass per time) represent the average fraction of mass input from that source that reaches northeastern streams. For such source terms representing inputs directly to streams (such as from point sources), coefficients substantially different from 1.0 may therefore be indicative of inaccurate input data or problems with the model specification (Schwarz and others, 2006). In contrast, coefficients corresponding to extensive source terms (with units of area or length) represent the average annual yield to streams from such sources (Schwarz and others, 2006).

The land-to-water and aquatic decay coefficients represent the fate and transport of water, nutrients, and sediment in terrestrial uplands and in flowing and impounded streams (Schwarz and others, 2006). For land-to-water delivery terms, the sign of the estimated coefficient provides insight into how they act on the sources; delivery terms with positive coefficients enhance or exacerbate delivery to streams, whereas those with negative coefficients attenuate or mitigate delivery. The relative importance of these terms in each model can be interpreted from their absolute values. Specifically, when land-to-water terms are log-transformed (as in the models described herein), the coefficient estimates the percent change in load caused by a 1-percent increase in the land-to-water variable. The coefficients for the stream and impoundment decay terms, when multiplied by the values for those terms, represent the ratio between the amount of water, sediment, or nutrients entering a waterbody to that which is discharged from that waterbody. When aquatic decay terms are specified as time of travel, estimated coefficients can be interpreted as loss rates (Schwarz and others, 2006).

Coefficients corresponding to binary terms in the phosphorus and suspended-sediment models can be interpreted as fitted scaling factors for converting between two groups of calibration data. If the estimated coefficient is defined as C, this scaling factor is equivalent to the inverse of e^C.

Addressing Bias in the Model Calibration Owing to Nested Calibration Stations

Calibration stations in SPARROW models are often nested within the watersheds of other downstream calibration stations. In such cases, the model-estimated load at each upstream station is replaced during calibration with its measured load to eliminate propagation of errors down the stream network and to reduce the correlation across the error terms (Smith and others, 1997). The resulting downstream load is referred to as the “conditioned” load in model calibration, whereas the load completely estimated by the model is referred to as the “unconditioned” or estimated load. This use of conditioned loads reduces the potential influence of downstream stations on the coefficients in the SPARROW model but can result in an underestimation of the conditioned residuals compared to unconditioned residuals. During calibration, it is optimal for each monitoring station to have similar influence on model fit and coefficient estimates. Because heavily nested sites tend to have lower residual variance, however, these sites may be underrepresented in the SPARROW calibration process.

Potential bias associated with nested calibration stations was addressed using calibration weights representing the portion of the watershed for each calibration station that is downstream from any upstream calibration stations (the nested percent). The models were first calibrated with equal weights applied to all calibration stations, and the squared residuals from these models were regressed on the nested percent. The inverse of the predicted values from this regression then served as weights in the recalibration of the models, with greater weights placed on observations that are heavily nested. Spatial correlation among residuals of closely spaced (with 5 km) nested stations in the resulting models are insignificant for all four models.

Model Predictions

The calibrated models were used to predict streamflow and nutrient and suspended-sediment loads in northeastern streams. Coefficients from the weighted NLLS procedure were used to estimate the water, nitrogen, phosphorus, or suspended-sediment load in each stream reach, and uncertainty in those predictions was estimated through 200 iterations of parametric bootstrapping (Schwarz and others, 2006). Such predictions are reported herein as local (incremental) and accumulated source-specific and total loads in each reach as well as the fraction of such loads delivered to the downstream end of the NHDPlus stream network within tidal waters or at the Canadian border. Downstream terminal reaches in the stream network are well within tidal stretches of some streams, and fractions of loads delivered to those reaches may therefore not necessarily represent load delivery to the head of tide. Because the models were calibrated to long-term average or detrended (flow-normalized) measured instream loads, these predictions represent loads that would have occurred in watershed streams during 2012 under long-term average hydrologic and weather conditions, rather than, necessarily, the loads that actually occurred during that year. Because major goals of the modeling include predicting loads in unmonitored areas and understanding observed conditions in monitored streams, these predictions were adjusted to match measured loads at calibration stations, and source-specific loads were adjusted on the basis of estimated source shares (Schwarz and others, 2006). This adjustment also affects downstream accumulated loads but does not affect incremental loads, model calibration, or coefficient estimates. Any spatial inconsistencies in predictions stemming from such adjustments to different types of calibration data in the phosphorus or suspended-sediment models (see section “Conversions Between Different Types of Calibration Data”) are limited as the adjustment affects fewer than 4 percent of stream reaches in either model.

SPARROW Model of Streamflow

The streamflow model represents major sources of water to northeastern streams and summarizes landscape properties affecting the generation of streamflow from precipitation. Explanatory terms in the model explain more than 99 percent of the spatial variability in streamflow (load) at 741 calibration stations in the region and 84 percent of the variability in streamflow per unit area (average yield) (table 2; fig. 6). The estimated point-source coefficient in the model is very close to one (table 2), as would be expected given that point sources are specified in units equivalent to the dependent streamflow variable and do not interact with upland land-to-water terms. The distribution of residuals suggests no apparent spatial bias (fig. 7) or heteroscedasticity (fig. 6) that might preclude the use of the model to provide useful predictions of mean-annual streamflow in unmonitored areas.

Precipitation is the dominant source of streamflow in the Northeastern United States. Although effluent from wastewater treatment plants may supplement streamflow locally, natural runoff of surplus precipitation over evapotranspiration supplies the vast majority of flow in most streams (fig. 8). This surplus precipitation is generally greater in the Delaware River watershed and to the north than in central and western Pennsylvania and to the south, reflecting a similar spatial distribution of average annual precipitation (fig. 4*A*). Similarly, the mean-annual incremental yield of water from uplands to local streams in the Northeast (fig. 9) averages more than 600 millimeters per year (mm/yr) in the Delaware River watershed and to the north but only around 350 mm/yr in the Potomac, Rappahannock, and James River watersheds (fig. 8).

Streamflow generation reflects the delivery of precipitation from uplands to stream channels as well as the distribution of source precipitation. Within the Northeast, this upland delivery is greater in areas with cooler air temperatures, less soil moisture, and less EVI than elsewhere (table 2). The soil moisture term in the model likely represents water storage in upland landscapes; water loss to the atmosphere through evapotranspiration is likely greater in areas with warmer average air temperatures and greater EVI. Within the stream network, water also may be lost to diversions and to evaporation, particularly in impoundments (table 2). The spatial distribution of delivered yields to terminal reaches (fig. 10) is generally very similar to that of local incremental yields (fig. 9).

Table 2. Summary of calibration results for the Northeast SPARROW water model. Calibration incorporated adjustment for the effects of the amount of the upstream watershed that was included in watersheds of other calibration sites.

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; ft^3/s, cubic foot per second; EVI, enhanced-vegetative index; °C, degrees Celcius; m, meter; km, kilometer; RMSE, root mean square error; R^2, coefficient of determination; <, less than; Ln, natural logarithm]

Variable	Variable unit	Coefficient unit	Model coefficient value[a]	90-percent confidence interval for the model coefficient: Low	90-percent confidence interval for the model coefficient: High	Standard error of the model coefficient	*p*-value[b]	*t*-value	Variance inflation factor
Source									
Mean-annual precipitation minus actual evapotranspiration, 2000–14	ft^3/s	Fraction, dimensionless	1.24	1.18	1.30	0.0358	<0.0001	34.5	22.8
Wastewater point sources	ft^3/s	Fraction, dimensionless	0.998	0.653	1.34	0.210	<0.0001	4.8	1.1
Transfers from outside region	ft^3/s	Fraction, dimensionless	1						
Land-to-water delivery									
Ln(Mean-annual EVI, 2012)			–0.405	–0.515	–0.295	0.0668	<0.0001	–6.1	7.4
Ln(Mean-annual air temperature, 2000–14)	°C	$°C^{-1}$	–0.129	–0.167	–0.0920	0.0227	<0.0001	–5.7	1.4
Ln(Mean-annual soil moisture, 2000–14)	m^3	m^{-3}	–0.0314	–0.0459	–0.169	0.00880	0.0004	–3.6	12.1
Aquatic loss									
Evaporation from impoundments	Percent	Dimensionless	1.22	0.637	1.79	0.351	0.0003	3.5	2.1
Withdrawals for public supply	Percent	Dimensionless	0.0528	0.0237	0.0819	0.0177	0.0014	3.0	1.0
Diversions coded in network	ft^3/s	Fraction, dimensionless	1						
Spatial test	**Number**	**Correlation/ value**	***p*-value**						
Tight clusters—pairs of nested sites within 5 km	16	–0.303	0.2536						
Model summary statistic									
Conditioned RMSE[c] in natural logarithm units		0.1265							
Conditioned RMSE[c], percent in real space units[d]		12.7							
Unconditioned RMSE[e] in natural logarithm units		0.1206							
Unconditioned RMSE[e], percent in real space units[d]		12.1							
Mean exponentiated weighted error		1.007							
R^2		0.9952							
Yield R^2		0.8357							
Number of sites		741							

[a]Coefficients for tranfers from outside the region and diversions coded in the network were not estimated by the model but rather coded as boundary conditions.

[b]Listed *p*-values are one-sided for source and aquatic decay terms and two-sided for other terms.

[c]Conditioned RMSE: Root mean squared error of the difference between the natural logarithm of measured calibration loads and the natural logarithm of predicted accumulated loads that were reset to the measured loads at the calibration sites.

[d]RMSE in terms of percent in real space units was computed as $100 \times (\exp[RMSE^2]-1)^{0.5}$; RMSE in the equation is in natural logarithm units (Hoos and Roland, 2019).

[e]Unconditioned RMSE is similar to the conditioned RMSE except the predicted accumulated loads were not reset to the measured loads at the calibration sites.

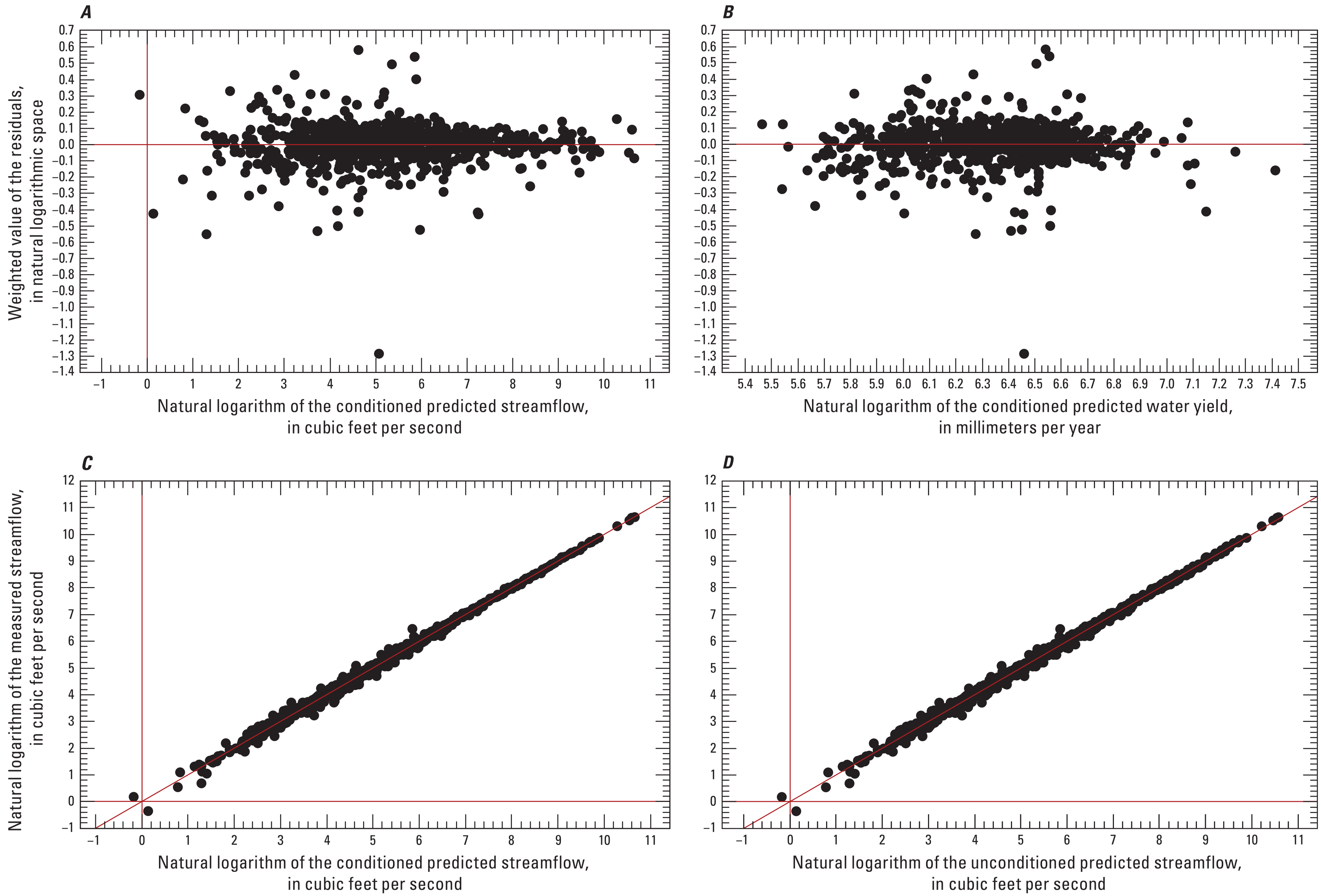

Figure 6. Diagnostic plots for the fit of the Northeast SPARROW (SPAtially Referenced Regression On Watershed attributes) streamflow model. *A*, weighted residuals versus conditioned predicted streamflows, *B*, weighted residuals versus conditioned predicted water yields, *C*, measured streamflows versus conditioned predicted streamflows, and *D*, measured streamflows versus unconditioned predicted streamflows. Plotted residuals are unconditioned. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

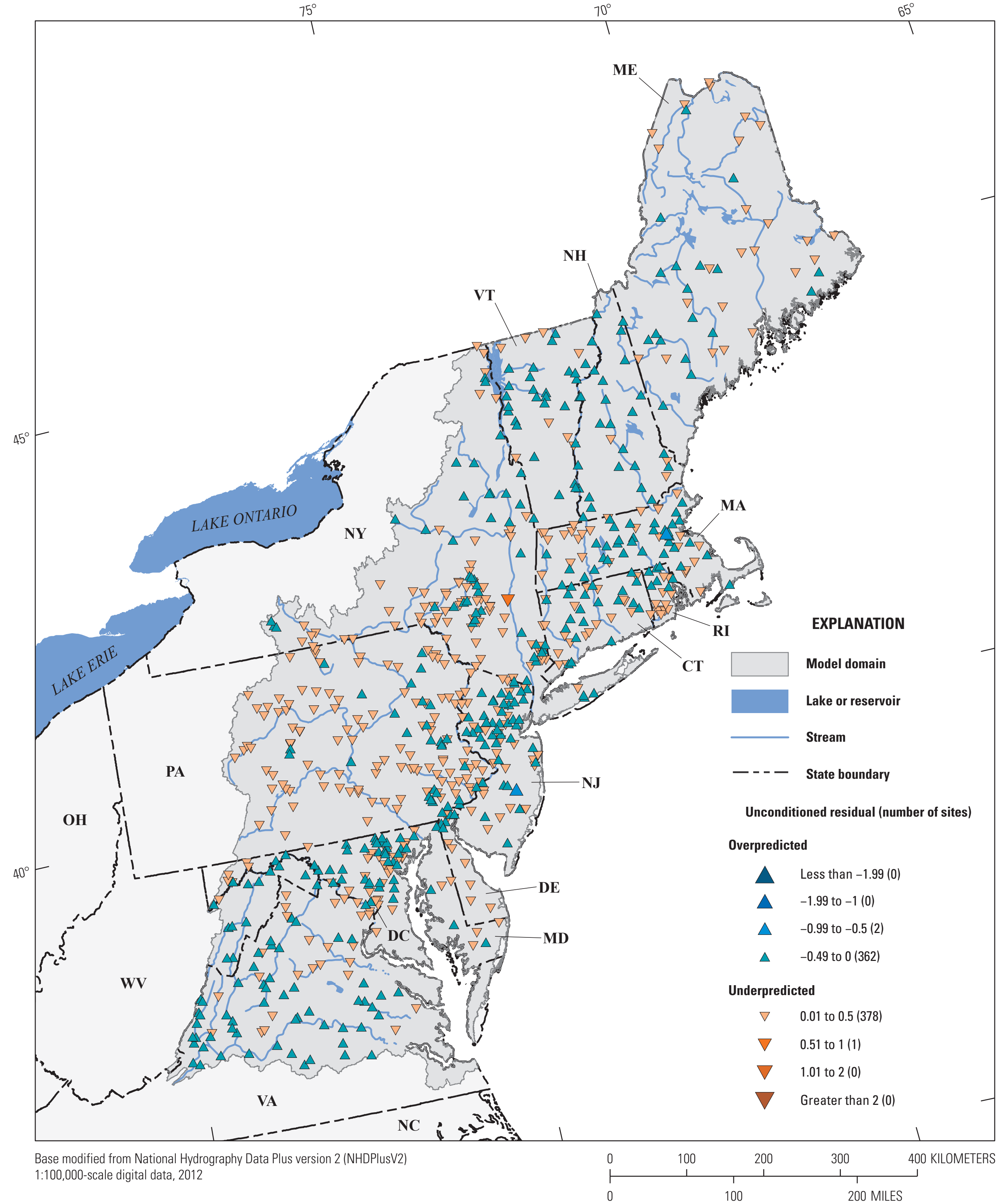

Figure 7. Spatial distribution of unconditioned residuals from the northeast streamflow model. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

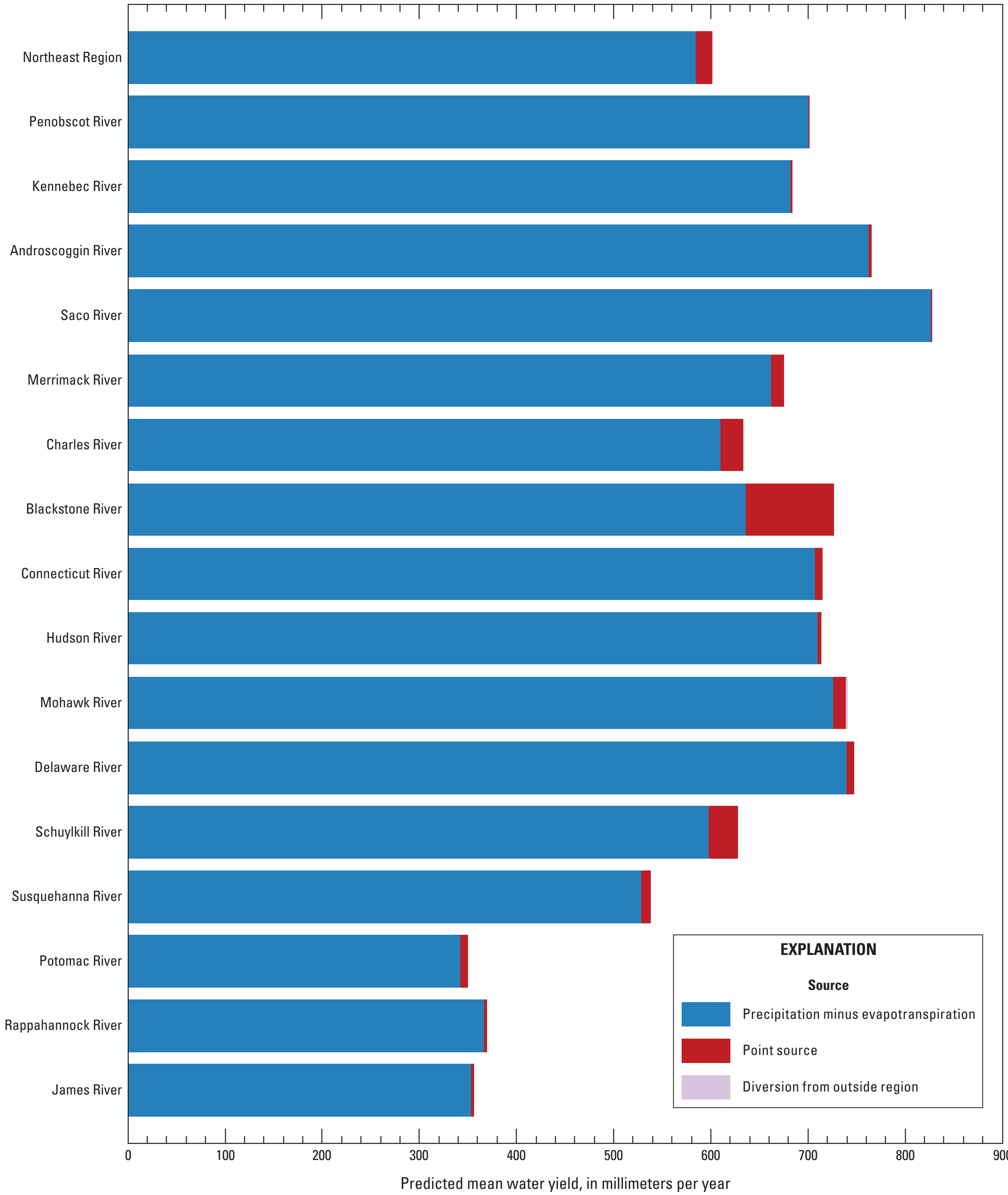

Figure 8. Predicted mean-annual water yield, by source, from the Northeastern United Sates and major northeastern watersheds.

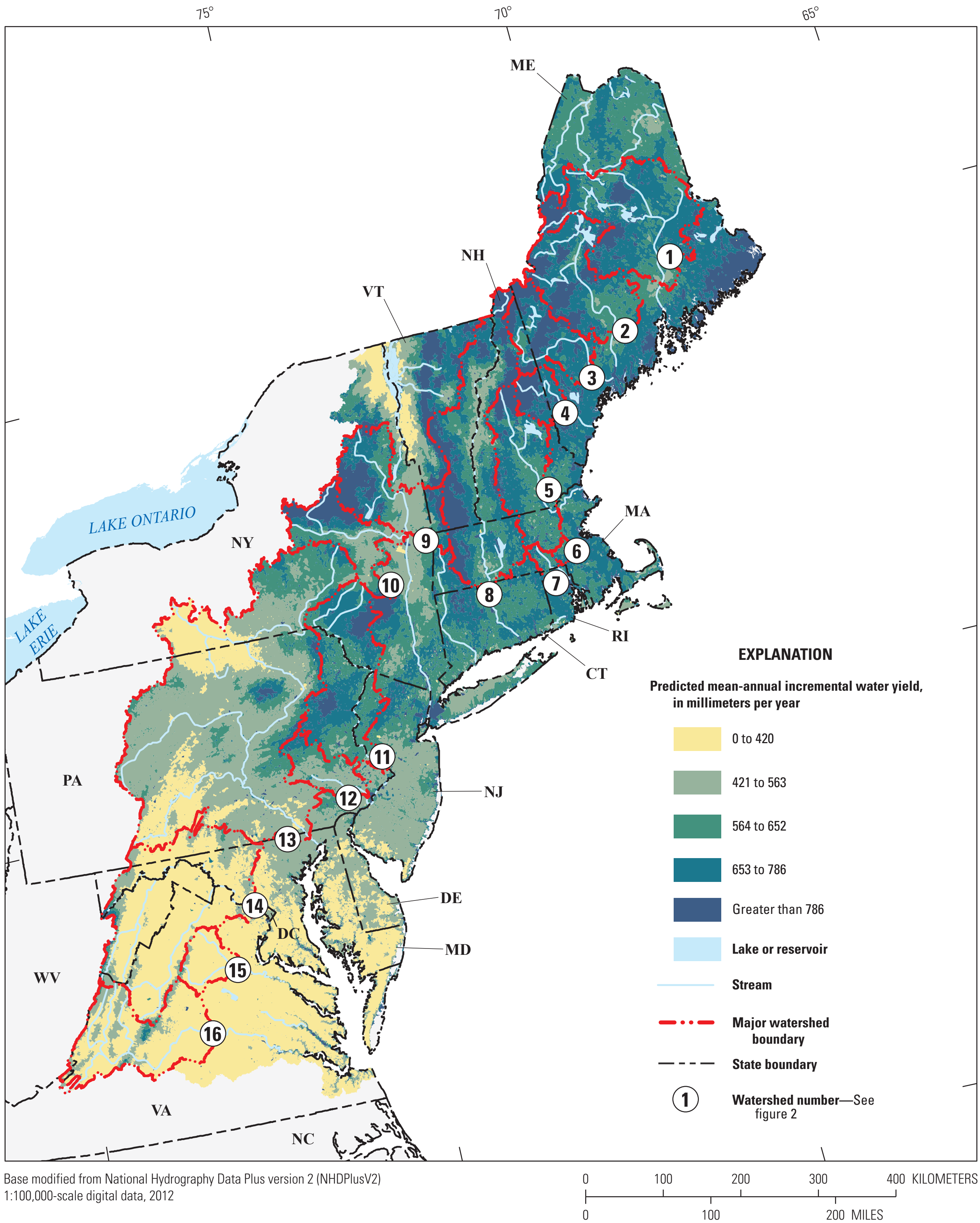

Figure 9. Predicted mean-annual incremental yield of water to streams in the Northeastern United States, 2012.

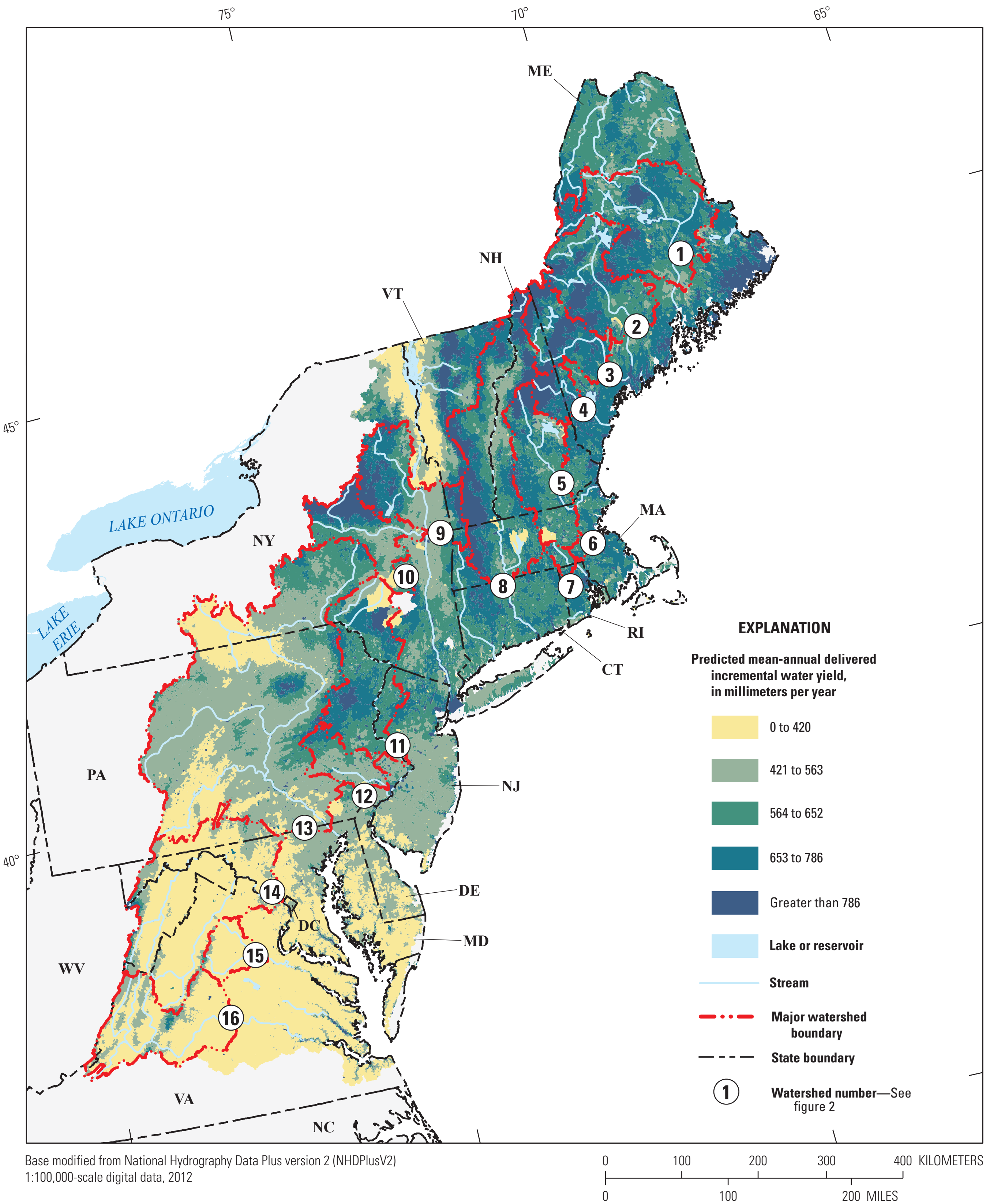

Figure 10. Predicted mean-annual delivered incremental yield of water to estuaries in the Northeastern United States, 2012.

SPARROW Model of Total Nitrogen

The nitrogen model quantifies multiple sources of, and effects of numerous natural and human landscape properties on, nitrogen load in northeastern streams. Explanatory terms in the model explain 97 and 81 percent of the spatial variability in the annual load and average yield, respectively, of nitrogen at 383 calibrations stations on northeastern streams during 2012 (table 3). The distribution of residuals suggests no apparent heteroscedasticity (fig. 11) or spatial bias (fig. 12) that might preclude the use of the model for quantifying the sources, fate, and transport of nitrogen to northeastern streams or for estimating nitrogen load in unsampled areas. Calibration data are relatively scarce in northern New England (particularly in New Hampshire and Maine), and the representativeness of the model estimates and predictions for that area is consequently uncertain. Predictions from the model should still be useful and informative for that area, however, particularly where local land use, nitrogen sources, and other natural and human landscape conditions are similar to those in other areas of the Northeast that are better represented by available calibration data.

Agriculture is a substantial source of nitrogen to streams in the Northeast, particularly in the mid-Atlantic region (fig. 13). Model-estimated coefficients suggest that approximately 10 percent (on average) of nitrogen applications to agricultural areas in the form of fertilizer or manure reaches northeastern streams and that areas planted in nitrogen-fixing crops yield an average of 2,730 kg km^{-2} of nitrogen, annually, to surface waters (table 3). Previous estimates of the delivery of nitrogen from manure to northeastern streams are similar, whereas such estimates for fertilizer are generally higher (Preston and Brakebill, 1999; Ator and others, 2011; Moore and others, 2011; Hoos and others, 2013) but may represent some nitrogen from direct fixation by crops in models where such inputs are not explicitly specified. Previous estimates of average nitrogen yields from cropland or cultivated land, in general, vary from less than 1,000 kg km^{-2} in New England (Moore and others, 2004) to as much as 4,500 kg km^{-2} in the Chesapeake Bay watershed (Shenk and Linker, 2013) but exceed 10,000 kg km^{-2} in Chesapeake Bay tributaries draining carbonate settings (Ator and others, 2019). Shenk and Linker (2013) estimate average annual yields of 1,200 kg km^{-2} and 1,400 kg km^{-2} to Chesapeake Bay tributaries from pasture and hayland, respectively.

Urban and atmospheric sources contribute substantial nitrogen to streams throughout the Northeast and most of the nitrogen to streams in New England (fig. 13). Wastewater point sources contribute nitrogen directly to streams; the model-estimated coefficient of less than 0.6 (table 3) suggests that such inputs in the model may be overestimated. Additionally, approximately one-half of nitrogen effluent from septic systems reaches northeastern streams; other urban nonpoint sources contribute 549 kg km^{-2} of nitrogen annually, on average, to surface waters (table 3). Previous estimates of the average annual nitrogen yield from all nonpoint urban sources to streams in the region generally vary from about 900 to 1,700 kg km^{-2} (Preston and Brakebill, 1999; Moore and others, 2004; Ator and others, 2011; Moore and others, 2011; Hoos and others, 2013; Ator and others, 2019) suggesting that septic effluent may contribute substantially to that total. Approximately 25 percent (on average) of nitrogen deposited to uplands from atmospheric sources reaches streams (table 3). Moore and others (2011) and Ator and others (2011) estimated that a similar proportion of nitrogen from wet atmospheric deposition reaches northeastern streams, although Moore and others (2004) estimated that New England streams receive 37 percent of the total nitrogen (on average) that is deposited from the atmosphere to contributing uplands. Hoos and others (2013) estimated that 14 percent of nitrogen from wet and dry atmospheric deposition reaches streams of the Eastern United States.

Nitrogen fate and transport from upland application areas to local streams and downstream receiving waters is affected by a variety of natural and human influences. Nitrogen transport to streams is greater in areas of greater average runoff and in carbonate settings than elsewhere (table 3). Greater average runoff likely reflects greater opportunity for nitrogen to be transported to surface waters, and the importance of carbonate geology likely reflects the relatively efficient and conservative transport of nitrogen to streams (often as nitrate through groundwater) reported previously in carbonate areas of the Northeast (Lizarraga, 1997; Miller and others, 1997; Ator and others, 2011). The reduced nitrogen delivery in areas of forest or wetland, greater soil depths, and warmer temperatures (table 3) may reflect conditions particularly conducive to denitrification, the largest upland sink for nitrogen in the Northeast (Van Breemen and others, 2002; Ator and García, 2016). Nitrogen losses from upland agricultural areas to streams are negatively correlated with the use of agricultural cover crops but positively correlated with no-till or conservation tillage practices (table 3). Cover crops may substantially reduce nitrogen losses from agriculture to groundwater (Staver and Brinsfield, 1998), but no-till practices may promote nitrate flux to the water table through macropores (Tan and others, 1998; Catt and others, 2000; Golmohammadi and others, 2016; Daryanto and others, 2017). Once in surface waters, nitrogen loads are substantially reduced in flowing and impounded waters (table 3). The model-estimated loss rate of nitrogen to denitrification, sedimentation, or other aquatic processes in small flowing streams is greater than in larger streams (table 3), as has been reported previously in the Chesapeake Bay watershed (Preston and Brakebill, 1999; Ator and others, 2011) and the wider conterminous United States (Smith and others, 1997). The rate of net nitrogen loss in impoundments (table 3) is similar to previous estimates for the Chesapeake Bay watershed (Ator and others, 2011).

The spatial distribution of nitrogen contributions to northeastern streams and downstream receiving waters reflects the distribution of sources and other relevant landscape conditions. Incremental (fig. 14) and delivered (fig. 15) yields are generally greatest in areas of the most intensive agriculture or

Table 3. Summary of calibration results for the Northeast SPARROW total nitrogen model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; kg, kilogram; yr, year; km, kilometer; °C, degrees Celcius; mm, millimeter; m, meter; ft^3/s, cubic foot per second; RMSE, root mean square error; R^2, coefficient of determination; <, less than; Ln, natural logarithm; GT, greater than; LE, less than or equal to]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Source									
Wastewater point sources	$kg\ yr^{-1}$	Fraction, dimensionless	0.589	0.411	0.766	0.108	<0.0001	5.5	1.2
Septic system effluent	$kg\ yr^{-1}$	Fraction, dimensionless	0.509	0.316	0.702	0.117	<0.0001	4.4	3.9
Fertilizer applications	$kg\ yr^{-1}$	Fraction, dimensionless	0.105	0.0454	0.164	0.0360	0.0019	2.9	10.0
Crops that fix nitrogen	km^{-2}	$kg\ km^{-2}\ yr^{-1}$	2,730	154	5,310	1,560	0.0407	1.7	9.9
Manure applications	$kg\ yr^{-1}$	Fraction, dimensionless	0.0940	0.0307	0.157	0.0384	0.0074	2.4	7.2
Atmospheric deposition	$kg\ yr^{-1}$	Fraction, dimensionless	0.244	0.191	0.297	0.0320	<0.0001	7.6	6.3
Urban area	km^{-2}	$kg\ km^{-2}\ yr^{-1}$	549	286	812	159	0.0003	3.4	7.5
Land-to-water delivery									
Ln(Carbonate rock)	Percent	Dimensionless	0.0472	0.00791	0.0864	0.0238	0.0483	2.0	2.0
Ln(Forest or wetland)	Percent	Dimensionless	–0.276	–0.371	–0.180	0.0581	<0.0001	–4.7	4.2
Ln(Mean-annual air temperature, 2000–14)	°C	$°C^{-1}$	–0.868	–1.18	–0.553	0.191	<0.0001	–4.6	4.5
Ln(Cover crops)	Percent of agriculture	Dimensionless	–0.167	–0.329	–0.00467	0.0984	0.0906	–1.7	37.8
Ln(Mean soil depth)	Inches	$Inches^{-1}$	–0.205	–0.398	–0.0110	0.117	0.0822	–1.7	2.5
Ln(Conservation tillage or no-till)	Percent of agriculture	Dimensionless	0.210	0.000411	0.420	0.127	0.0993	1.7	81.1
Ln(Mean-annual runoff)	mm	mm^{-1}	0.336	0.0656	0.606	0.164	0.0412	2.0	2.5
Aquatic loss									
Travel time in streams with mean-annual discharge LE 5 ft^3/s	Days	$Days^{-1}$	1.31	–0.258	2.88	0.952	0.0845	1.4	5.0
Travel time in streams with mean-annual discharge GT 5 ft^3/s and LE 50 ft^3/s	Days	$Days^{-1}$	0.154	–0.246	0.555	0.243	0.2627	0.6	5.5

Table 3. Summary of calibration results for the Northeast SPARROW total nitrogen model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.—Continued

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; kg, kilogram; yr, year; km, kilometer; °C, degrees Celcius; mm, millimeter; m, meter; ft^3/s, cubic foot per second; RMSE, root mean square error; R^2, coefficient of determination; <, less than; Ln, natural logarithm; GT, greater than; LE, less than or equal to]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Reservoir inverse hydraulic load	$yr\ m^{-1}$	$m\ yr^{-1}$	6.60	3.82	9.38	1.69	<0.0001	3.9	1.5
Spatial test	**Number**	**Correlation / value**	***p*-value**						
Tight clusters—pairs of nested sites within 5 km	17	0.0057	0.9828						
		Model summary statistics							
Conditioned RMSE[b] in natural logarithm units		0.3482							
Conditioned RMSE[b], percent in real space units[c]		35.9							
Unconditioned RMSE[d] in natural logarithm units		0.3680							
Unconditioned RMSE[d], percent in real space units[c]		38.1							
Mean exponentiated weighted error		1.071							
R^2		0.9718							
Yield R^2		0.8094							
Number of sites		383							

[a]Listed *p*-values are one-sided for source and aquatic decay terms and two-sided for other terms.

[b]Conditioned RMSE: Root mean squared error of the difference between the natural logarithm of measured calibration loads and the natural logarithm of predicted accumulated loads that were reset to the measured loads at the calibration sites.

[c]RMSE in terms of percent in real space units was computed as $100 \times (\exp[RMSE^2]-1)^{0.5}$; RMSE in the equation is in natural logarithm units (Hoos and Roland, 2019).

[d]Unconditioned RMSE is similar to the conditioned RMSE except the predicted accumulated loads were not reset to the measured loads at the calibration sites.

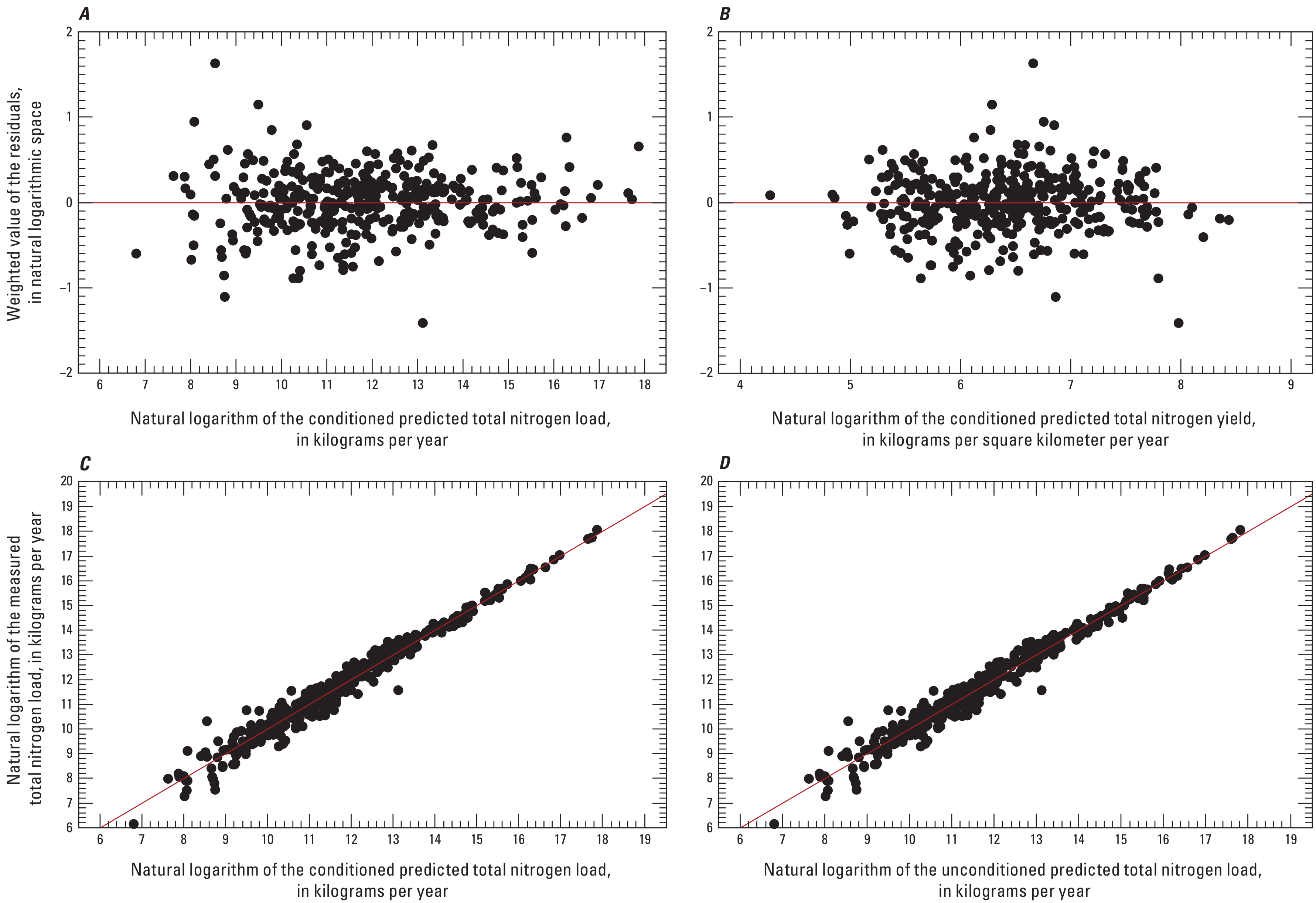

Figure 11. Diagnostic plots for the fit of the Northeast SPARROW nitrogen model. *A*, weighted residuals versus conditioned predicted loads, *B*, weighted residuals versus conditioned predicted yields, *C*, measured loads versus conditioned predicted loads, and *D*, measured loads versus unconditioned predicted loads. Plotted residuals are unconditioned. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

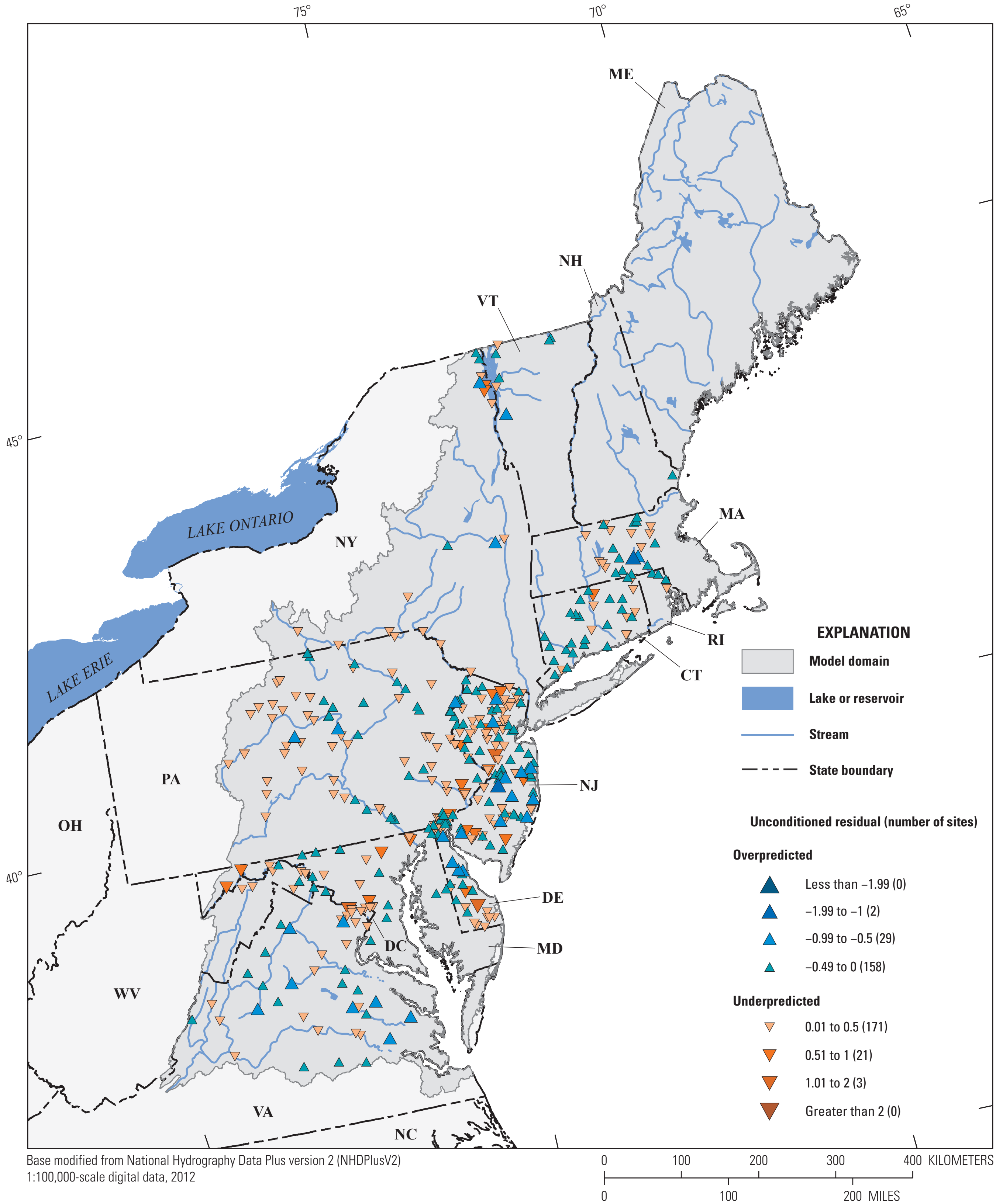

Figure 12. Spatial distribution of unconditioned residuals from the Northeast SPARROW nitrogen model. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

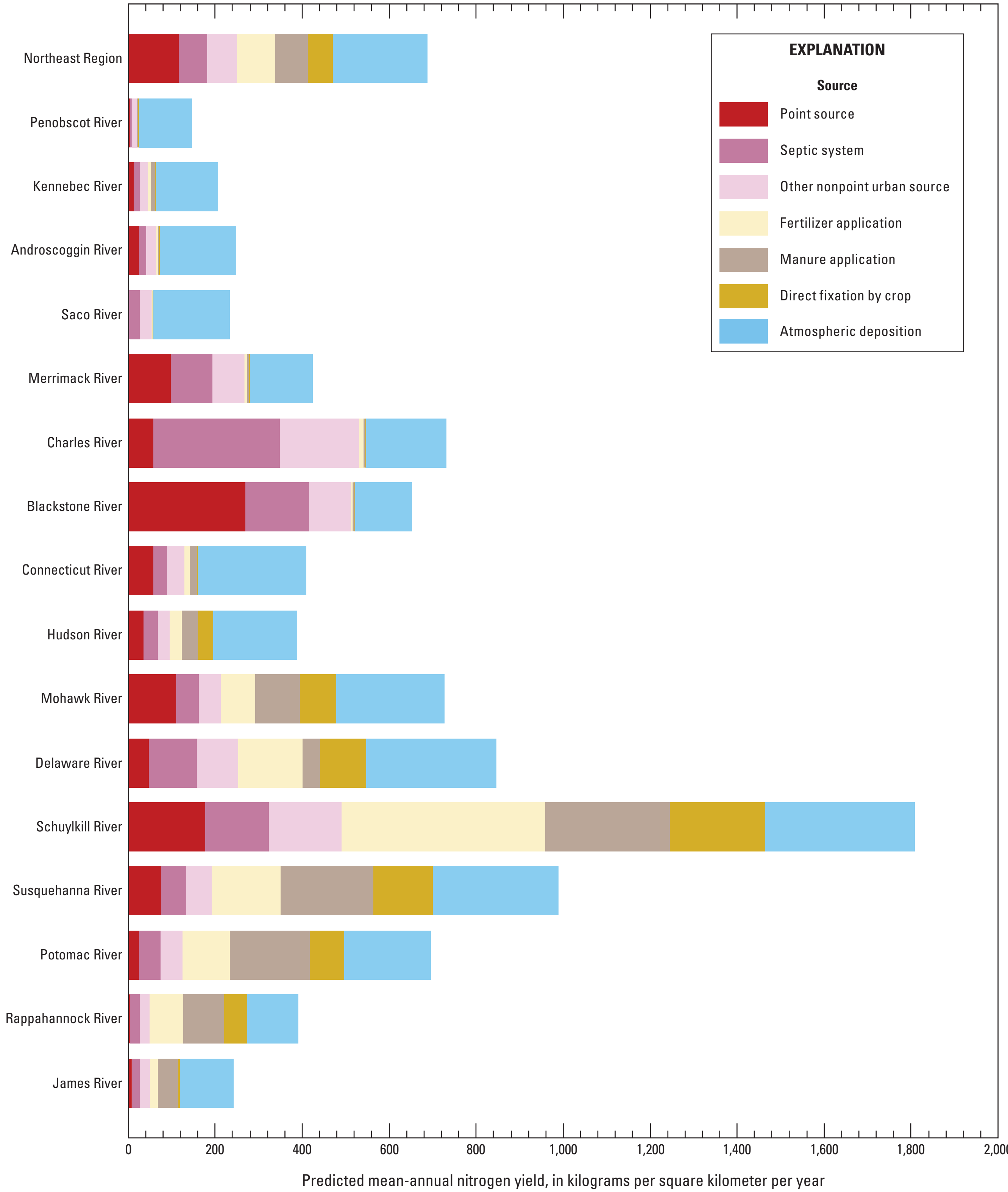

Figure 13. Predicted mean-annual nitrogen yield, by source, from the Northeastern United Sates and major northeastern watersheds.

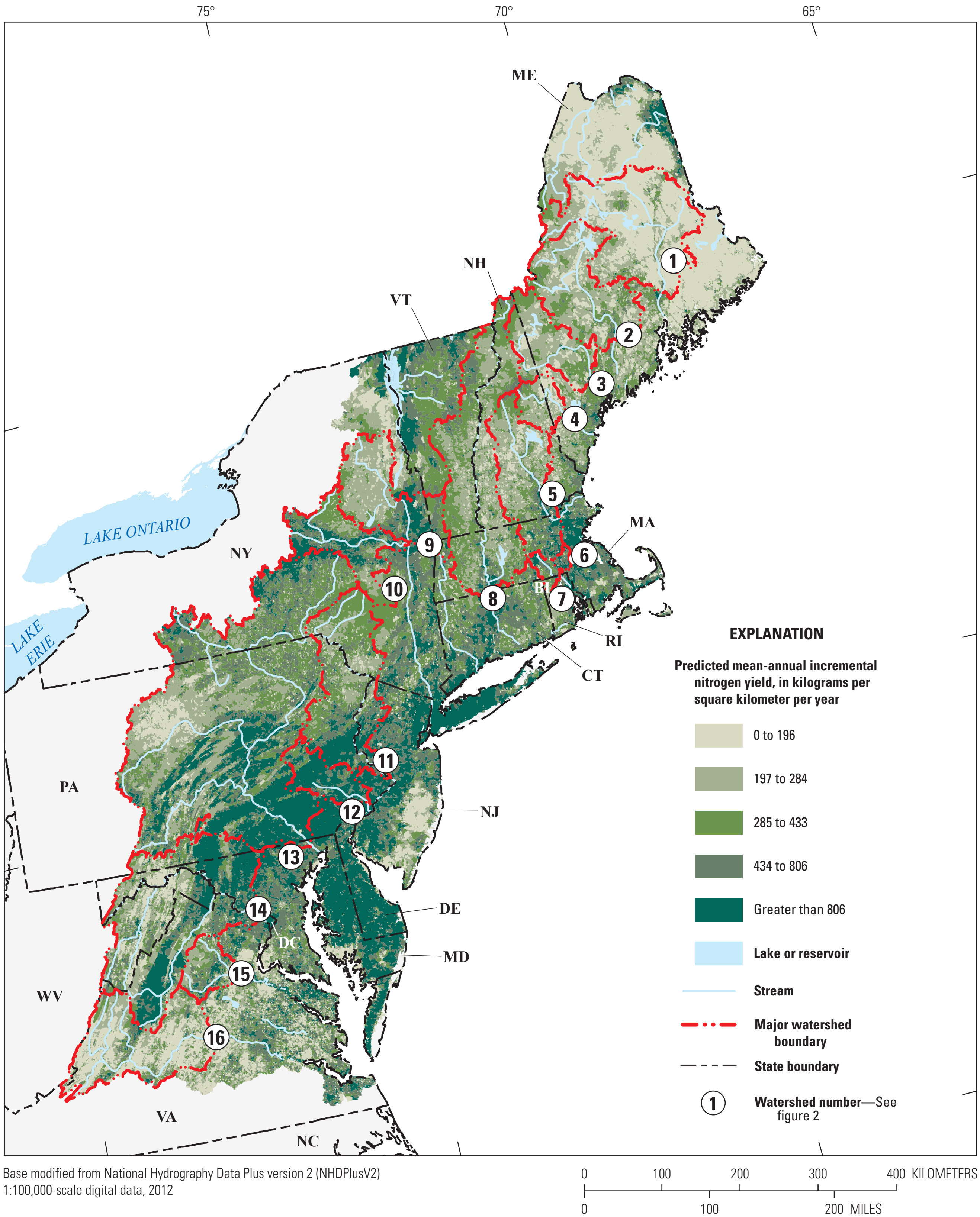

Figure 14. Predicted mean-annual incremental yield of nitrogen to streams in the Northeastern United States, 2012.

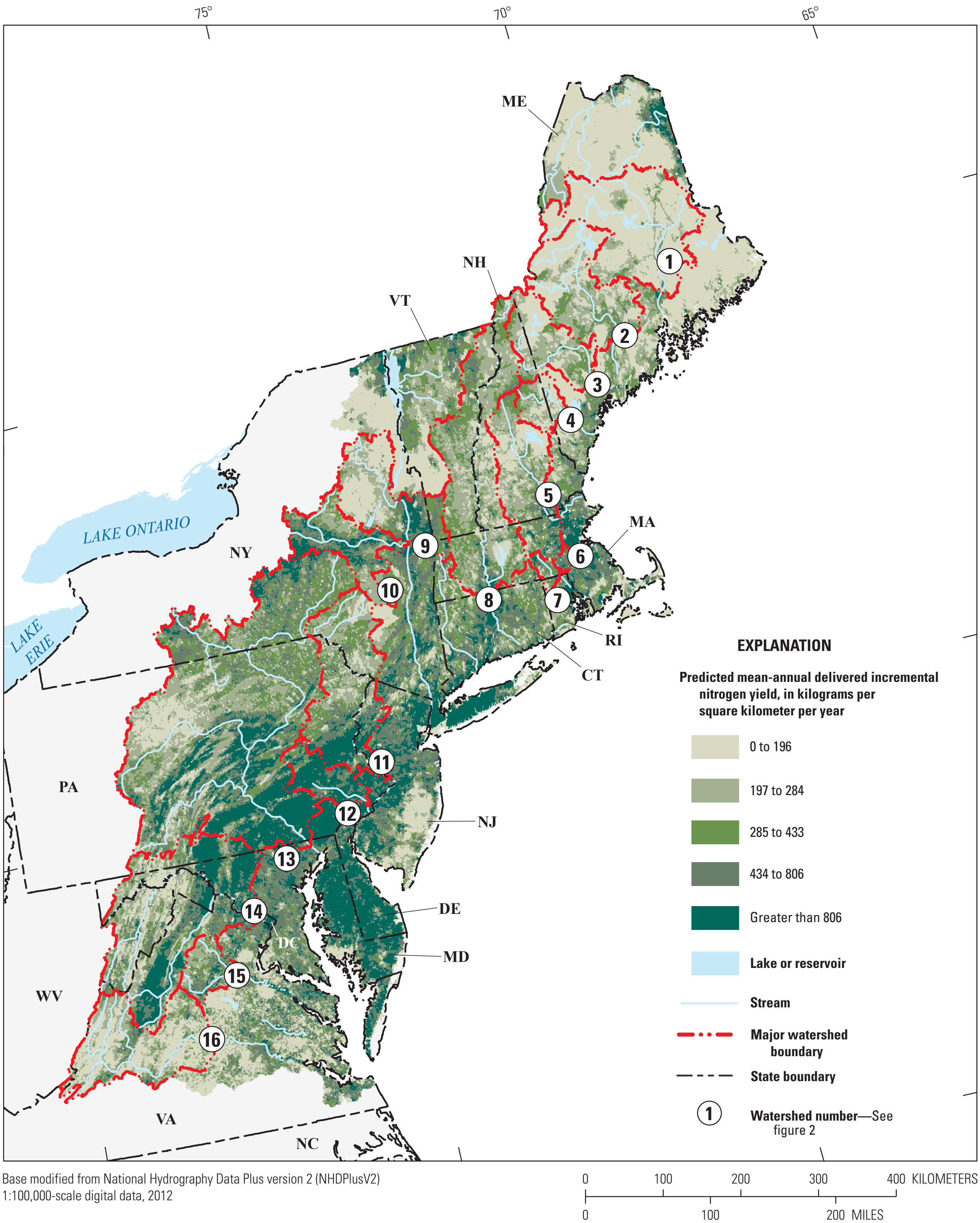

Figure 15. Predicted mean-annual delivered incremental yield of nitrogen to streams in the Northeastern United States, 2012.

urban development (fig. 3), particularly where underlain by carbonate geology (fig. 2). Such areas include intensely cultivated and densely populated parts of the mid-Atlantic region, the Hudson, Connecticut, and Mohawk River valleys, and eastern Massachusetts (fig. 14) where average yields even over some major river basins exceed 600 kg km^{-2} (fig. 13). Because many of these areas are close to tidal waters, they can be particularly important to coastal water quality. Opportunities for aquatic losses from such areas are limited by relatively short traveltimes, and delivered yields to downstream receiving waters (fig. 15) are often similar to incremental yields to local streams (fig. 14). Smaller average yields in the James and Rappahannock Rivers in Virginia and in many of the New England streams (figs. 13, 14) reflect the mostly forested land cover (fig. 3) and consequent lesser nitrogen sources. Atmospheric deposition provides most of the nitrogen inputs to many of these watersheds (fig. 13). Delivered nitrogen yields to coastal waters are particularly low (< 200 kg km^{-2}) from many of these areas (fig. 15) where sources are limited and relatively long traveltimes within the stream network provide opportunities for substantial aquatic losses.

SPARROW Model of Total Phosphorus

The phosphorus SPARROW model was specified and calibrated to represent the major sources and landscape factors affecting phosphorus loads within the Northeastern United States. Explanatory terms representing phosphorus sources and upland and aquatic fate and transport explain 93 percent of the spatial variability in mean-annual phosphorus load and 60 percent of the spatial variability in phosphorus yields at 258 calibration stations on northeastern streams (table 4). The distribution of residuals (figs. 16, 17) suggests the model is well suited for quantifying phosphorus sources and estimating phosphorus loads in unmonitored areas. As with the nitrogen model, however, the representativeness of the model for northern New England is uncertain owing to the paucity of available calibration data for that area (fig. 17). The binary term adjusts the model for any bias stemming from the use of non-nested streamflow and water-quality stations in developing calibration data.

More than one-half of the phosphorus reaching terminal reaches from the Northeastern United States is contributed by wastewater point sources or urban nonpoint sources (fig. 18). The estimated wastewater coefficient close to one (table 4) suggests that phosphorus point-source effluent in the model is well representative of true inputs. Additionally, the model estimates that urban nonpoint sources contribute about 48 kg km^{-2} of phosphorus, annually, on average, to northeastern streams (table 4). Moore and others (2011) and Hoos and others (2013) estimated average annual phosphorus yields to northeastern streams from urban nonpoint sources during 2002 to be 106 kg km^{-2} and 58 kg km^{-2}; other previous such estimates for parts of the area include 39 kg km^{-2} for New England (Moore and others, 2004) and between 49 and 104 kg km^{-2} for the Chesapeake Bay watershed (Ator and others, 2011; Ator and others, 2019). To construct a model for the Chesapeake Bay watershed, Shenk and Linker (2013) used a literature review to develop calibration targets representing annual phosphorus yields to streams from uplands and small stream channels of 70 kg km^{-2}, 240 kg km^{-2}, and 780 kg km^{-2} for pervious developed areas, impervious developed areas, and construction, respectively.

Northeastern streams receive phosphorus from agricultural and natural mineral sources as well as urban sources (fig. 18). Model-estimated coefficients suggest that approximately 12 percent and 9 percent, on average, of upland phosphorus applications of fertilizer and manure, respectively, reach streams in the Northeast (table 4). Previous such estimates for parts of the study area vary from about 3 percent to as high as 23 percent (Ator and others, 2011; Moore and others, 2011; Hoos and others, 2013). Additionally, mineral sources in igneous, metamorphic, and clastic sedimentary rocks contribute on average 11 kg km^{-2}, annually, of phosphorus to northeastern streams. Ator and others (2011) similarly estimated average annual yields of 8.5 kg km^{-2} and 6.8 kg km^{-2} of phosphorus to Chesapeake Bay tributaries from siliciclastic and crystalline rocks, respectively, which are similar to prior estimates from natural forested areas underlain by similar rocks (Dillon and Kirchner, 1975; Likens and others, 1977). Other previous estimates of average annual phosphorus yields to streams from forested areas or attributed to mineral erosion include 13.4 kg km^{-2} for New England (Moore and others, 2004), 19.8 kg km^{-2} for the Chesapeake Bay watershed (Ator and others, 2019), and 11.4 kg km^{-2} for the entire Northeast (Moore and others, 2011).

Phosphorus transport from upland source areas into and through the stream network is affected by soil properties and agricultural management practices and subject to long-term storage in stream impoundments (table 4). Land-to-water and aquatic decay terms significant to phosphorus fate and transport in the model reflect the relatively insoluble nature of most phosphorus compounds and the consequent importance of particulate-phase transport to and within surface waters. Phosphorus load attributable to natural mineral erosion is greater in areas with greater phosphorus concentrations in soils and, presumably, underlying parent rocks (table 4). Phosphorus transport from uplands is also greater in areas with more erodible soils and in agricultural areas with fewer no-till or conservation tillage practices (table 4), which are typically employed to reduce soil erosion (Staver and Brinsfield, 2001). Reductions of instream phosphorus loads owing to sedimentation and storage in lakes, reservoirs, and other stream impoundments (table 4) have been well documented throughout the Northeastern United States (Moore and others, 2004; Ator and others, 2011; Moore and others, 2011) and elsewhere (Smith and others, 1997; García and others, 2011).

The spatial variability of phosphorus yields from uplands to streams (fig. 19) and downstream receiving waters (fig. 20) in the Northeastern United States is similar to that of nitrogen

Table 4. Summary of calibration results for the Northeast SPARROW total phosphorus model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; kg, kilogram; yr, year; km, kilometer; m, meter; mg, milligram; RMSE, root mean square error; R^2, coefficient of determination; <, less than; Ln, natural logarithm]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Source									
Wastewater point sources	kg yr^{-1}	Fraction, dimensionless	0.786	0.516	1.06	0.164	<0.0001	4.8	1.1
Fertilizer applications	kg yr^{-1}	Fraction, dimensionless	0.122	0.0468	0.198	0.0458	0.0040	2.7	3.0
Manure applications	kg yr^{-1}	Fraction, dimensionless	0.0884	0.0438	0.133	0.0270	0.0006	3.3	2.0
Urban area	km^{-2}	kg km^{-2} yr^{-1}	48.1	31.5	64.6	10.0	<0.0001	4.8	2.2
Area underlain by unconsolidated sediments or igneous, metamorphic or clastic sedimentary rocks	km^{-2}	kg km^{-2} yr^{-1}	11.0	8.02	14.1	1.83	<0.0001	6.0	2.4
Land-to-water delivery									
Ln(Conservation tillage or no-till)	Percent of agriculture	Dimensionless	–0.386	–0.495	–0.278	0.0660	<0.0001	–5.9	2.6
Ln(Soil erodibility)	Dimensionless	Dimensionless	1.49	0.939	2.03	0.331	<0.0001	4.5	2.0
Ln(Soil phosphorus)	mg kg^{-1}	kg mg^{-1}	0.484	0.0597	0.909	0.257	0.0609	1.9	1.2
Aquatic loss									
Reservoir inverse hydraulic load (year/m)	yr m^{-1}	m yr^{-1}	9.84	2.21	17.5	4.62	0.0171	2.1	1.5

Table 4. Summary of calibration results for the Northeast SPARROW total phosphorus model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.—Continued

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; kg, kilogram; yr, year; km, kilometer; m, meter; mg, milligram; RMSE, root mean square error; R^2, coefficient of determination; <, less than; Ln, natural logarithm]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Other									
Binary (0 if water-quality and streamflow stations are nested, 1 if otherwise)[b]			–0.311[b]	–0.478	–0.145	0.101	0.0022	–3.1	1.4
Spatial test	**Number**	**Correlation / value**	***p*-value**						
Tight clusters—pairs of nested sites within 5 km	3	–0.0844	0.9462						
Model summary statistics									
Conditioned RMSE[c] in natural logarithm units		0.6151							
Conditioned RMSE[c], percent in real space units[d]		67.8							
Unconditioned RMSE[e] in natural logarithm units		0.6201							
Unconditioned RMSE[e], percent in real space units[d]		68.5							
Mean exponentiated weighted error		1.250							
R^2		0.9276							
Yield R^2		0.5994							
Number of sites		258							

[a]Listed *p*-values are one-sided for source and aquatic decay terms and two-sided for other terms.

[b]This coefficient corresponds to a conversion factor between loads estimated from non-nested (NON) and nested (NES) flow and water-quality stations of NES = 1.4 * NON.

[c]Conditioned RMSE: Root mean squared error of the difference between the natural log of measured calibration loads and the natural logarithm of predicted accumulated loads that were reset to the measured loads at the calibration sites.

[d]RMSE in terms of percent in real space units was computed as $100 \times (\exp[\mathrm{RMSE}^2]-1)^{0.5}$; RMSE in the equation is in and the natural logarithm units (Hoos and Roland, 2019).

[e]Unconditioned RMSE is similar to the conditioned RMSE except the predicted accumulated loads were not reset to the measured loads at the calibration sites.

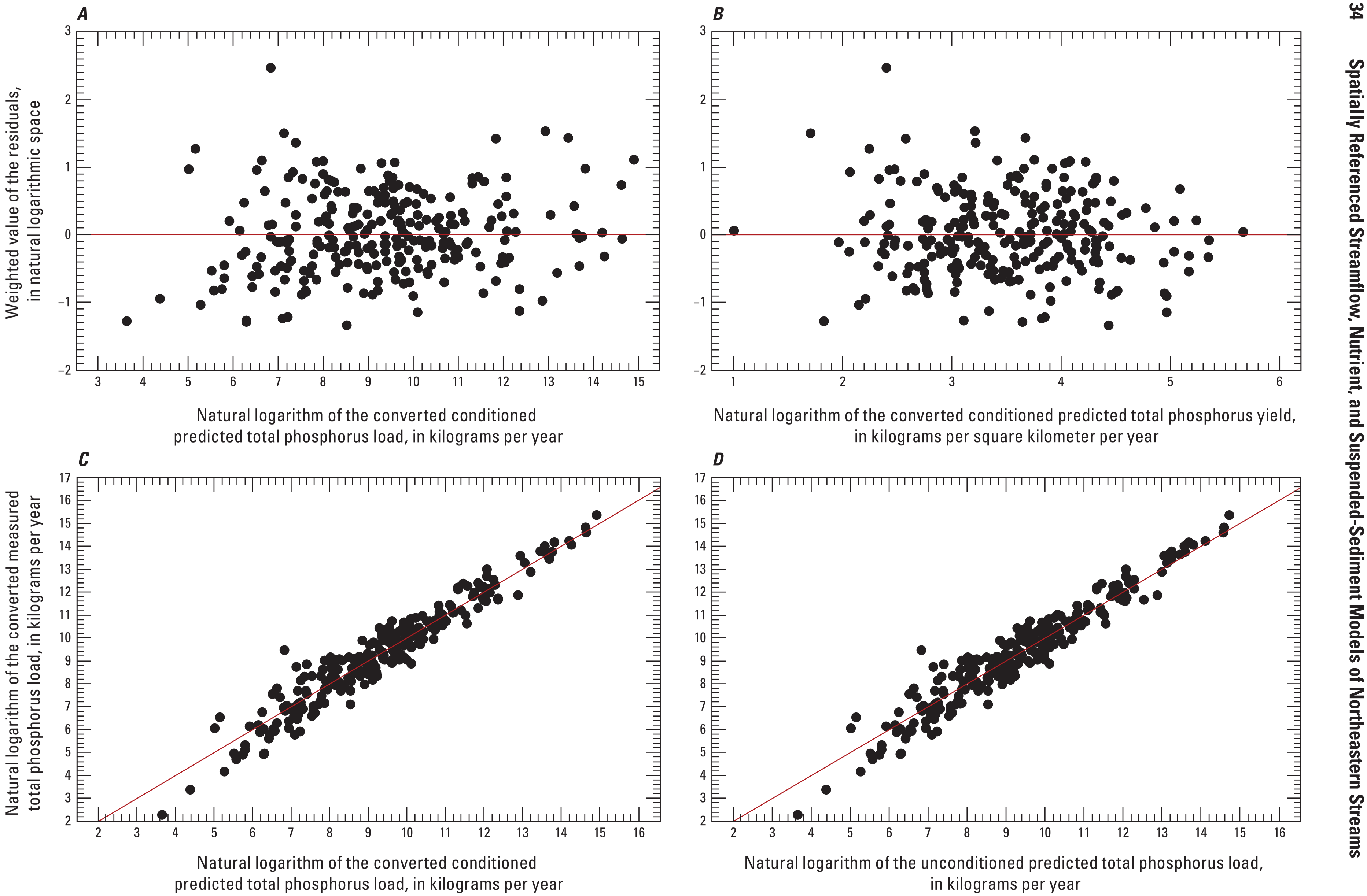

Figure 16. Diagnostic plots for the fit of the Northeast SPARROW phosphorus model. *A*, weighted residuals versus converted conditioned predicted loads, *B*, weighted residuals versus converted conditioned predicted yields, *C*, converted measured loads versus converted conditioned predicted loads, and *D*, converted measured loads versus unconditioned predicted loads. Plotted residuals are unconditioned. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

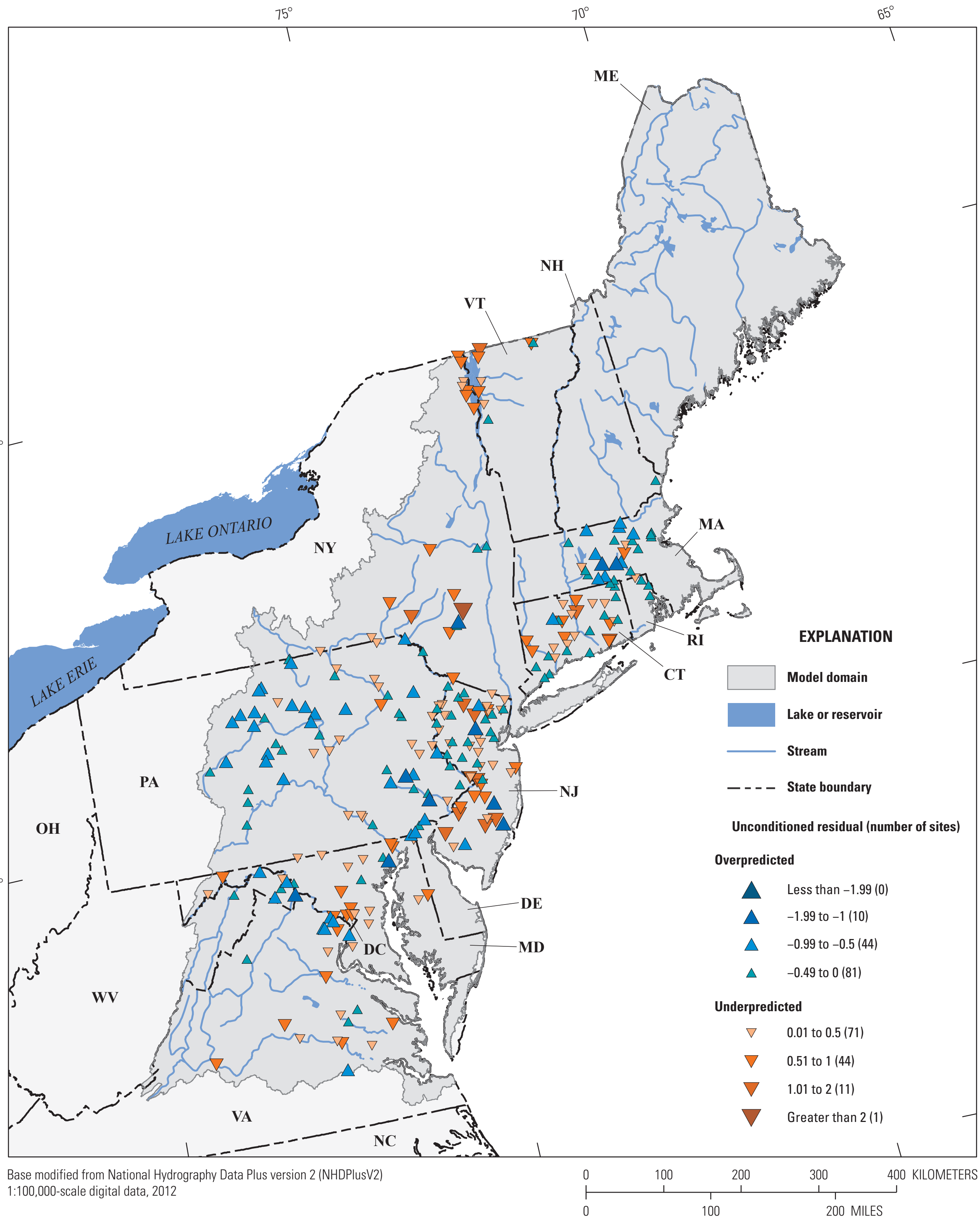

Figure 17. Spatial distribution of unconditioned residuals from the Northeast SPARROW phosphorus model. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

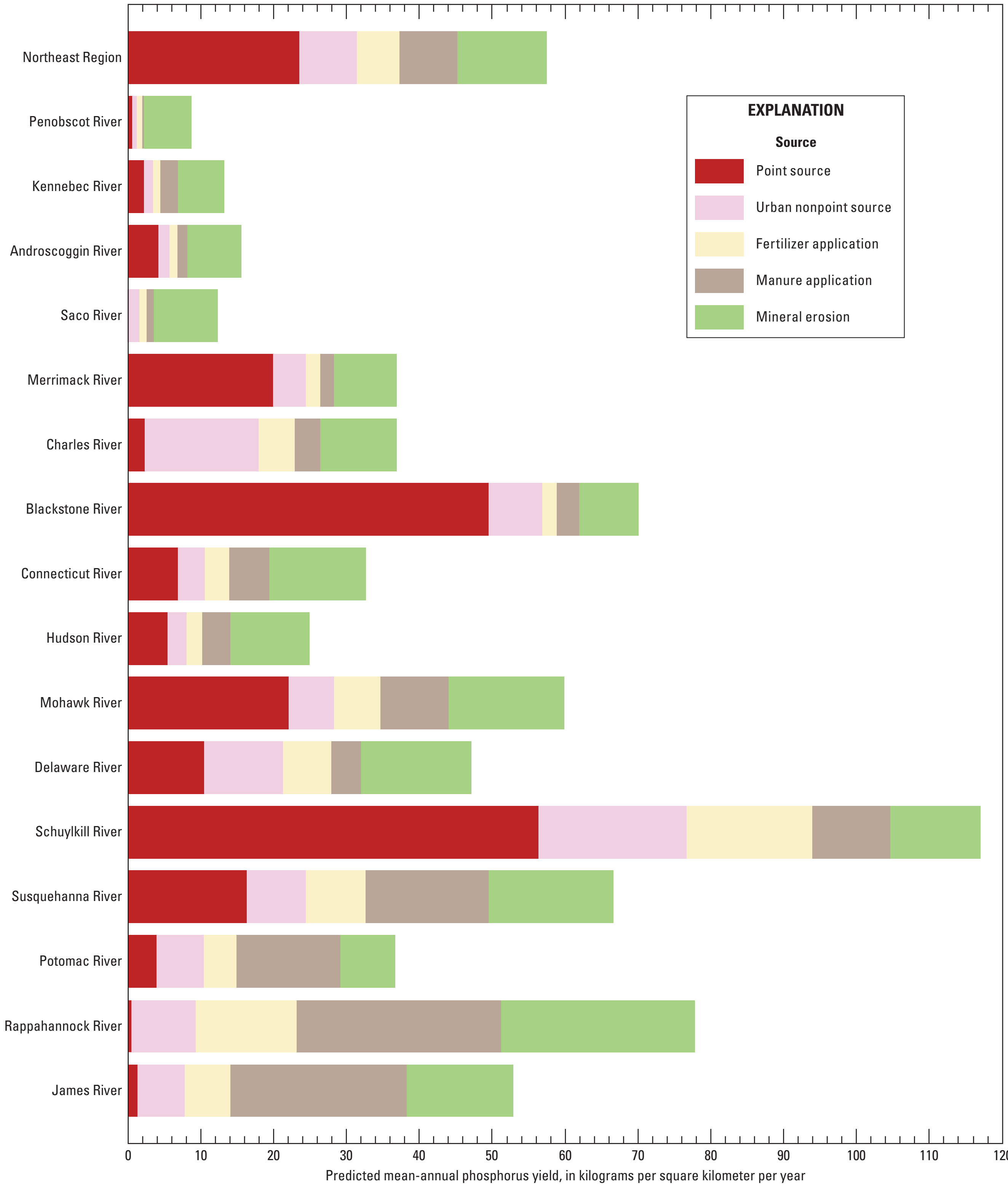

Figure 18. Predicted mean-annual phosphorus yield, by source, from the Northeastern United States and major northeastern watersheds.

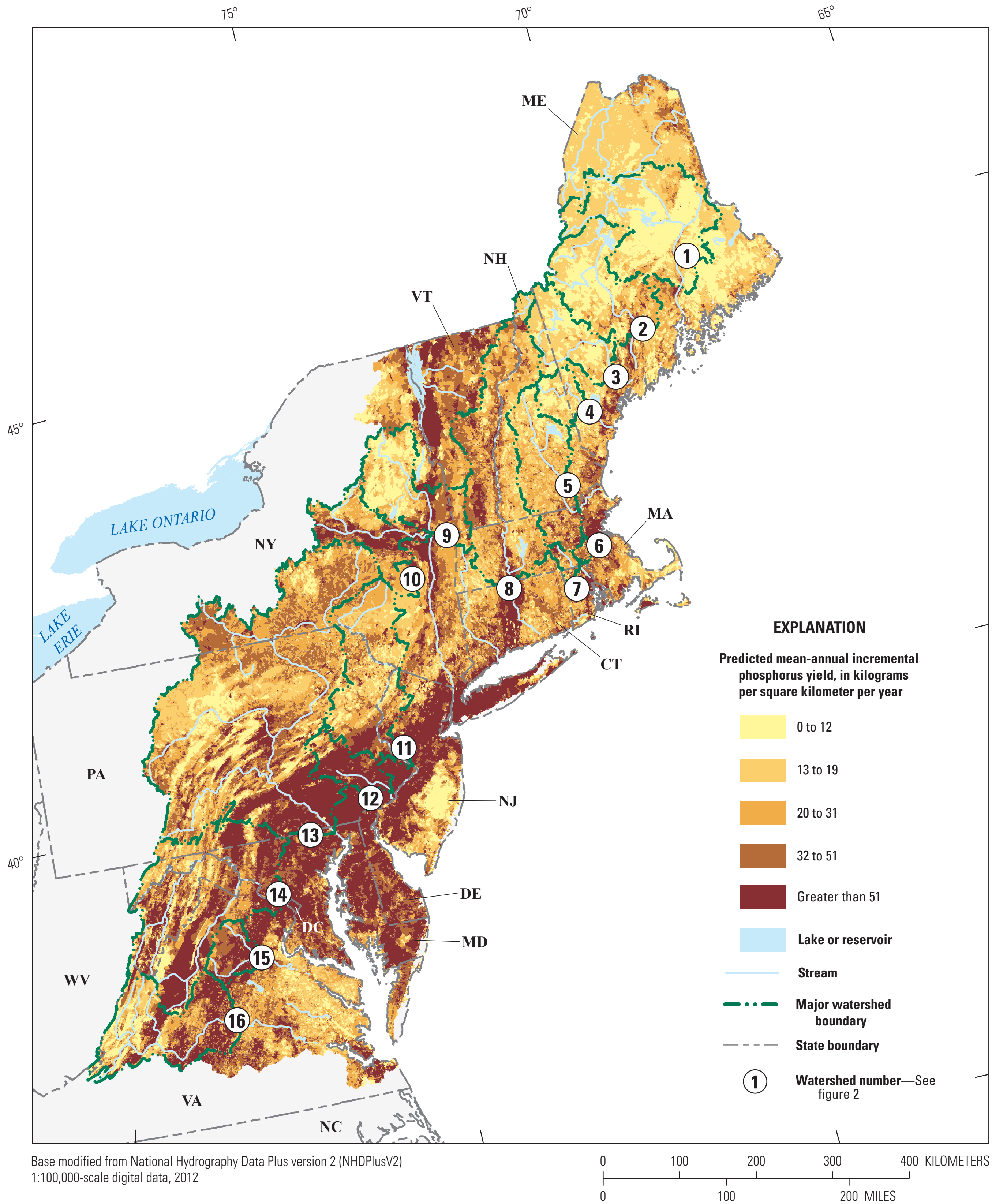

Figure 19. Predicted mean-annual incremental yield of phosphorus to streams in the Northeastern United States, 2012.

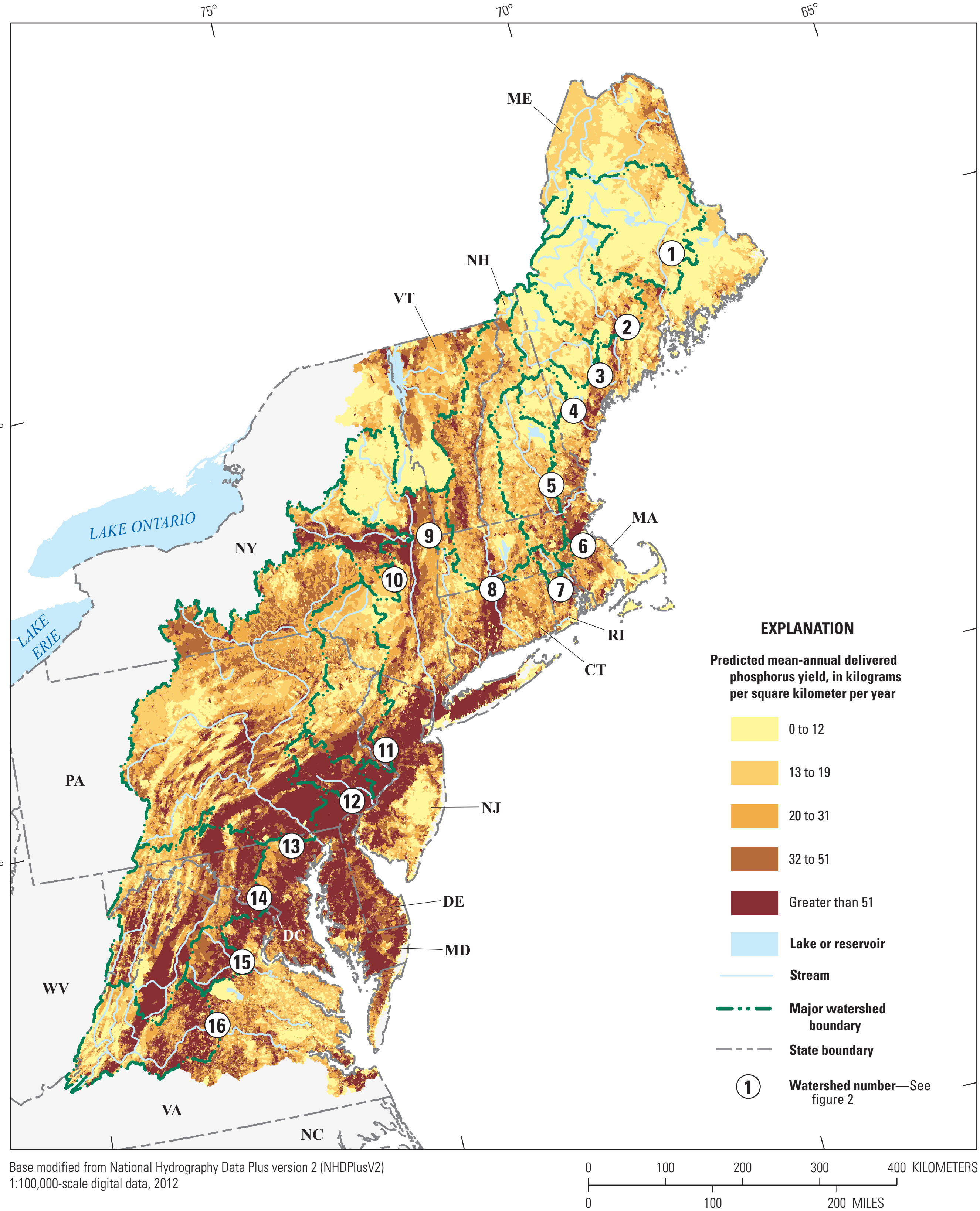

Figure 20. Predicted mean-annual delivered yield of phosphorus to streams in the Northeastern United States, 2012.

(figs. 14, 15), reflecting the importance of local agricultural or urban sources for both nutrients. Local phosphorus yields are greatest in the most intensively cultivated or densely populated areas (fig. 3), particularly in the southern half of the region (fig. 19). Delivered yields to downstream receiving waters are similarly distributed, except in areas upstream from impoundments that may intercept and store substantial masses of sediment and associated phosphorus (fig. 20). Differences in incremental and delivered phosphorus yields are therefore particularly notable in New England where natural lakes and ponds are common and upstream from major artificial reservoirs to the south (fig. 20).

SPARROW Model of Suspended Sediment

The suspended-sediment model summarizes major upland and stream-channel sources of sediment to northeastern streams and major landscape properties controlling erosion and sedimentation. Explanatory terms in the model explain 93 percent of the spatial variability in suspended-sediment load at 337 calibration stations on northeastern streams and 67 percent of spatial variability in suspended-sediment yields (table 5). Review of model residuals (figs. 21, 22) suggests no major limitations in the model for quantifying and understanding suspended-sediment sources, fate, and transport in the region or for estimating suspended-sediment loads in unmonitored streams. As with the nutrient models, however, model predictions for streams in northern New England may be particularly uncertain owing to the paucity of available calibration data for that area (fig. 22). The binary terms adjust the model for any potential bias stemming from the use of suspended-sediment and TSS loads, and of non-nested streamflow and water-quality stations, in model calibration.

The suspended-sediment SPARROW model suggests that erosion in terrestrial uplands and along stream channels are both important to generating suspended-sediment load in streams of the Northeastern United States (table 5; fig. 23). The model-estimated coefficient corresponding to stream length suggests that a net increase of 6.12 metric tons (t) of sediment is contributed annually, on average, over each kilometer of stream channels in streams outside of the Coastal Plain or in small streams of the Coastal Plain, although the relatively broad confidence interval on this and other source coefficients may suggest erosion rates are particularly variable, spatially (table 5; fig. 2). Brakebill and others (2010) estimated a substantially larger annual erosion rate of 291 t km^{-1} for small streams outside of the Coastal Plain in the Chesapeake Bay watershed, suggesting that streambank erosion rates may be greater than average in that part of the Northeast. Streambank erosion is greater in streams with greater flow velocity (table 5), which likely serves as a proxy for stream power or erosion potential. Average annual upland erosion rates are generally greater in agricultural areas than in urban or forested areas (table 5), which may reflect the repeated land disturbance for cultivation common in agricultural areas and the relative stability of soils in forested and (at least following initial construction) urban areas. Among agricultural areas, erosion rates are greater in areas with relatively fine surficial geologic materials (table 5), as might be expected considering the importance of fine silt and clay to suspended-sediment load. As with phosphorus load (table 4), suspended-sediment load from upland sources is greater in areas of greater soil erodibility and in agricultural areas in which no-till or conservation tillage practices are less common (table 5). Within the stream network, a net loss of suspended-sediment load occurs in impoundments and along relatively large streams in the Coastal Plain (table 5).

Mean-annual yields of suspended sediment to local streams (fig. 24) and downstream receiving waters (fig. 25) reflect the presence of agricultural or urban sources in contributing watersheds and the spatial variability of major sediment storage locations within the stream network. Local yields to streams are generally greatest in agricultural areas of the mid-Atlantic region and the Hudson and Mohawk River valleys (fig. 24), and upland contributions of suspended sediment to streams in those areas tend to be greater than to streams draining the predominantly forested watersheds of New England (fig. 23). One notable difference between the local yields of suspended sediment (fig. 24) and of nutrients (figs. 14, 19) is the relatively low yields on the Coastal Plain of Delaware, eastern Maryland, and southern New Jersey, likely owing to the relatively low erodibility of the typically permeable soils in such relatively low-relief landscapes. Relatively high average annual phosphorus yields despite low soil erodibility from areas of Maryland and Delaware east of Chesapeake Bay likely reflect relatively high agricultural phosphorus inputs in those areas. The spatial distribution of delivered suspended-sediment yields (fig. 25) reflects the importance of sediment storage in impoundments and in relatively large streams of the Coastal Plain. Delivered yields to terminal reaches are notably lower than incremental yields particularly in New England where ponds and lakes such as Lake Champlain are common and in watersheds of the Delaware, Potomac, Rappahannock, and James Rivers (figs 24, 25), for which the model network terminates in the Coastal Plain. Because predicted delivered yields from the model include losses in some large streams, they likely underrepresent delivery to the head of tide in watersheds where the NHDPlus network terminates downstream from the head of tide.

Table 5. Summary of calibration results for the Northeast SPARROW total suspended-sediment model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; t, metric ton; ft^3/s, cubic foot per second; yr, year; km, kilometer; sec, second; m, meter; ft, foot; yr, year; RMSE, root mean squared error; R^2, coefficient of determination; <, less than; Ln, natural logarithm; GE, greater than or equal to; LT, less than or equal to]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Source									
Reach length for streams above the fall line or in the Coastal Plain with mean-annual discharge LT 100 ft^3/s	km	t km^{-1} yr^{-1}	6.12	0.787	11.4	3.23	0.0296	1.9	20.1
Uplands that are not agricultural or urban	km^2	t km^{-2} yr^{-1}	2.43	–3.28	8.13	3.46	[b]0.2416	0.7	4.4
Urban uplands with fine sediments		t km^{-2} yr^{-1}	29.2	9.56	48.8	11.9	0.0073	2.5	1.4
Urban uplands with medium or coarse sediments	km^2	t km^{-2} yr^{-1}	19.0	2.23	35.8	10.2	0.0313	1.9	1.4
Urban uplands with residuum	km^2	t km^{-2} yr^{-1}	47.5	28.9	66.1	11.3	<0.0001	4.2	2.2
Agricultural uplands with fine sediments	km^2	t km^{-2} yr^{-1}	115	42.5	188	44.2	0.0047	2.6	3.9
Agricultural uplands with medium or coarse sediments or residuum	km^2	t km^{-2} yr^{-1}	54.8	5.22	104	30.0	0.0346	1.8	9.0
Land-to-water delivery									
Ln(Mean stream velocity)	ft sec^{-1}	sec ft^{-1}	5.29	3.86	6.72	0.867	<0.0001	6.1	11.2
Ln(Soil erodibility)	Dimensionless	Dimensionless	1.23	0.552	1.90	0.409	0.0029	3.0	2.1
Ln(Conservation tillage or no-till)	Percent of agriculture	Dimensionless	–0.101	–0.284	0.0811	[c]0.111	[c]0.3605	[c]–0.9	9.5
Aquatic loss									
Reservoir inverse hydraulic load	yr m^{-1}	m yr^{-1}	17.9	5.45	30.6	7.55	0.0091	2.4	1.5
Time of travel in streams of the Coastal Plain with mean-annual discharge GE 100 ft^3/s	Days	$Days^{-1}$	0.456	–0.106	1.02	0.341	0.0909	1.3	1.1

Table 5. Summary of calibration results for the Northeast SPARROW total suspended-sediment model. Calibration included adjustment for the amount of the upstream watershed that was included in watersheds of other calibration sites.—Continued

[SPARROW, SPAtially Referenced Regression On Watershed attributes; *p*-value, probability level; *t*-value, *t*-statistic; t, metric ton; ft^3/s, cubic foot per second; yr, year; km, kilometer; sec, second; m, meter; ft, foot; yr, year; RMSE, root mean squared error; R^2, coefficient of determination; <, less than; Ln, natural logarithm; GE, greater than or equal to; LT, less than or equal to]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value[a]	*t*-value	Variance inflation factor
				Low	High				
Other									
Binary (0 if calibration load is suspended sediment, 1 if total suspended solids)[d]			–1.46[d]	–1.63	–1.30	0.101	<0.0001	–14.5	3.4
Binary (0 if water-quality and streamflow stations are nested, 1 if otherwise)[e]			–0.216[e]	–0.396	0.0352	0.109	0.0496	–2.0	2.0
Spatial test	**Number**	**Correlation / value**	***p*-value**						
Tight clusters—pairs of nested sites within 5 km	6	–0.6546	0.1583						
Model summary statistics									
Conditioned RMSE[f] in natural log units		0.7815							
Conditioned RMSE[f], percent in real space units[g]		91.7							
Unconditioned RMSE[h] in natural log units		0.7962							
Unconditioned RMSE[h], percent in real space units[g]		94.1							
Mean exponentiated weighted error		1.392							
R^2		0.9252							
Yield R^2		0.6689							
Number of sites		337							

[a]Listed *p*-values are one-sided for source and aquatic decay terms and two-sided for other terms.

[b]Although not significantly different from zero, the coefficient corresponding to sediment sources in non-agricultural and non-urban areas was retained in the model to represent background erosion in such areas.

[c]The variance inflation factor (VIF) for this coefficient indicated the standard error may be overestimated by a factor of more than 3 (Schwarz and others, 2006).

[d]This coefficient corresponds to a conversion factor between the load of total suspended solids (TSS) and suspended-sediment concentration (SSC) of SSC = 4.3 * TSS.

[e]This coefficient corresponds to a conversion factor between loads estimated from non-nested (NON) and nested (NES) flow and water-quality stations of NES = 1.2 * NON.

[f]Conditioned RMSE: Root mean squared error of the difference between the natural log of measured calibration loads and the natural log of predicted accumulated loads that were reset to the measured loads at the calibration sites.

[g]RMSE in terms of percent in real space units was computed as $100 \times (\exp[RMSE^2]-1)^{0.5}$; RMSE in the equation is in natural log units (Hoos and Roland, 2019).

[h]Unconditioned RMSE is similar to the conditioned RMSE except the predicted accumulated loads were not reset to the measured loads at the calibration sites.

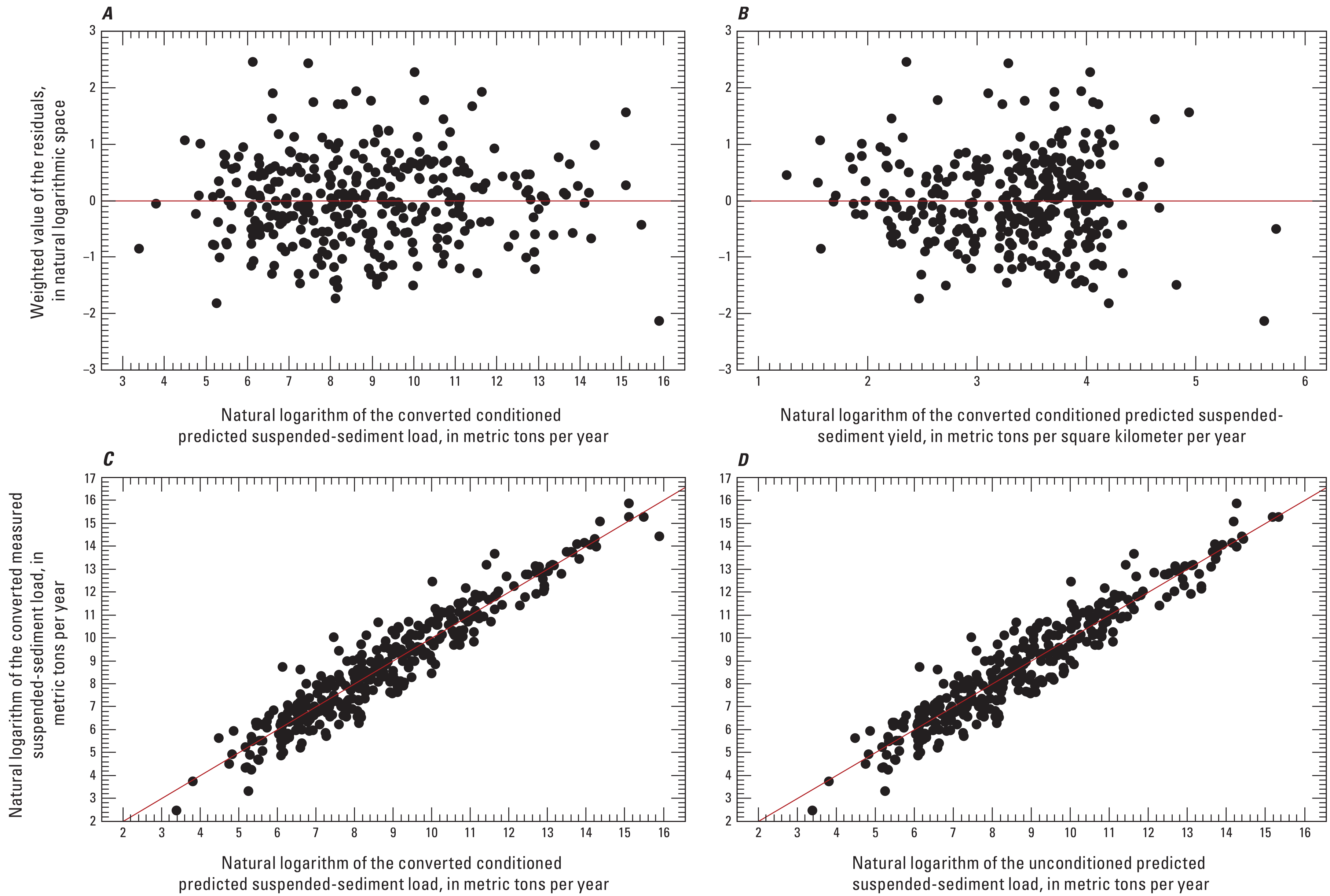

Figure 21. Diagnostic plots for the fit of the Northeast SPARROW suspended-sediment model. *A*, weighted residuals versus converted conditioned predicted loads, *B*, weighted residuals versus converted conditioned predicted yields, *C*, converted measured loads versus converted conditioned predicted loads, and *D*, converted measured loads versus unconditioned predicted loads. Plotted residuals are unconditioned. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

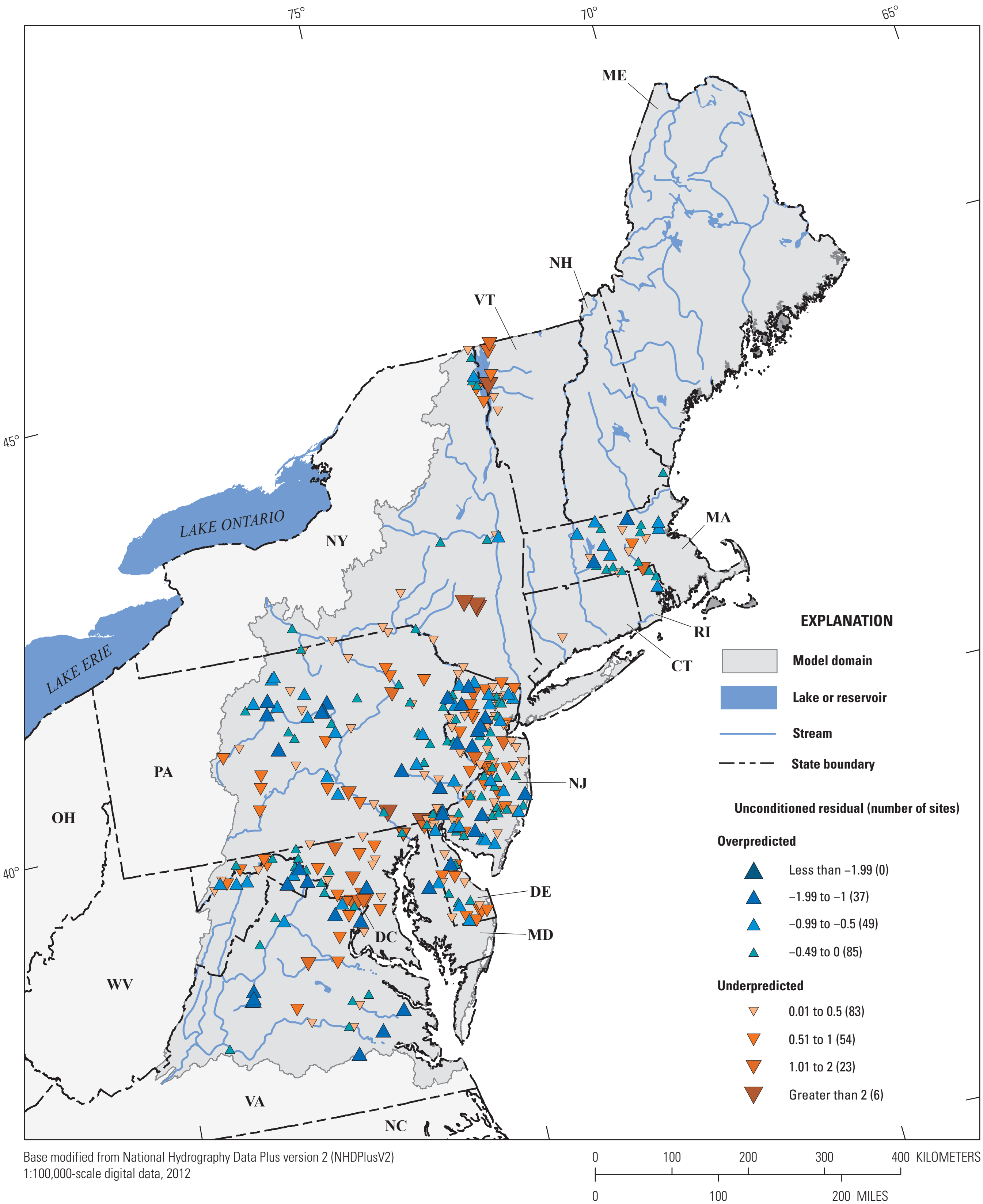

Figure 22. Spatial distribution of unconditioned residuals from the Northeast SPARROW suspended-sediment model. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at calibration stations.

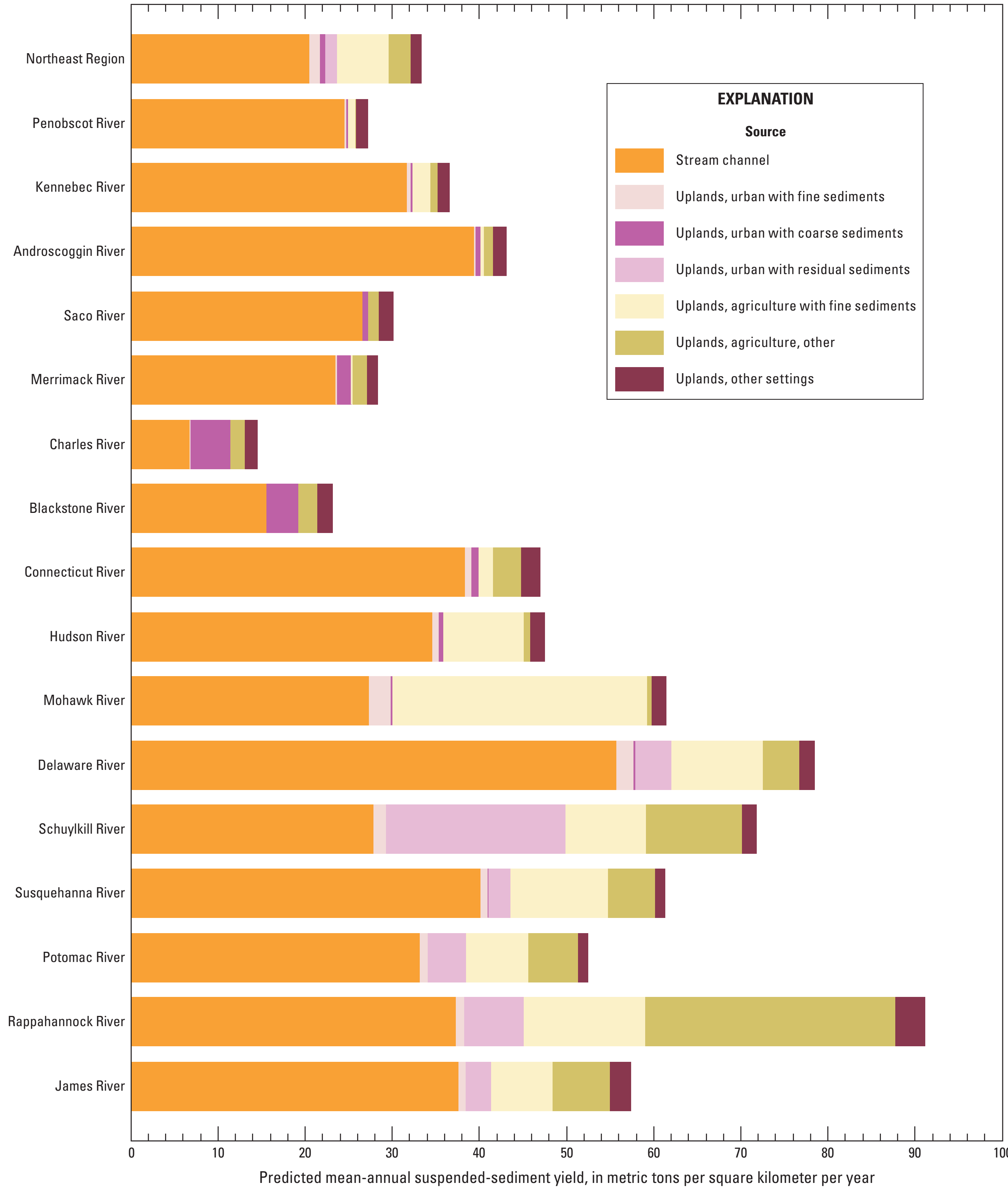

Figure 23. Predicted mean-annual suspended-sediment yield, by source, from the Northeastern United States and major northeastern watersheds.

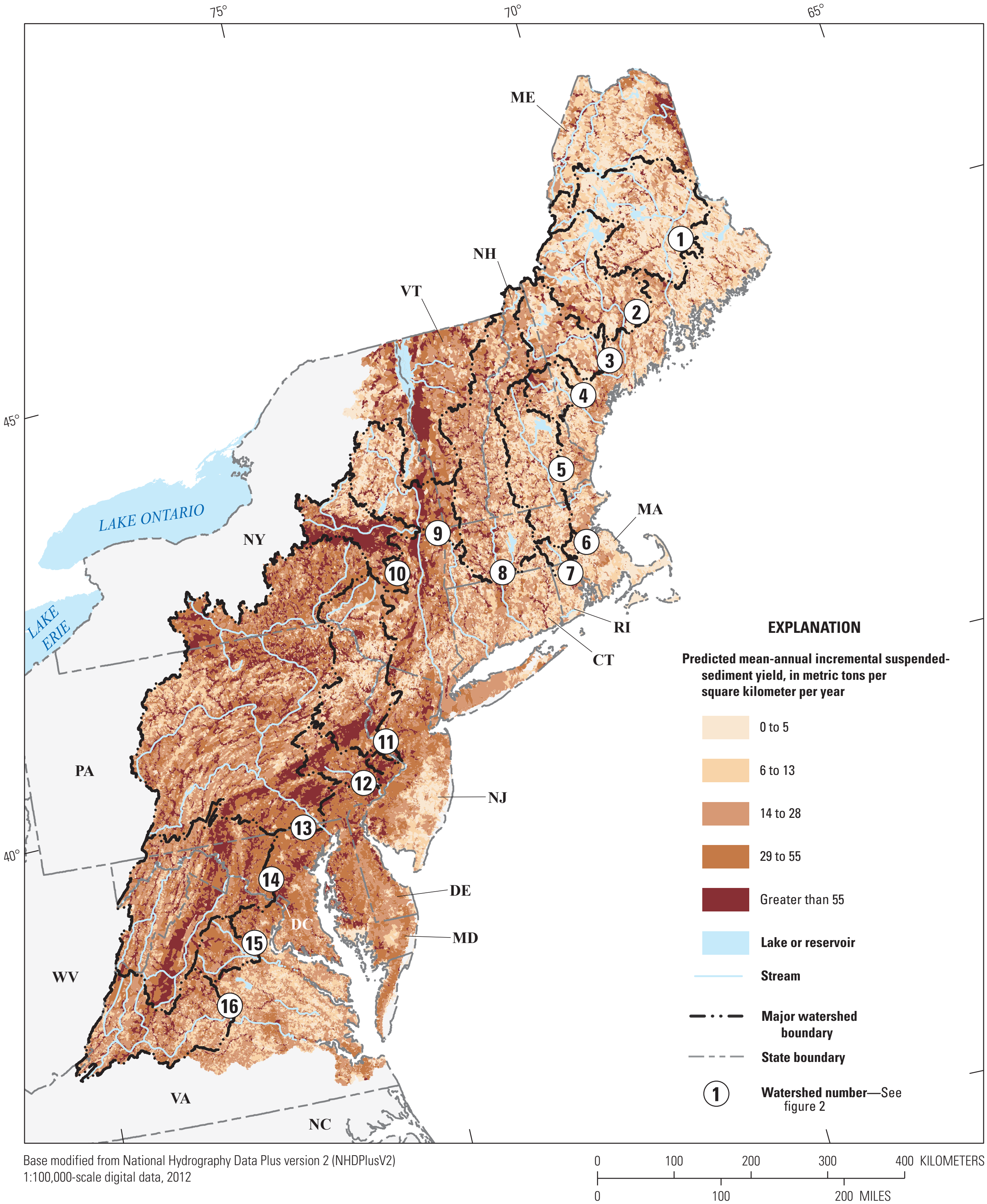

Figure 24. Predicted mean-annual incremental yield of suspended sediment to streams in the Northeastern United States, 2012.

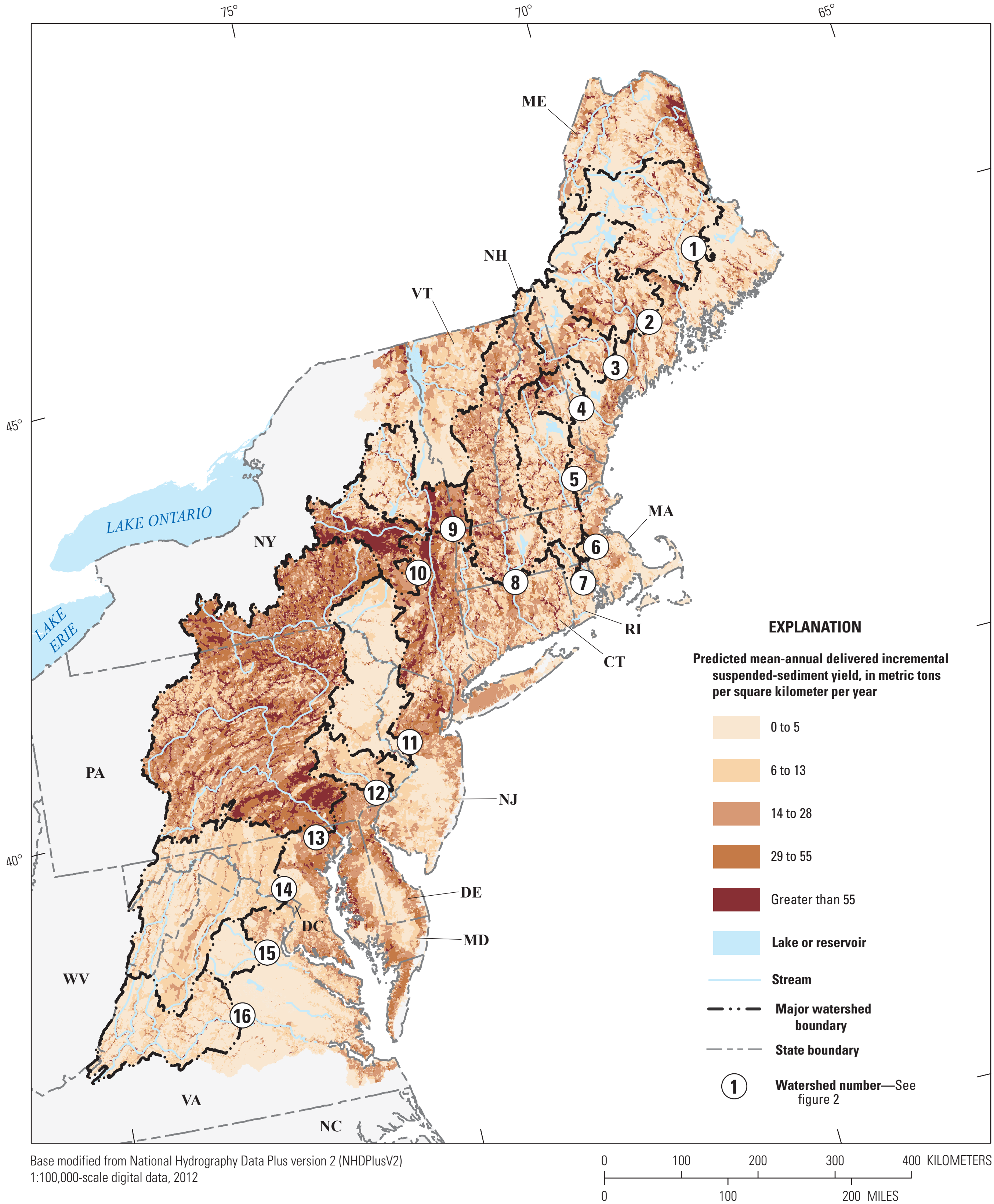

Figure 25. Predicted mean-annual delivered incremental yield of suspended sediment to streams in the Northeastern United States, 2012.

Discussion and Implications

Streams draining the Northeastern United States contribute 303,000 t of nitrogen, 25,300 t of phosphorus, and 14,700,000 t of suspended sediment, annually, to Atlantic coastal waters (table 6). Howarth and others (1996) previously estimated larger annual loads of 510,000 t of nitrogen and 67,000 t of phosphorus from the Northeastern United States during the 1980s. Major sources (table 3, table 4, table 5) and, consequently, areas contributing the greatest annual yields to northeastern streams and downstream receiving waters are similar for nitrogen (figs. 14, 15), phosphorus (figs. 19, 20), and suspended sediment (figs. 24, 25). Average annual nutrient and sediment yields are relatively low from the predominantly forested areas of New England and the western mountainous areas of the Northeast where human land disturbance is minimal and atmospheric deposition and natural erosion are the dominant sources of nitrogen and phosphorus, respectively, to streams. Areas of the mid-Atlantic region, the Hudson, Mohawk, and lower Connecticut River Valleys, and coastal parts of southern New England, in contrast, are more heavily cultivated or densely populated, receive greater nutrient inputs, and yield greater nutrients and suspended sediment to local streams and downstream receiving waters.

Landscape factors affecting the fate and transport of nutrients from upland applications areas to and within surface waters reflect important geochemical properties of nitrogen and phosphorus compounds. A substantial fraction of nitrogen transport in the Northeast occurs through groundwater in the form of nitrate, and nitrogen delivery to streams is therefore sensitive to geologic conditions (such as the presence of carbonate rocks; table 3) that promote such transport through oxic groundwater. Nitrogen transport is also sensitive to soil, climatic, and other landscape conditions (table 3) that promote denitrification, an important sink for nitrogen in uplands. Phosphorous, in contrast, is not removed to the atmosphere through biochemical processes, such as denitrification, and is relatively insoluble. Phosphorous transport is therefore sensitive to soil erodibility and tillage practices that also affect upland delivery of sediment to streams (tables 4, 5). Loads of nitrogen and phosphorus are substantially reduced in impounded streams (tables 3, 4), although such phosphorus reduction likely is due primarily to sedimentation and storage, whereas nitrogen reductions may be attributable to a greater variety of chemical and physical processes.

Nutrient flux from the Northeastern United States contributes to eutrophic conditions in coastal estuaries (Bricker and others, 2007; U.S. Environmental Protection Agency, 2009a; Prasad and others, 2010). Northeastern streams contributing the greatest nutrient yields (figs. 13, 18) discharge to coastal estuaries from the Chesapeake Bay through Cape Cod that have been described by Bricker and others (2007) as the "most impacted" by eutrophic conditions among five regions of the conterminous United States. Estuaries of this region are relatively poorly flushed, and most have been reported as at least moderately highly eutrophic (Bricker and others, 2007). TMDLs for nutrients have been established for major estuaries in this region, including Chesapeake Bay (U.S. Environmental Protection Agency, 2011) and Long Island Sound (U.S. Environmental Protection Agency, 2009a). In contrast, estuaries further north along the Gulf of Maine are well flushed, receive lower nutrient inputs, and have been described by Bricker and others (2007) as the "least impacted" nationally by eutrophication.

Improved understanding of the regional sources, fate, and transport of nutrients and sediment in northeastern streams provided by the updated SPARROW models suggest several implications for future watershed management. Maximization of water-quality, ecological, or other returns on future investments in watershed management and restoration likely

Table 6. Estimated loads of nutrients and suspended sediment from the Northeastern United States to the North Atlantic Ocean and major coastal estuaries.

[km^2, square kilometers; t, metric ton]

Receiving waterbody	Contributing land area (km^2)	Estimated annual load (t)		
		Nitrogen	Phosphorus	Suspended sediment
Atlantic Ocean[1]	441,000	303,000	25,300	14,700,000
Gulf of Maine	87,900	28,100	1,760	2,590,000
Long Island Sound	43,200	28,200	3,990	1,860,000
New York Harbor[2]	40,300	40,100	4,590	1,670,000
Delaware Bay	32,800	39,400	3,010	444,000
Chesapeake Bay	170,000	135,000	9,460	5,880,000

[1]Including streams draining through Canada.

[2]Including coastal drainages between Sandy Hook, New Jersey, and Rockaway Point, New York.

will be realized through customization of such investments to local landscape conditions, primary contaminant(s) of concern, and consideration of local versus regional objectives. Regional spatial patterns of local and delivered nutrient and sediment yields (figs. 14, 15, 19, 20, 24, and 25) reflect similar patterns in land use and land cover (fig. 3) and associated major sources as well as soil, geologic, and other landscape conditions (tables 3, 4, and 5) that affect upland and aquatic fate and transport. Improved odds of water-quality or ecological benefits of restoration or management activities may be expected through consideration of these factors, to the extent possible, in locating and designing such activities. The varying geochemical properties (such as solubility) between nitrogen and phosphorus substantially complicate the process of designing management practices for both (Staver and Brinsfield, 2001). Phosphorus may be more important to aquatic or estuarine ecology in certain surface waters or during certain time periods, but nitrogen may be more relevant in others (Vitousek and others, 1997; Correll, 1998; Prasad and others, 2010). Also, the relative importance of various sources varies with watershed scale as well as location. For example, reduced atmospheric nitrogen deposition has substantially reduced the nitrogen in streams in forested areas with limited other sources (Eshleman and others, 2013; Eshleman and Sabo, 2016) but may have more limited effects on nitrogen in estuaries also receiving nitrogen from substantially greater agricultural or urban sources (Ator and others, 2019).

Results of the updated regional SPARROW models also suggest future research that may be particularly useful for an improved understanding of nutrients and sediment in the Northeast. Average nitrogen yields to streams are substantial specifically from carbonate settings (table 3), which also tend to coincide with some of the greatest nitrogen sources, especially agriculture (figs. 2, 3). Research on the hydrology and potential watershed management approaches specific to this unique hydrogeologic setting may be particularly useful for reducing nitrogen transport to streams and estuaries. Additionally, effects of management practices intended to mitigate the flux of nutrients from agricultural areas to streams (Hassett and others, 2005; Hively and others, 2013; Sekellick and others, 2019) have been observed in some cases (Meisinger and others, 1991; Staver and Brinsfield, 1998; Hively and others, 2009; McCoy and others, 2010; Denver and others, 2018) but are less apparent in others (Lowrance and others, 1997; Boesch and others, 2001; Sutton and others, 2010; Kibet and others, 2011; Weller and others, 2011; Denver and others, 2014; Lee and others, 2016b) and have been difficult to detect in regional water quality. The significant regional correlation of cover crops and (or) tillage practices with nitrogen (table 3), phosphorus (table 4), and suspended-sediment (table 5) loads in the regional models suggest that cover crops and tillage practices, by 2012, had been implemented widely enough or over sufficient periods to affect regional water quality. This correlation also suggests that future such research at regional scales may be fruitful. Additionally, nutrient and sediment transport is driven primarily by the movement of water, and biochemical processes affecting nitrogen fate (such as denitrification) may be sensitive to temperature (table 3). Najjar and others (2010) note that effects of climate change on Chesapeake Bay likely will be nonlinear and that the effects on annual streamflow in the watershed are highly uncertain. Further research toward understanding the effects of climate change on future nutrient and sediment sources, fate, and transport to northeastern coastal waters may be particularly useful.

The predictions and representation of streamflow and nutrient and suspended-sediment transport from the regional SPARROW models presented herein must, like those of all models, be considered in light of the generalizations and assumptions used in the model specification and calibration. Such considerations inherent to use of the SPARROW tool, in general, are described in Schwarz and others (2006). SPARROW models for the Northeast were calibrated to annual nitrogen, phosphorus, and suspended-sediment loads at monitoring stations; these loads were estimated through other numerical models with their own simplifications and assumptions and are therefore uncertain (Lee and others, 2016a; Saad and others, 2019). This uncertainty may be particularly pronounced for calibration loads estimated from streamflow and water-quality observations collected from different locations. Explanatory data often are similarly estimated or extrapolated for use in the models because relevant variables are seldom directly measured over large regions. The accuracy of these explanatory data and therefore of model predictions also may vary spatially within the watershed; the estimated coefficient corresponding to point sources in the nitrogen model, for example, suggests these inputs are overestimated, on average, but not necessarily in every catchment. The models also are limited by the availability of input data, and predictions are particularly uncertain in areas where observations are sparse. Previous nitrogen and phosphorus models, calibrated with greater available data in New England (Moore and others, 2004; Moore and others, 2011), for example, are generally similar to the models presented herein but likely better represent that particular area. Also, the current models do not include all possible sources of nutrients or factors affecting delivery to northeastern streams; such conditions which could not be estimated for the region or were excluded for other reasons contribute to model error or are incorporated by the models as part of estimated coefficients of other explanatory terms that are similarly distributed, spatially. Important sources, and fate and transport processes, inferred from model terms and coefficients therefore may actually reflect these spatially correlated but excluded conditions. The models represent mean-annual conditions over long periods, and effects of processes over seasonal, diurnal, or other shorter periods are necessarily averaged or generalized. Estimates of aquatic decay in flowing and impounded reaches, in particular, are (like other explanatory terms) averaged over large areas and represent the net effects of multiple biogeochemical and physical processes on nutrient and sediment loads in surface waters (Schwarz and others, 2006).

Summary

SPAtially Referenced Regression on Watershed attribute (SPARROW) models were developed to represent streamflow and the sources, fate, and transport of nutrients and suspended sediment in streams draining to the Atlantic Coast from the Northeastern United States during 2012 (https://doi.org/10.5066/P9NKNVQO). The Northeast is primarily forested but includes intensively cultivated agricultural areas and some of the most densely populated urban centers in the Nation. Fluxes of nitrogen, phosphorus, and suspended sediment from upstream watersheds of the Northeast have contributed to ecological and economic degradation of estuaries along the northeastern coast. The nutrient SPARROW models disentangle and quantify the relative importance of multiple sources contributing nutrients to northeastern surface waters and numerous natural and human landscape conditions affecting the fate and transport of these constituents from upland applications areas, through flowing and impounded streams, to downstream receiving waters. The suspended-sediment model similarly quantifies the average yield (upland erosion rates) in various settings and quantifies factors affecting delivery of suspended sediment to streams and estuaries. Innovations and improvements over previous similar models for the area include an improved representation of stream hydrography and estimation of calibration data, an updated timeframe (to 2012), and improved and expanded explanatory data representing watershed sources and land-to-water fate and transport.

Streamflow in Northeastern United States is primarily generated through natural precipitation. Although diversions and extractions for municipal supply and other uses, and corresponding returns from point sources such as wastewater treatment plants, are common throughout the area, the surplus of precipitation over evapotranspiration in the humid, temperate region vastly exceeds such human modifications in most areas and provides most of the flow in most streams. Spatial variability in the average yield of water to streams therefore reflects similar variability in precipitation, which is generally greatest in the northern part of the study area. Delivery of water to streams is further affected by average air temperature, soil moisture, and vegetative growth; these terms likely reflect the storage of water in soils and spatial variability in evapotranspiration.

Although atmospheric deposition and natural erosion contribute nitrogen and phosphorus (respectively) to northeastern surface waters, nutrient loads in streams are attributable largely to inputs from upland agriculture and urban areas. Significant agricultural inputs include nitrogen and phosphorus in fertilizer and manure applications; areas planted in nitrogen-fixing crops yield an additional 2,730 kilograms per square kilometer (kg km^{-2}) annually to streams. Effluent from wastewater treatment plants and (for nitrogen) septic systems also contributes significantly to nutrient loads in northeastern streams, and other urban nonpoint sources collectively yield 549 kg km^{-2} and 48 kg km^{-2} annually of nitrogen and phosphorus, respectively, to surface waters Average annual nutrient yields to local streams and downstream receiving waters are therefore greatest from areas with the greatest concentrations of agriculture or urban land, including much of the mid-Atlantic region, the Hudson, Mohawk, and Connecticut River valleys, and coastal areas of southern New England. Average nutrient yields from northern New England and from forested areas in the western mountains further south typically are lower.

The spatial variability in nutrient yields from uplands to stream channels reflects natural and human landscape conditions affecting nutrient fate and transport as well as the distribution of sources. Nitrogen delivery from uplands to streams is greater in areas of carbonate rocks than in other geologic settings and in areas of greater average runoff. Nitrogen transport is reduced in areas with more forest or wetlands, thicker soils, and (or) greater average air temperatures, conditions that may reflect greater denitrification potential. In agricultural areas, nitrogen transport also is mitigated in areas with greater use of cover crops but increased in areas with greater use of conservation tillage or no-till practices. Phosphorus transport from uplands to streams is greatest where soils are more erodible and in agricultural areas in which conservation tillage or no-till practices are uncommon.

Suspended sediment in northeastern streams is generated from erosion in uplands and along stream channels. Upland erosion rates contributing to suspended-sediment loads in streams are greater in agricultural areas than in urban or forested areas and in geologic settings with fine sediments (table 5). Because agricultural and urban areas are more common in the southern part of the northeastern region, average yields are generally greater, and upland erosion contributes a greater portion of suspended sediment to streams, in that area than in New England. Like phosphorus, suspended-sediment delivery from uplands to streams is greater in areas with greater soil erodibility and in agricultural areas where conservation tillage or no-till practices are less common. Erosion contributing to suspended sediment along stream channels is greater in streams with greater average flow velocity. Suspended-sediment loads are reduced by sedimentation in impounded reaches and along large streams in the Coastal Plain.

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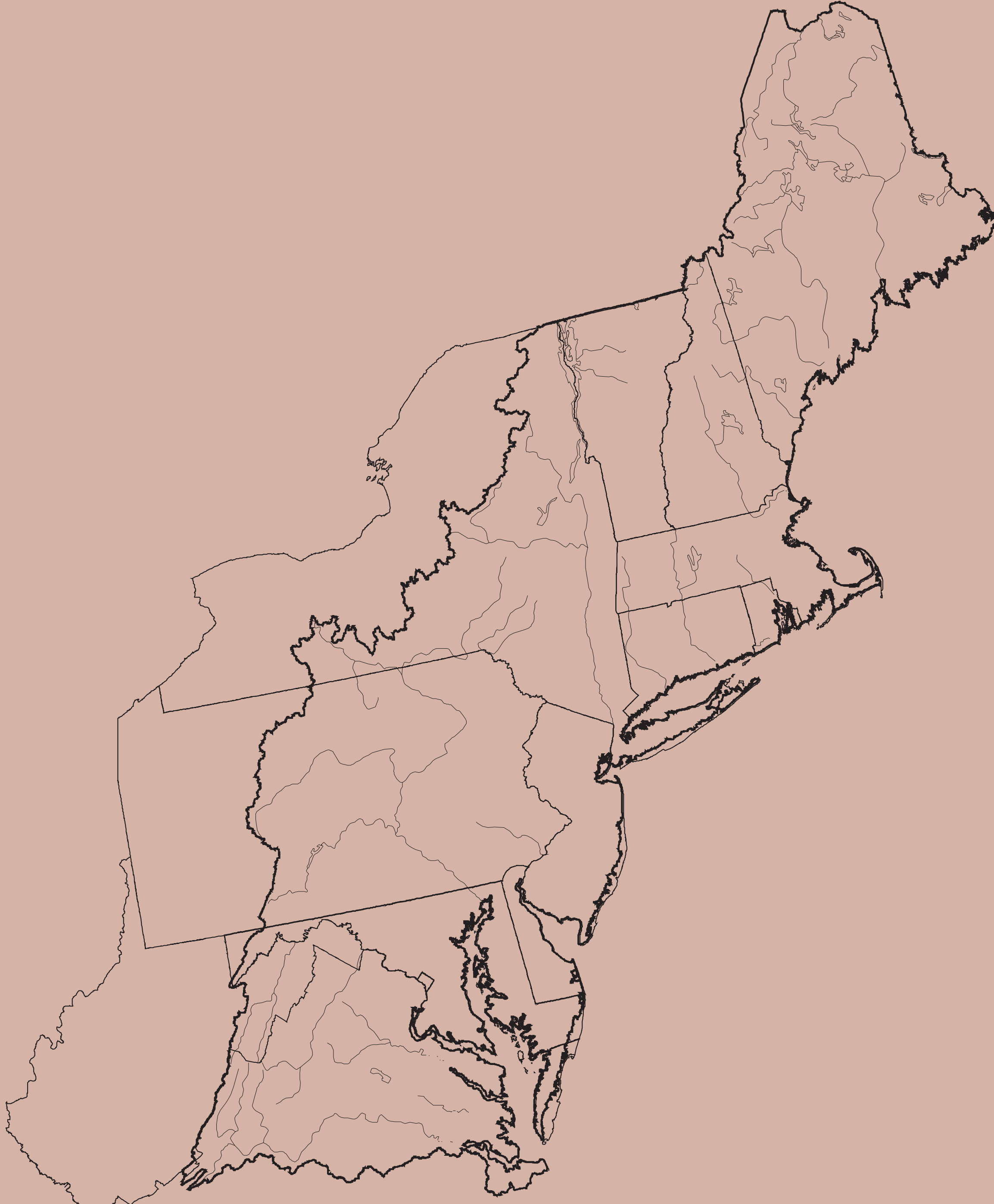

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