Science Summary—Sources, Fate, and Transport of Nitrogen and Phosphorus in the Chesapeake Bay Watershed—Interpretations and Applications of Spatially Referenced Regression on Watershed Attributes (SPARROW) Nutrient Model Results

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Introduction

As the largest and most productive estuary in North America, Chesapeake Bay is a vital ecological and economic resource. The bay and its tributaries have been degraded in recent decades, however, by excessive inputs of nutrients (nitrogen and phosphorus) and sediment from contributing watersheds. In 2000, the bay was listed as “impaired” under the Clean Water Act, and in 2010, a Total Maximum Daily Load (TMDL) was established to reduce nutrient and sediment inputs to meet water-quality standards in the bay (U.S. Environmental Protection Agency, 2010). The TMDL requires that all practices designed to reduce nutrient and sediment loads to the bay be implemented by 2025 to achieve progress toward meeting standards for dissolved oxygen, water clarity, and chlorophyll. The six States in the watershed and the District of Columbia have each prepared a Watershed Implementation Plan (WIP) that describes the types of management practices that will be used to meet the TMDL requirements.

Continued restoration of Chesapeake Bay requires effective and efficient management of nutrient inputs. Limited restoration and management resources can be applied most effectively with the benefit of a comprehensive understanding of the spatial distribution and relative magnitude of nutrient sources and the landscape characteristics affecting nutrient fate and transport. To contribute to this understanding, the U.S. Geological Survey (USGS) developed two computer models [known as Spatially Referenced Regression on Watershed Attributes (SPARROW) models] of the Chesapeake Bay watershed--one for nitrogen and one for phosphorus. These models complement the characterization of nutrient sources and transport obtained with the U.S. Environmental Protection Agency (EPA) Chesapeake Bay Program (CBP) watershed model (WSM) by providing a finer scale, regional perspective on the sources, transport, and losses of nitrogen and phosphorus in the hydrologic system.

USGS Models of Nutrient Sources and Transport in the Chesapeake Bay Watershed

The most recent Chesapeake Bay watershed SPARROW models are described in Ator and others (2011). For each of more than 80,000 nontidal tributary stream reaches, the SPARROW models provide predictions of:

- long-term mean annual nitrogen and phosphorus loads,
- nitrogen and phosphorus loads generated within local drainage areas and transported to local streams or directly into tidal waters,
- nitrogen and phosphorus loads generated within local drainage areas and transported to Chesapeake Bay, and
- contributions to instream nitrogen and phosphorus loads from individual point and nonpoint sources (such as wastewater, agriculture, urban areas, atmospheric deposition, and natural mineral deposits).

The SPARROW models are a product of the USGS Priority Ecosystems Science (PES) and National Water-Quality Assessment (NAWQA) Programs. They incorporate updated monitoring and associated geospatial data, including nutrient source and transport information. Simulation results quantify nutrient

loads at a map scale of 1:100,000 in streams that drain small watersheds averaging 2.5 square kilometers (0.96 square miles) in size.

This Science Summary is one in a series designed to facilitate the understanding and applications of relevant USGS studies by Chesapeake Bay resource managers and policy makers. The summary provides a brief overview of key findings based on the updated (2011) SPARROW models and described in Ator and others (2011); an understanding of how this information can be used to develop effective management policies and practices; a description of data availability; and a list of resources that can be accessed for additional information.

Key Findings

Nutrient Sources

- Significant sources of nitrogen to streams in the Chesapeake Bay watershed include the application of commercial fertilizer and manure and fixation by crops in agricultural areas, point sources (primarily municipal), atmospheric deposition, and urban activities. Agriculture (primarily fertilizer application and crop fixation) contributes more than half of the nitrogen transported from the watershed to the bay.

- On average, more than 71.8 x 10^6 kilograms (kg) (24 percent) of the nitrogen applied annually to agricultural areas in the form of commercial fertilizer or fixed directly by crops (fig. 1a) does not contribute to crop growth but is instead exported to local streams or tidal waters. Approximately 1.3 x 10^6 kg (6 percent) of the nitrogen applied in the form of manure (fig. 1b) reaches local streams or drains directly into tidal waters.

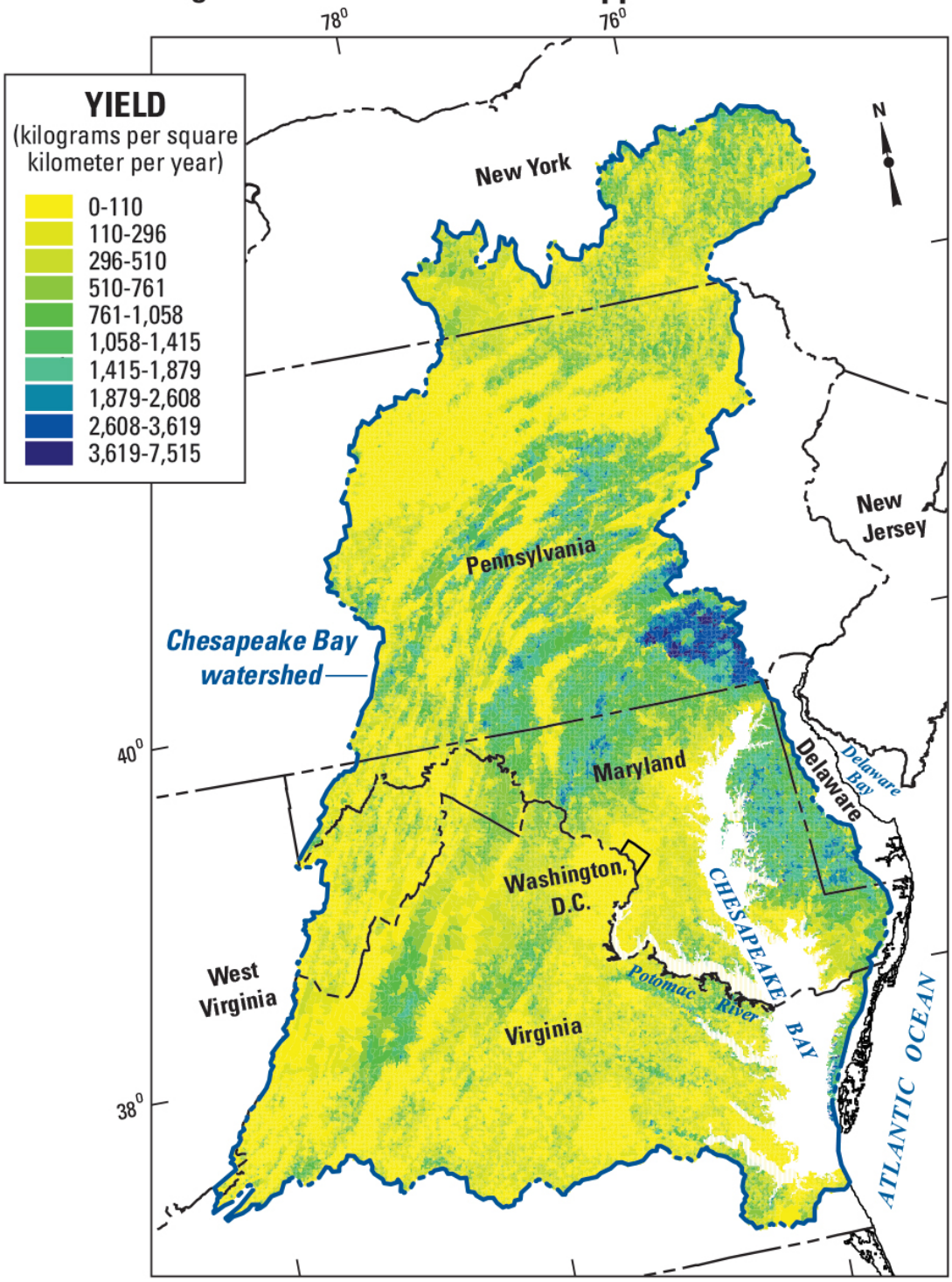
- Local nitrogen yields in the Chesapeake Bay watershed (except in areas affected by large point sources) are greatest in the predominantly agricultural areas of the Shenandoah Valley, the Great Valley and Piedmont regions in Pennsylvania and central Maryland, and the Delmarva Peninsula.

- Significant sources that contribute phosphorus to local streams or directly into tidal waters in the watershed are nearly evenly divided between agricultural (fertilizer and manure application) and urban (including wastewater) sources.

- Natural mineral dissolution from crystalline and siliciclastic rocks that underlie 70 percent of the bay watershed contributes about 14 percent of the phosphorus load to Chesapeake Bay.

- More than 5.8 x 10^6 kg (6 percent) of the phosphorus applied to agricultural areas in the form of fertilizer (fig. 1c) and manure (fig. 1d) is transported to local streams or drains directly into tidal waters.

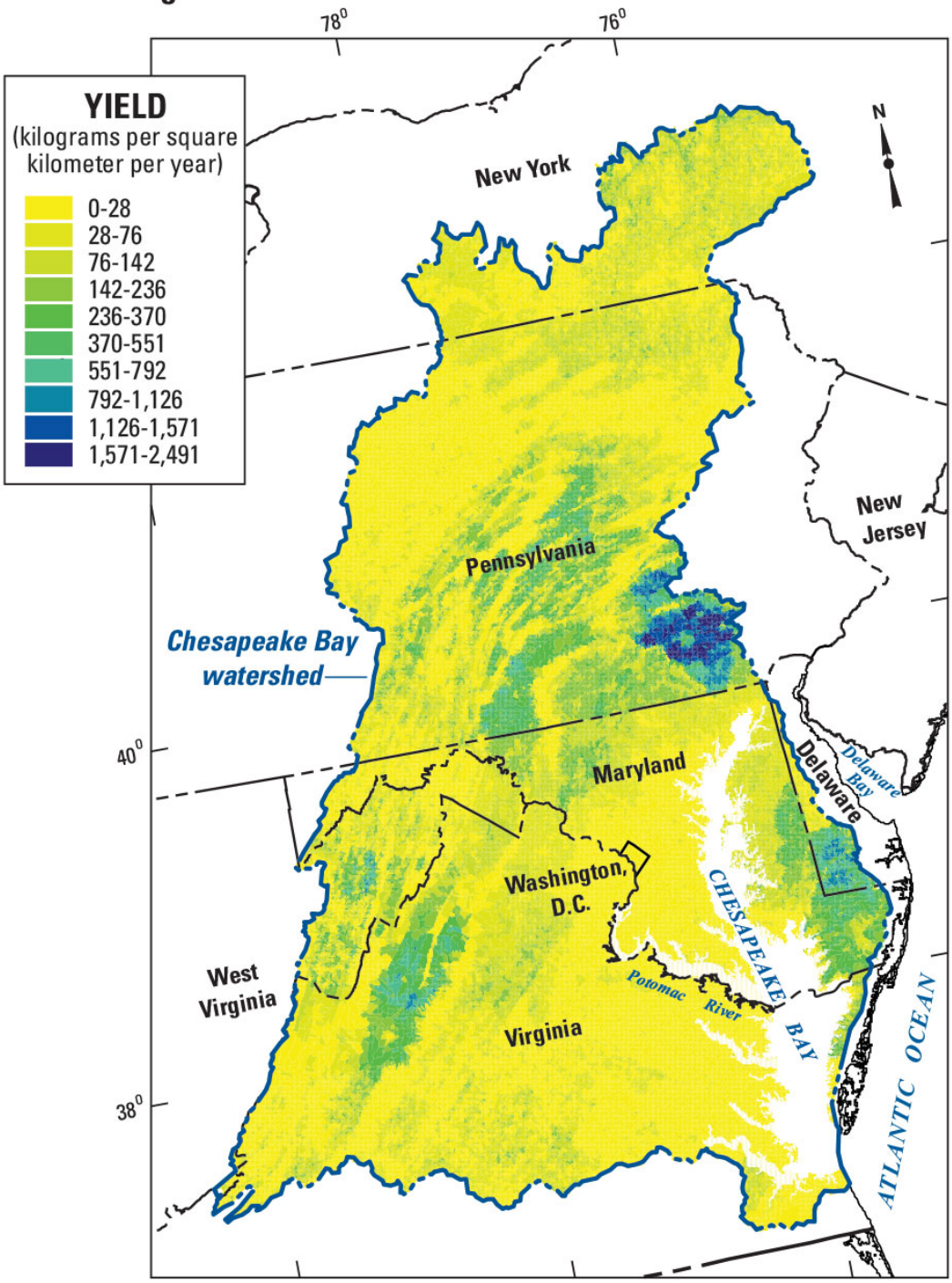
A. Total nitrogen attributable to fertilizer application and fixation



BASE FROM U.S. GEOLOGICAL SURVEY 1:2,000,000
STATE BOUNDARY DIGITAL LINE GRAPH, ALBERS
EQUAL AREA PROJECTION, NAD 1983

0 50 KILOMETERS
0 50 MILES

B. Total nitrogen attributable to manure



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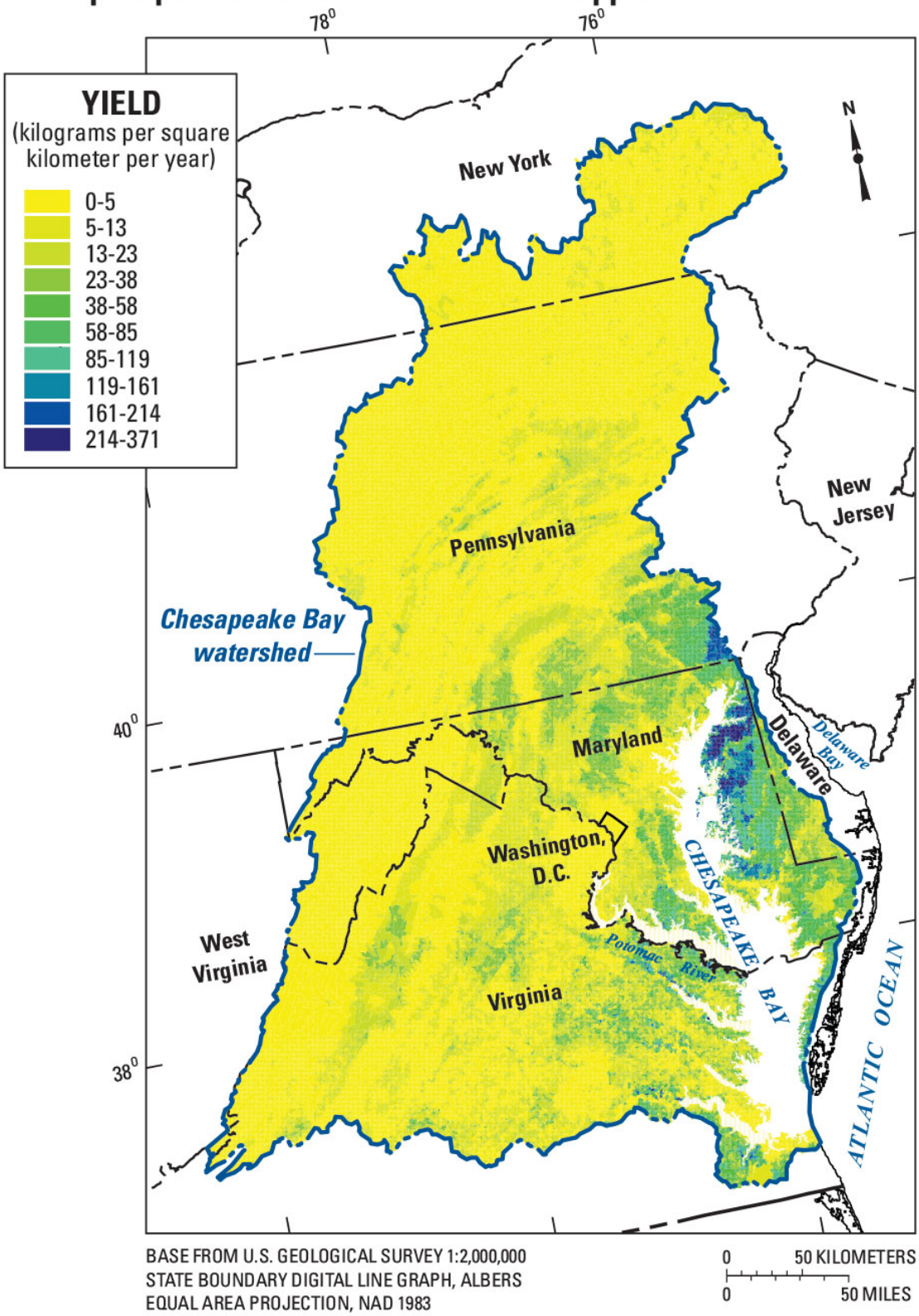
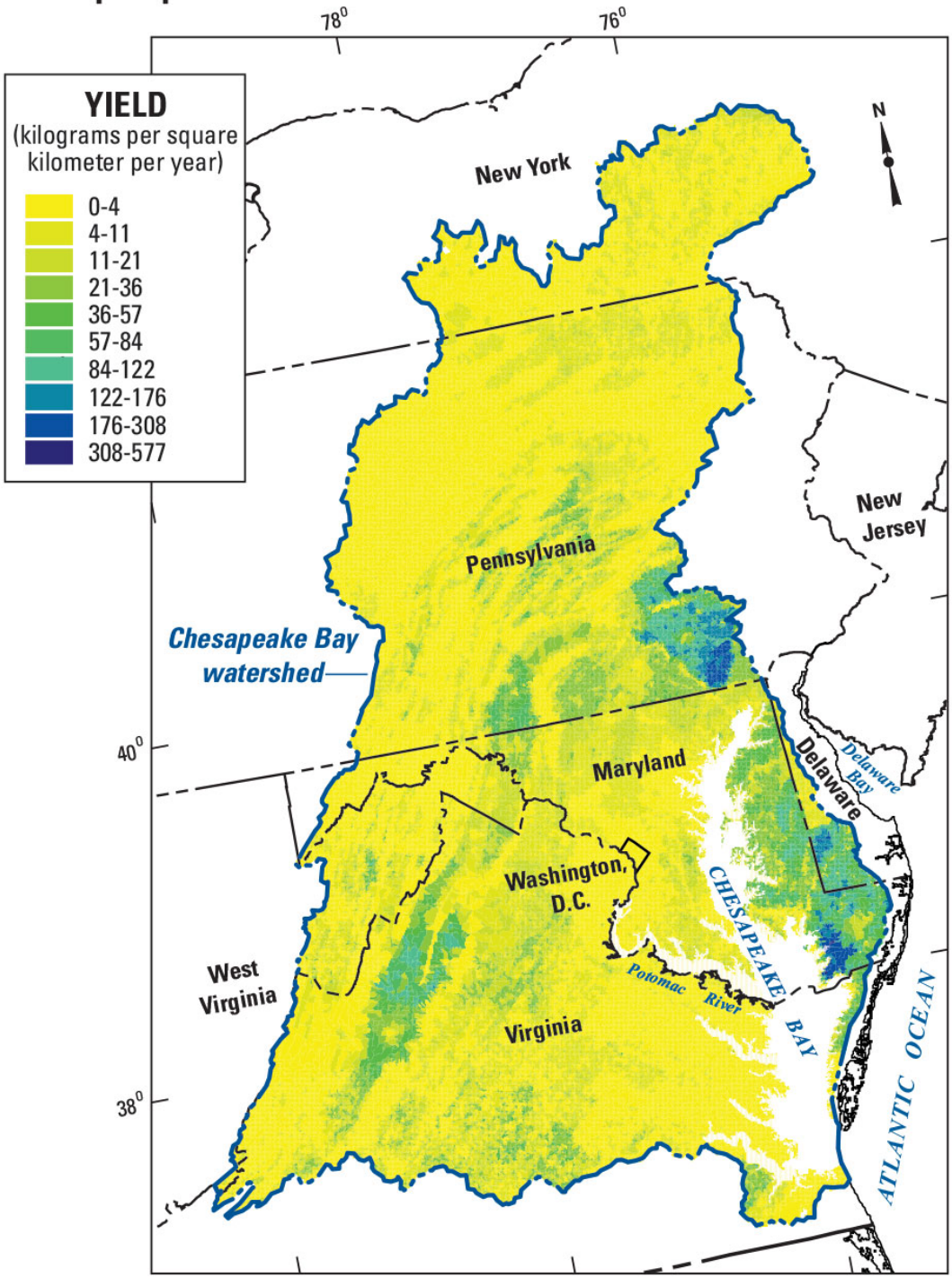
C. Total phosphorus attributable to fertilizer application



D. Total phosphorus attributable to manure



BASE FROM U.S. GEOLOGICAL SURVEY 1:2,000,000
STATE BOUNDARY DIGITAL LINE GRAPH, ALBERS
EQUAL AREA PROJECTION, NAD 1983

0 50 KILOMETERS
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Figure 1. Estimated local yields of total nitrogen and total phosphorus from agricultural sources in the Chesapeake Bay watershed. (Modified from Ator and others, 2011). Spatially descriptive maps of nutrient yields from specific sources are useful for maximizing the effectiveness of restoration actions by allowing resource managers to target the location and type of sources associated with the greatest yields.

Nutrient Fate and Transport

- Most of the nutrient load (nearly two-thirds of the nitrogen and nearly half of the phosphorus) to Chesapeake Bay is contributed by the two largest tributaries in the watershed, the Susquehanna and Potomac Rivers (fig. 2).

- Impoundments such as lakes, ponds, or reservoirs significantly decrease the instream flux of nutrients.
    - Nitrogen losses in impoundments are likely caused primarily by denitrification, a natural process that occurs when bacteria convert nitrogen in the form of nitrate to nitrogen gas.

    - The settling of particulates with attached phosphorus within the water column accounts for phosphorus storage in impoundments. Over many decades, some reservoirs continue to retain large amounts of sediment. Others, such as those on the lower Susquehanna River, however, are rapidly reaching or have already reached their retention capacities, and are no longer effective sinks of sediment and its associated phosphorus. During high flows, when reservoir scour can occur, this “legacy sediment” becomes remobilized, providing an additional source of phosphorus to the bay.

- Terrestrial nitrogen losses occur through plant uptake and soil denitrification.

- Groundwater is an important pathway for the transport of nitrogen (as nitrate) to local streams or directly into tidal waters, particularly in areas underlain by carbonate bedrock (such as limestone) or permeable sand and gravel (such as much of the Delmarva Peninsula).

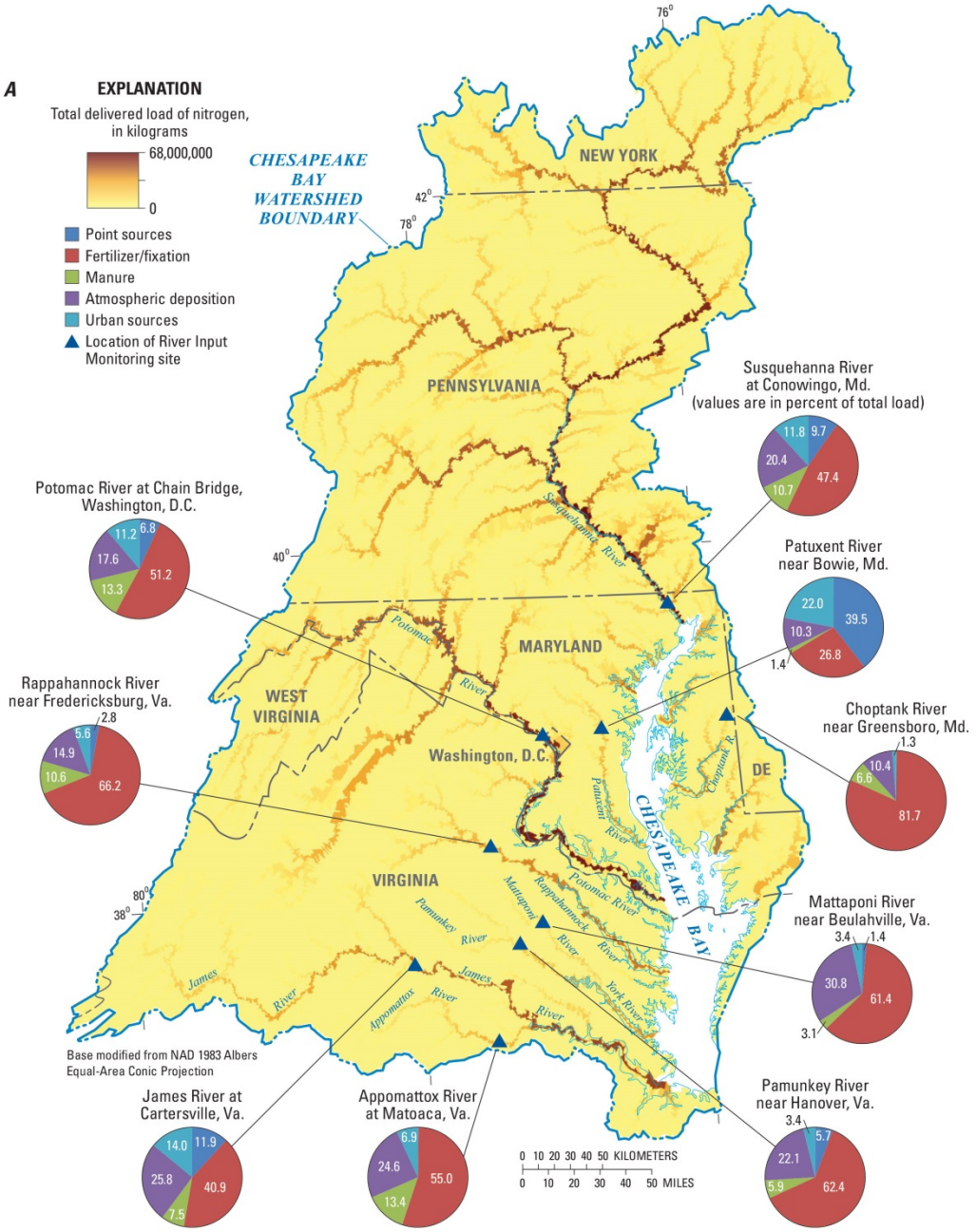
- Nitrogen transport is most efficient (that is, more of the available nitrogen is transported to streams) in areas where groundwater recharge from precipitation is substantial, in areas of the Piedmont Physiographic Province that are underlain by carbonate rocks, and in locations where groundwater is oxic (contains dissolved oxygen), such as in the well-drained soils in agricultural areas of the Piedmont and Coastal Plain Provinces.

- Nitrogen transport in flowing streams is least efficient (that is, losses are greatest and less of the available nitrogen is transported to the bay) in small streams where water has the greatest contact with the streambed and, therefore, is most affected by the biological and chemical processes that occur there. In larger tributaries, nitrogen transport is more efficient (losses are smaller and more of the available nitrogen is transported to the bay), particularly in the colder (more northerly) parts of the watershed, where biological processes are limited by lower temperatures.

- Although much nitrogen is lost along streams, particularly in the upper Potomac River watershed, the greatest yields (loads per unit area of watershed) of nitrogen delivered to Chesapeake Bay are contributed from agricultural areas of the northern Piedmont and Valley and Ridge Provinces, where cooler temperatures and (or) short travel distances to the bay limit nitrogen losses as the water moves downstream to the bay.

- Phosphorus transport to streams is most efficient in areas with poorly drained, erodible soils and (or) higher than average precipitation.

- Phosphorus transport to streams is greater in the Coastal Plain than in other physiographic regions. Because this region has a long agricultural history, the soils may be at or near saturation with respect to accumulated phosphorus from the application of chemical fertilizer and animal manure, thereby decreasing the retention of additional applied compounds by the soil.



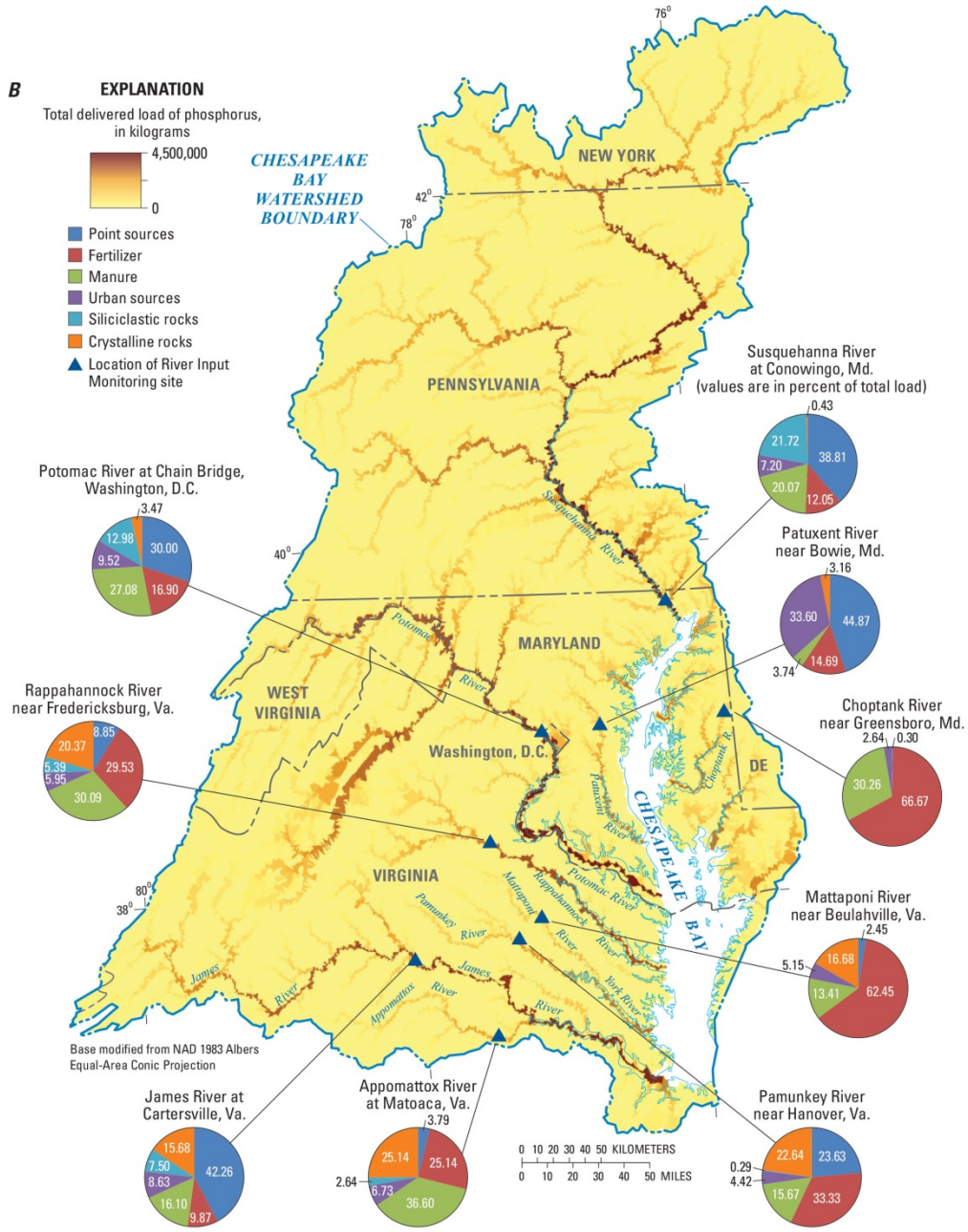


Figure 2. Estimated instream loads and contributions to total loads from individual sources for (*A*) total nitrogen and (*B*) total phosphorus in major tributaries of the Chesapeake Bay watershed. The relative magnitudes of sources of nitrogen and phosphorus loads differ among these nine Chesapeake Bay tributaries. (Data from Ator and others, 2011)

Implications for Management Policies and Practices and Next Steps

- SPARROW results are being used at various scales by Federal, State, and municipal water-quality agencies to identify the sources and geographic areas that produce significant nutrient inputs to Chesapeake Bay. These evaluations are used to set priorities and allocate resources in order to carry out the WIPs. These plans are designed to reduce nutrient inputs and focus resources and management practices where they will have the greatest impact in order to meet established TMDLs (U.S. Environmental Protection Agency, 2010) (fig. 3).

- Simulation results obtained by using the previous Chesapeake Bay SPARROW models (Brakebill and Preston, 2004) have been used regionally by the U.S. Department of Agriculture (USDA) and EPA to identify and prioritize watersheds that contribute high nutrient yields from agricultural sources. As a result, these Federal agencies allocated most of the funding from the Chesapeake Bay Watershed Initiative (CBWI) Farm Bill Program to these areas.

- The USGS is expanding its collaboration with the EPA, USDA, and State agencies to assist in the application of the new SPARROW results so that additional partner agencies can prioritize areas and allocate monetary resources to local governments. The following programs are currently utilizing the new SPARROW models to help direct resources for implementing water-quality-improvement actions: EPA implementation grants, EPA Chesapeake Bay Regulatory and Accountability Program grants, several USDA Conservation Programs, the National Fish and Wildlife Foundation, the Chesapeake Bay Stewardship Fund (National Fish and Wildlife Foundation, 2012), and the Maryland Bay Trust Fund.

- The USGS is working directly with County agencies applying SPARROW results to identify areas that contribute large nutrient yields from point and nonpoint sources. These activities support current TMDL allocations by providing detailed information that can be used to help local partners implement their WIPs and associated assessments. These plans allow resource managers to prioritize specific areas and nutrient-source sectors at the sub-county level, to direct resources to those management actions that have the greatest potential to improve local water-quality conditions, and to maximize the effectiveness of their investment to reduce nutrient transport to Chesapeake Bay in order to meet local TMDLs and achieve the greatest water-quality benefit.

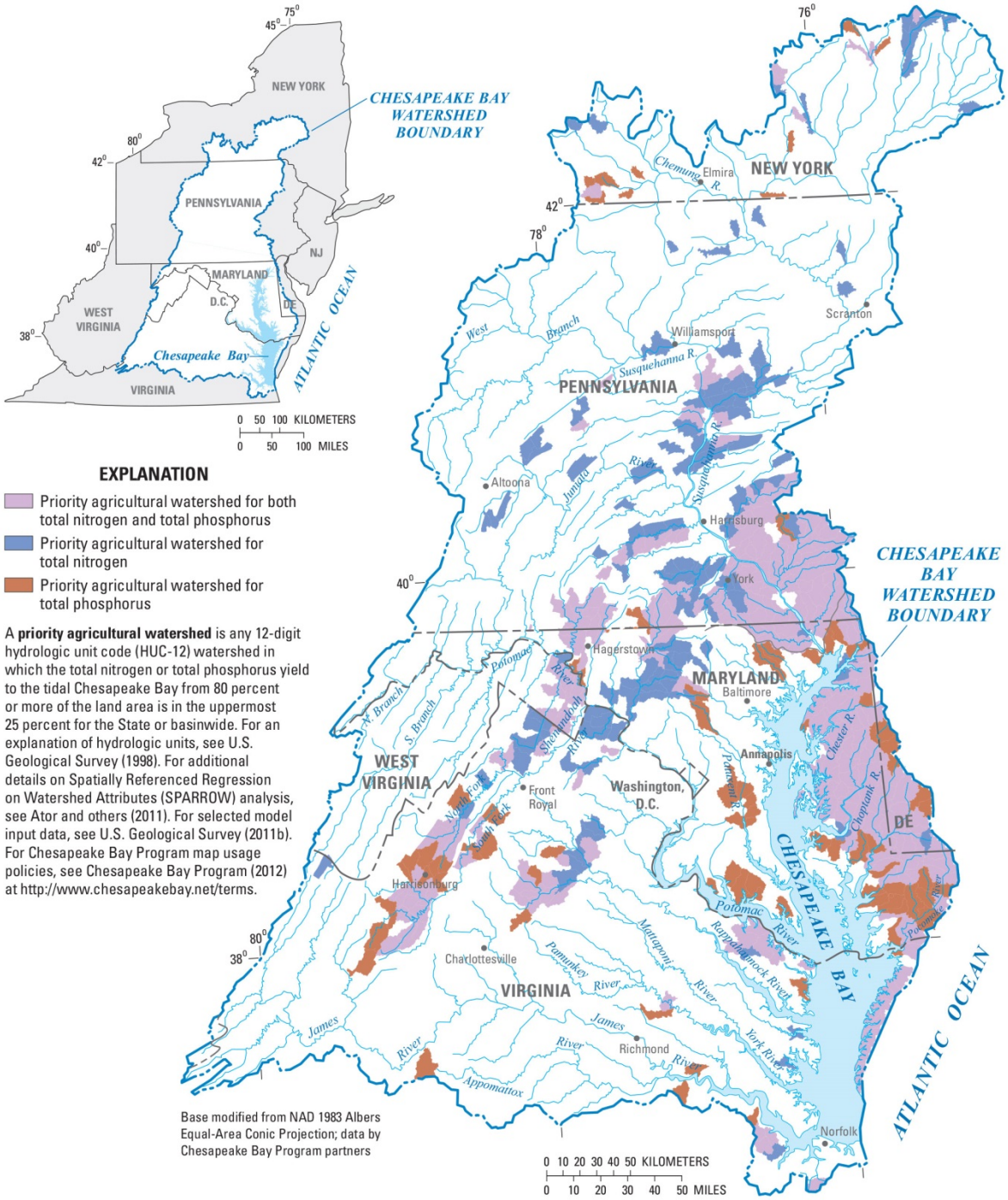


Figure 3. Priority agricultural watersheds were computed by Chesapeake Bay Program partners using nutrient SPARROW model results. The identification of priority agricultural watersheds helped to direct Chesapeake Bay Stewardship Fund grants to areas that contribute the greatest yields of total nitrogen and total phosphorus to Chesapeake Bay (National Fish and Wildlife Foundation, 2012). This and other similar maps allow Government agencies and nonprofit groups to focus limited resources where they are likely to have the greatest impact.

Data Availability

- A Web-based Decision Support System (DSS) has been developed that allows users to visualize results obtained with the Chesapeake Bay watershed SPARROW and other regional and national models to evaluate potential local and downstream effects of changes to nutrient inputs for all or part of the model region (*http://cida.usgs.gov/sparrow/*) (U.S. Geological Survey, 2011a).

- SPARROW predictions and measures of model uncertainty are available in Ator and others (2011, appendix) and are easily georeferenced to the 1:100,000-scale National Hydrography Dataset Plus (NHDPlus, an integrated suite of application-ready geospatial datasets) stream and catchment datasets (Horizon Systems, 2010) for detailed analysis within geographic information systems.

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For More Information

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