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Regional Assessments of the Nation's Water Quality—Improved Understanding of Stream Nutrient Sources Through Enhanced Modeling Capabilities

The U.S. Geological Survey (USGS) recently completed assessments of stream nutrients in six major regions extending over much of the conterminous United States. SPARROW (SPAtially Referenced Regressions On Watershed attributes) models were developed for each region to explain spatial patterns in monitored stream nutrient loads in relation to human activities and natural resources and processes. The model information, reported by stream reach and catchment, provides contrasting views of the spatial patterns of nutrient source contributions, including those from urban (wastewater effluent and diffuse runoff from developed land), agricultural (farm fertilizers and animal manure), and specific background sources (atmospheric nitrogen deposition, soil phosphorus, forest nitrogen fixation, and channel erosion).

These regional SPARROW modeling assessments

- Provide the most comprehensive studies to date of the sources, transport, and fate of nutrients in the streams of six major regions of the conterminous United States (U.S.), based on national compilations of water-resource geospatial data from federal, state, and local water agencies. Advances in scientific understanding and modeling tools made from these assessments can be used by decision-makers to evaluate the sources and environmental factors that control stream nutrients at scales ranging from small catchments and counties to large watersheds, states, and regions.
- Confirm the importance of urban and agricultural sources as major contributors of nutrients to U.S. streams but provide new information about local and regional differences in nutrient contributions from contrasting types of agricultural (farm fertilizers and animal manure) and urban (wastewater effluent and diffuse runoff from developed land) sources.
- Indicate that highly diffuse background sources of nutrients that may be natural or anthropogenic in origin are the dominant sources of nutrients to many U.S. streams where other large sources are not present. This adds new information that has been difficult to quantify in local water-quality assessments yet is needed to develop comprehensive and realistic nutrient-management goals.
- Describe the sources and quantities of nutrients that are delivered to downstream sensitive water bodies, such as reservoirs and estuaries, where nutrient inputs can contribute to excessive algal growth and degraded water-quality conditions. These results account for the effects of natural factors (such as climate, soils, and hydrology) and human-related factors (such as farm tile drainage) that influence the attenuation and transport of nutrients at local scales in small drainages as well as at regional scales in large watersheds.

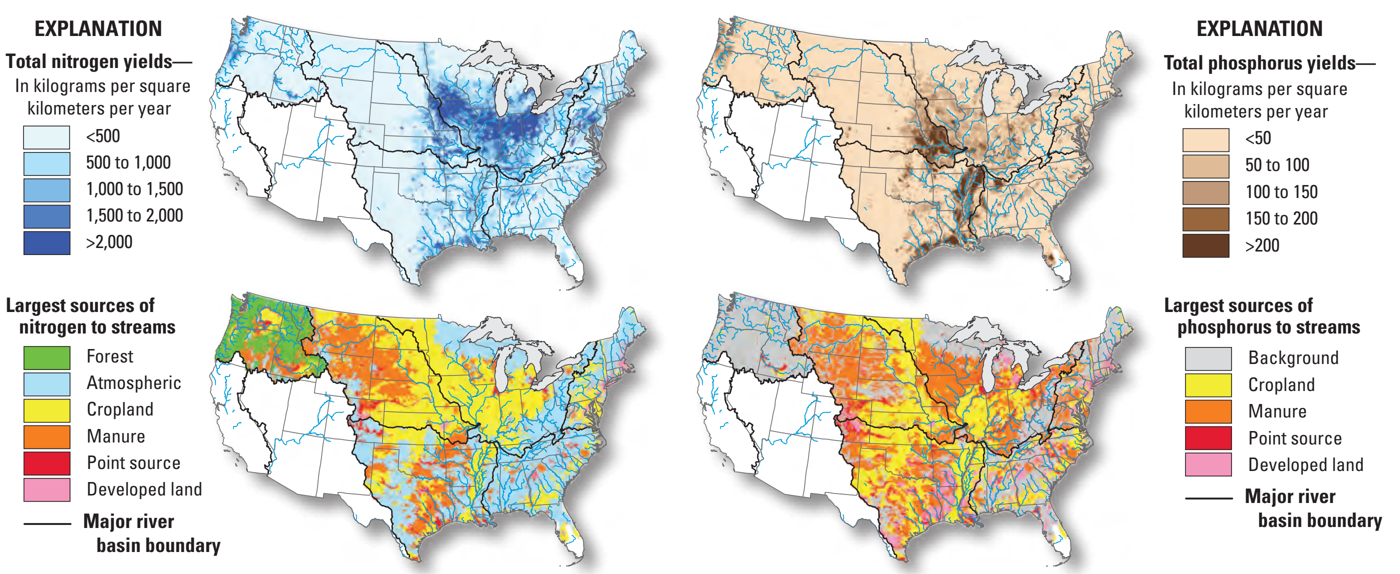


Figure 1. Estimates developed from separate regional models for six large regions of the conterminous United States illustrate the spatial distribution of total nitrogen and total phosphorus yield from individual stream-reach drainages and the largest contributing source to each stream reach drainage.

Urban and Agricultural Sources of Nutrients to Streams

On a regional basis, urban sources (wastewater effluent, diffuse runoff from developed land) contribute from 12 to 48 percent of the nitrogen to streams and from 19 to 63 percent of the phosphorus; the largest contributions occur in the Northeast and Mid-Atlantic regions. Wastewater effluent contributes the largest share of nutrient mass to urban streams (more than 69 percent) and can compose a relatively large percentage of the total load to downstream receiving waters. In some areas, nutrients from wastewater-effluent discharges are transported over hundreds of kilometers in streams and are the largest contributor among all sources to distant downstream water bodies. Urban diffuse runoff contributes less overall mass of nutrients, but given its highly diffuse nature, it affects a larger number of urban streams and is the larger local source to 43 to 98 percent of urban streams, depending on the region.

Agricultural sources (farm fertilizers, animal manure) contribute from 23 to 70 percent of the nitrogen and 13 to 59 percent of the phosphorus to streams; the largest contributions occur in the Midwest and central regions of the Nation. Over broad areas of these regions and in selected areas of the East, animal manure contributes larger quantities of nitrogen and phosphorus compared to farm fertilizer (fig. 1). In most other areas, farm fertilizers (and the associated runoff from cultivated lands) generally contribute more nitrogen to streams and nearly equal quantities of phosphorus compared to animal manure.

Background Sources of Nutrients to Streams

In all drainages, some of the nutrient mass transported to streams is due to highly diffuse or even ubiquitous sources that could be natural or anthropogenic in origin. For example, nitrogen fixation or plant degradation are naturally occurring processes that provide some nitrogen to streams broadly across the landscape. Soil erosion occurring across an entire region can add phosphorus to streams that could be naturally occurring or that could have originated from human activities. Lastly atmospheric deposition is a widespread source of nitrogen that is highly diffuse in nature but is entirely anthropogenic in origin. In general, we refer to these highly diffuse sources as “background” simply because they tend to occur ubiquitously throughout the landscape and are difficult to quantify without a model like SPARROW. Further, these diffuse sources are important because they can be the largest sources in some drainages, and accounting for them is critical for establishing water-quality management goals that are both appropriate and feasible. The SPARROW model results described herein provide unique information for identifying and quantifying background sources for such water-quality management goals.

Natural background sources are the largest contributors of nutrients, among all sources, in many streams in the Pacific Northwest, the Northeast and mid-Atlantic, and the Southeast where other major nutrient sources do not occur. In the Pacific Northwest, forests contribute 51 percent of the nitrogen to streams and represent the largest source to 70 percent of the stream miles. Forests (especially red alder stands that foster nitrogen fixation) contribute as much as 97 percent of the nitrogen to streams of the western Cascade Mountains. Forest land also was identified as a source of phosphorus in a number of the regional models. However, forest land generally serves as a surrogate indicator of sources that are assumed to be from the erosion of soil or geologic material, or from plant degradation that may be associated with forests.

Background sources of phosphorus identified by the models include stream-channel erosion, geologic properties (soils), and forested lands. Stream-channel erosion is an especially important phosphorus source in the Missouri River basin, where it contributed 23 percent to stream reaches on average and as much as 97 percent to some streams. Phosphorus in eroded sediments may originate from both natural sources (such as soils) and human sources (such as wastewater-treatment effluent). Soils are a major natural phosphorus source to streams of the Southeast, contributing 41 percent on average and more than 73 percent to some streams. Forests are important natural background sources in three regions including the Northeast and upper and lower Midwest.

Atmospheric deposition from local and distant anthropogenic sources is the largest contributor of nitrogen to many streams in the south-central, mid-Atlantic, and northeastern U.S. Across the six regions atmospheric deposition contributes from 5 to 46 percent of the total mass of nitrogen to streams. The largest contributions occur to streams of the Southeast, where atmospheric deposition contributes up to 46 percent of the nitrogen and is the largest source to 78 percent of the stream miles. Although atmospheric deposition contributes less than 20 percent of the nitrogen to the streams of the Northeast, it is the largest source to nearly 50 percent of the stream miles in this region. Atmospheric sources in the models primarily reflect nitrogen deposition from distant stationary emission sources, such as power plants, but also include minor contributions from local ammonia emissions associated with farm fertilizers and livestock and nitrogen from urban sources associated with automotive exhaust.

Percentage of Phosphorus Yield Due to Naturally Occurring Geologic Material

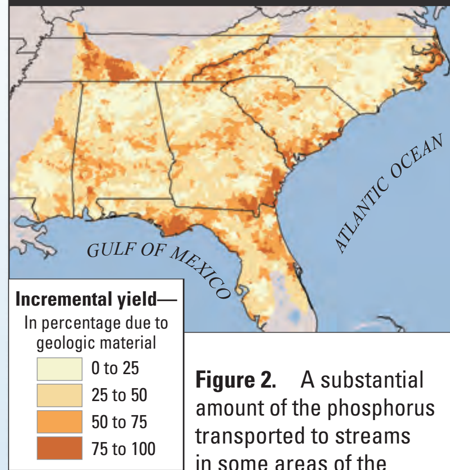


Figure 2. A substantial amount of the phosphorus transported to streams in some areas of the Southeast is derived from naturally occurring geologic sources. Understanding the distribution of natural and human sources of phosphorus transported to streams is critical in developing realistic nutrient-reduction strategies.

Environmental Processes Affecting Nutrient Delivery to Streams and Downstream Waters

Natural environmental processes and some human activities on the landscape can affect the delivery rates of nutrients to streams either by enhancing delivery or by reducing it through attenuation processes. Knowledge of the effects of these environmental factors can be used to identify high-priority watersheds with low levels of natural attenuation where nutrient-source reductions generally would be expected to have greater downstream benefits—that is, the most efficient response per unit of upstream reduction. Conversely, watersheds with high natural attenuation of nutrients could be given lower priority if the goal was to improve downstream water quality.

In most areas of the country, only a small fraction of the nutrient mass that is input to watersheds on an annual basis is actually delivered to streams and downstream water bodies. This is because nitrogen and phosphorus commonly are attenuated during transport as a result of the effects of many physical and biochemical processes. These may include nutrient uptake by plants, adsorption to soil particles, storage in the subsurface from leaching to groundwater, and denitrification (the conversion of reactive nitrogen to an inert gaseous form that is released to the atmosphere). Human activities also can affect the rates of nutrient attenuation. For example, large quantities of nutrients on cultivated lands (from farm fertilizers or natural nitrogen fixation) are assimilated in crops and exported from watersheds in harvested grains and plant residues. In addition, natural processes in streams and reservoirs (such as assimilation, settling and storage of and denitrification) remove nutrients before they can reach downstream waters.

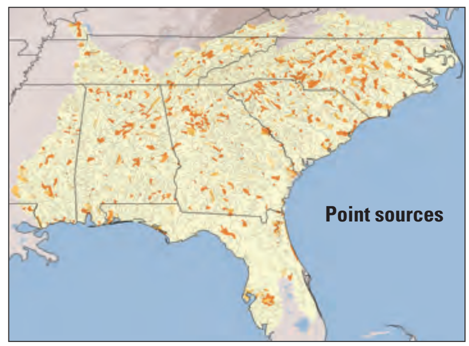
Large differences in nutrient yields from west to east across the U.S. (fig. 1) are explained in part by variations in climatic factors (precipitation and temperature). These are fundamental measures of water and energy availability that control the rates of nutrient movement and loss on the land and in streams and reservoirs. For example, nutrient yields are among the lowest throughout much of the West because of the prevailing arid conditions that limit nutrient runoff and delivery to streams and downstream waters. This occurs despite a diversity of important sources,

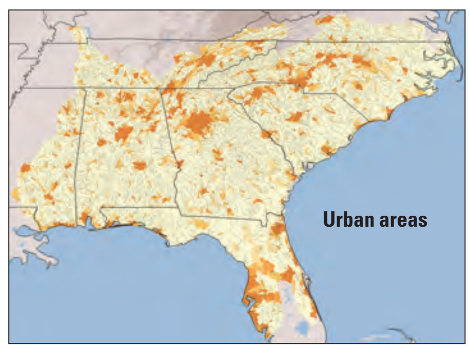
SPARROW Decision Support System—Informing Nutrient Management Decisions

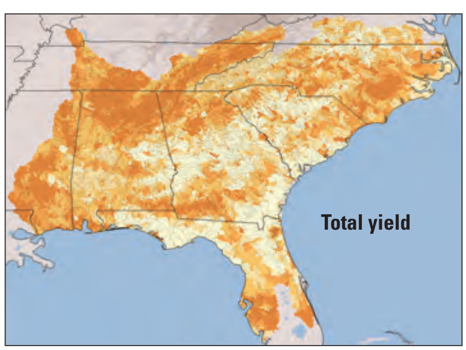
Water-resource managers and policy makers have relied on hydrologic and chemical models to estimate current water-quality conditions and predict how conditions might change in response to a selected policy decision. It is often difficult, however, for decision makers to readily access model information and use models directly to evaluate a range of alternative scenarios. The SPARROW Decision Support System provides easy access to SPARROW model results. By making this capability available over the Internet in a user interface with familiar controls, modelers and water-resource managers alike can experiment with hypothetical scenarios and develop science-based estimates regarding the effects that specific contaminant sources or changes may have on water quality. These estimates can then be easily communicated to stakeholders and the general public through the same website. Equally important, the Decision Support System provides estimates of model uncertainty to inform managers about the range of variability in model predictions of stream loads that can be attributed to uncertainties about how well the models describe actual water-quality conditions and the factors that influence these conditions.

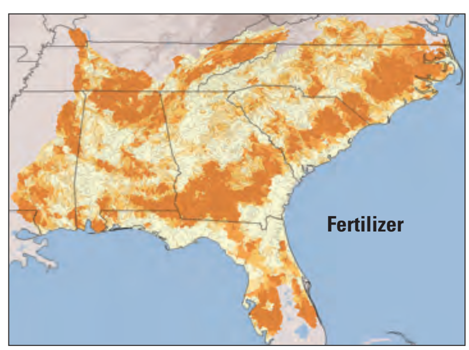
Comprehensive information on how the SPARROW models were developed, data sets used to calibrate the models, and instructional videos are available on the Decision Support System. Users also can save user-defined management scenarios and share the session with colleagues. Options also are available to export model output data from selected areas for use in other applications.

The Decision Support System can produce a variety of maps to show the spatial variability in nutrient yields and the sources that contribute the largest amounts of nutrients throughout a large region, such as the southeastern U.S.









Incremental yield—
In kilograms per square kilometers per year

- <240
- 240 to 320
- 320 to 400
- 400 to 580
- >580

Incremental yield—
In kilograms per square kilometers per year

- 0 to 30
- 30 to 60
- 60 to 90
- 90 to 120
- >120

The SPARROW Decision Support System can be accessed at *http://water.usgs.gov/nawqa/sparrow/dss*.

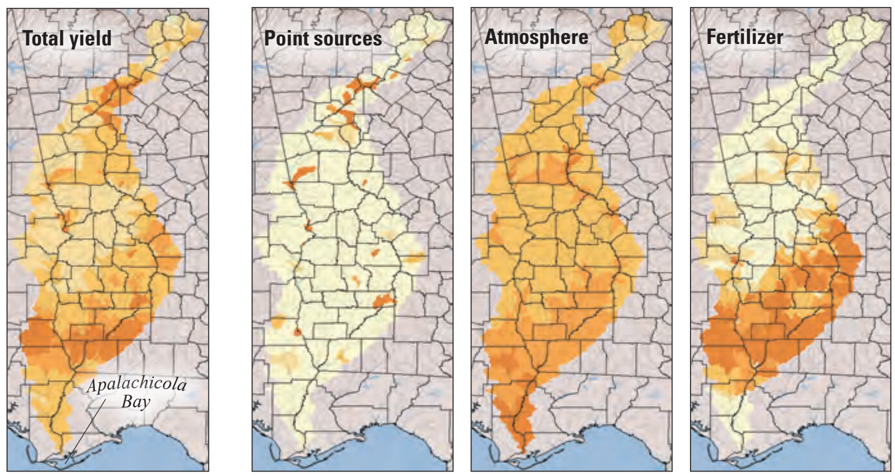
Nitrogen Delivery to Estuaries

Over past decades, human activities have accelerated nutrient inputs to U.S. estuaries, thus contributing to excessive algal growth and degraded conditions in the estuaries. About two-thirds of the 138 U.S. estuaries have moderate to high levels of eutrophication, with about one-half identified as having impaired human or ecological uses that are associated with eutrophic conditions (Bricker and others, 1999). Managers can use the Decision Support System to identify the watersheds and sources that contribute the largest amounts of nutrients that are delivered to nutrient-sensitive estuaries. These capabilities are illustrated for the Apalachicola Bay where agriculture (fertilizer applications to cultivated lands) and atmospheric deposition account for about two-thirds of the total nitrogen load entering the bay, with wastewater effluent contributing nearly 20 percent of the total load. Additional displays from the system can be used to identify inland watersheds that deliver the highest amounts of nitrogen to the bay and may, therefore, be useful for ranking management actions. Watersheds contributing the highest amounts to the bay are near Atlanta (from point sources) and in the southern parts of Georgia and Alabama (from the atmosphere and fertilizer). Reductions in the stream-nutrient loads leaving the watersheds with the highest contributions generally would be expected to lead to a more efficient reduction in loads entering the bay—that is the reduction in load to the bay per unit of load removed upstream would be expected to be larger for these watersheds compared to the reduced loads in watersheds with relatively low delivered yields. A notable management challenge faced in the Apalachicola Bay, as in other southeastern coastal waters where atmospheric deposition is a large source, is that atmospheric nitrogen frequently originates from distant sources (such as power plants) located outside of the watershed.

The Decision Support System can be used to evaluate nutrient-reduction scenarios. The model estimates that a 25-percent reduction in point, atmospheric, or fertilizer sources individually results in a less than 10-percent reduction in the nitrogen load delivered to Apalachicola Bay. Reducing all three sources by 25 percent would reduce the nitrogen load delivered to the bay by 21 percent.

Understanding the sources and which watersheds contribute the largest amounts of nutrients to nutrient-sensitive waters can assist managers in the development of nutrient-management strategies.

Nitrogen Yields Delivered from Upland Watersheds to Apalachicola Bay



Incremental delivered yield—
In kilograms per square kilometers per year

- 0 to 75
- 75 to 150
- 150 to 300
- 300 to 420
- > 420

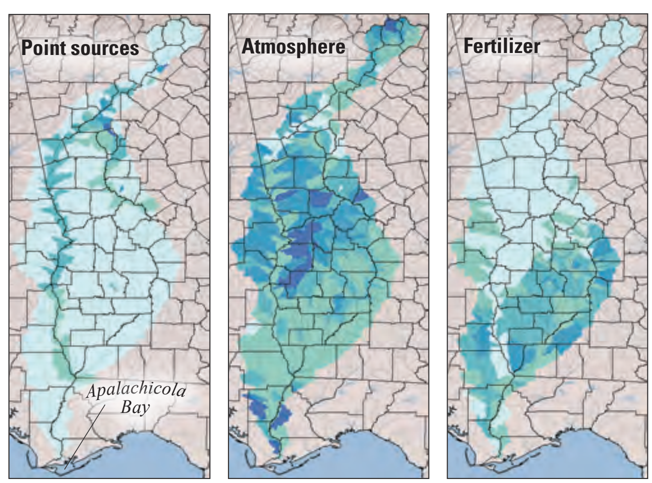
Incremental delivered yield—
In kilograms per square kilometers per year

- 0 to 25
- 25 to 50
- 50 to 100
- 100 to 140
- > 140

Three Nitrogen Reduction Scenarios
25-Percent Reduction in Nitrogen Inputs

Change in total delivered load of nitrogen, in percentage, to Apalachicola Bay

- –25 to –20
- –20 to –15
- –15 to –10
- –10 to –5
- –5 to 0



Reduction in nitrogen load delivered to Apalachicola Bay

5 percent **9 percent** **7 percent**

ranging from agriculture and atmospheric deposition in drier areas of the Midwest to forest and other background sources in the Pacific Northwest. By contrast, nutrient yields are generally higher in the more humid watersheds of the Midwest and East. Figure 3 illustrates precipitation patterns and phosphorus yields in the Missouri River basin where the highest delivered yields to the mouth of the river occur in the lower end where precipitation rates are higher. Nutrients generated in the upper portions of the drainage tend to have low delivery rates due in part to lower precipitation and other environmental characteristics that may affect delivery to streams or limit the amount transported downstream.

Soil and topographic properties (soil permeability and depth, erodibility, acidity, organic matter, and land slope) were found to be important factors affecting nutrient delivery to streams in many of the regional models. Soil permeability was important in three of the six regions and was inversely related to nutrient loads in streams; the observance of lower nutrient loads in streams of watersheds with higher soil permeability may reflect the effects of greater infiltration of water and nutrients in these watersheds with subsequent storage and (or) denitrification-related losses in soils and groundwater. Farm-management activities also can affect soil drainage and nutrient delivery to streams. For example, the nitrogen transport to streams in the Midwest and the Missouri River basin was appreciably affected by the use of irrigation and tile drains. Stream nitrogen loads entering the Mississippi River from the Missouri River basin were estimated to be reduced by as much as 17 percent as a result of increased anoxia and denitrification on irrigated farm lands. By contrast, nitrogen loads in streams of the upper Midwest region were found to increase with the percentage of land area drained by tile-drainage systems which are extensively used in the Midwest to support corn and soybean cultivation.

Nutrient attenuation processes in streams and reservoirs, caused by denitrification and the nutrient storage in particulates, reduce the quantities of nutrients delivered to local and distant downstream waters in many of the regions. Nutrient removal in reservoirs was identified as important in five of the six regions. Approximately 16 percent of the nitrogen load and 33 percent of the phosphorus load in the Missouri River were removed with nearly half of the total removal occurring in the eight largest reservoirs. The rates of nitrogen removal in streams (expressed as a fraction of the nutrient mass removed per unit of water travel time) declined with increases in stream depth (stream size) in many of the regions, thereby indicating that the largest rates of in-stream nutrient removal generally occur in the smallest streams. This relation reflects the reduced capability of streams to remove nitrogen as water volumes increase with stream size, leading to less particulate settling (nitrogen and phosphorus storage) and less water and nitrogen contact with benthic sediments (where denitrification occurs).

Development of Regional SPARROW Models for the Conterminous United States

The USGS developed the spatial water-quality model SPARROW to assist with the interpretation of available water-resource data and provide predictions of water quality in unmonitored streams. The modeling framework was developed originally for and applied at the national scale, but models have since been developed for specific regions of the U.S. and outside of the U.S. for specific countries. SPARROW is a hybrid empirical and process-based mass-balance model that has been used previously in major U.S. river basins to estimate the primary sources and environmental factors that affect the supply, transport, and fate of contaminants in streams for mean annual conditions (see *http://water.usgs.gov/nawqa/sparrow/* for a more detailed description).

Recently, the USGS developed new SPARROW models to assess nutrient conditions in streams of six large regions of the conterminous U.S. (Major River Basins; fig. 4). The documentation for these models and the results and example nutrient-management applications were published as part of a featured collection in the Journal of the American Water Resources Association (Preston and others, 2011). These regional models provide an updated assessment of nutrients in most streams of the conterminous U.S. based on a more current and refined set of national geospatial data. Major advances were made in expanding the number of sites

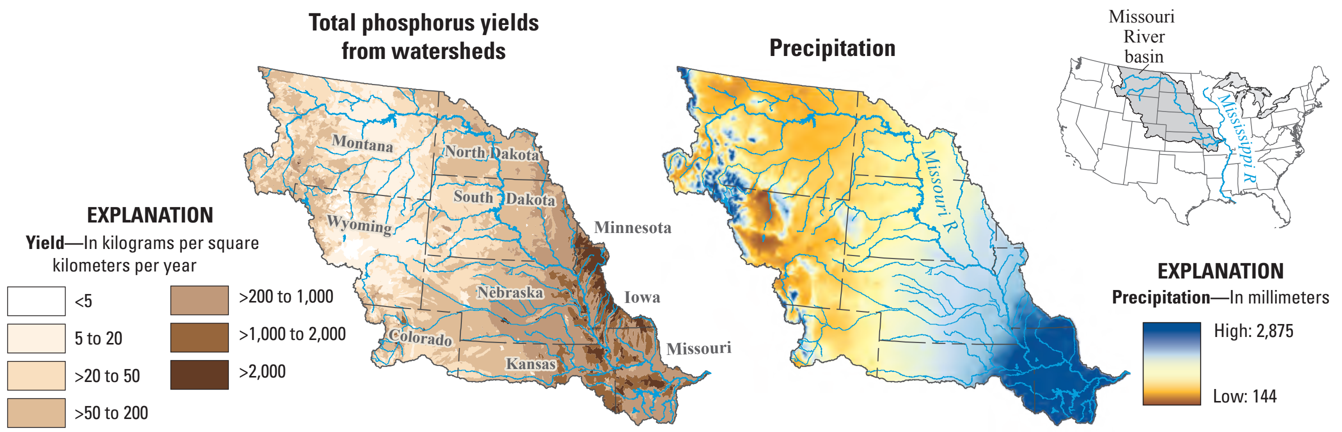


Figure 3. The amount of phosphorus transported to streams in the Missouri River basin is related to climatic conditions. The highest phosphorus yields occur in the lower part of the basin in part because greater rainfall allows more agriculture and in part because greater rainfall increases the transport of phosphorus to streams.

with stream loads derived from monitoring information, developing a data base for describing effluent discharges from industrial and municipal wastewater-treatment facilities, and developing data sets for describing background nutrient sources. All of these data were used with other national geospatial data (for example farm fertilizer, animal manure, land-use, climate, soils, topography, stream-network properties) to calibrate the SPARROW models to provide accurate accounting of nutrient sources and environmental processes for reliable predictions of nutrient loads in unmonitored streams.

Stream water-quality monitoring data were obtained from approximately 125,000 sites operated by 186 governmental agencies across the country through retrievals from public data bases and contacts with agency personnel. The data were screened to ensure that the number and length of the water-quality and streamflow records were sufficient for estimating long-term loads. This resulted in the selection of approximately 2,700 sites (from 73 monitoring agencies) with sufficient data to calibrate the models. Note that one important reason for the sizeable loss of water-quality data from the screening process reflects the common practice of collecting water-quality samples from stream locations without a nearby water flow gage; measures of streamflow are necessary to calculate a reliable measure of the nutrient mass (load) as required for source-transport models such as SPARROW.

The estimates of long-term nutrient loads at monitoring sites used to calibrate the regional model reflect water-quality conditions for 2002, and also reflect long-term mean streamflows over the 1975 to 2005 period. The use of the long-term mean streamflows to estimate the monitoring site loads, rather than the flows during only 2002, ensures that the SPARROW regional model estimates of stream nutrient load, source contribution to streams, and environmental processes that govern the mean rates of nutrient removal and transport in watersheds are representative of long-term hydrologic variability.

Estimates of the nutrient loads in effluent discharges from 23,481 industrial and municipal wastewater-treatment facilities were based on data retrievals from the U.S. Environmental Protection Agency (USEPA) Permit Compliance System. The loads reflect the application of systematic procedures by USGS to evaluate and enhance the quality of the data for estimating loads. The procedures included the validation of facility locations, correction of erroneous data, and the use of “typical” effluent concentration values to represent missing or unreported data. The resulting data base provides the discharge estimates and point locations for nearly all of the major facilities that contribute the large majority of the point-source nutrient loads to streams.

Major River Basins

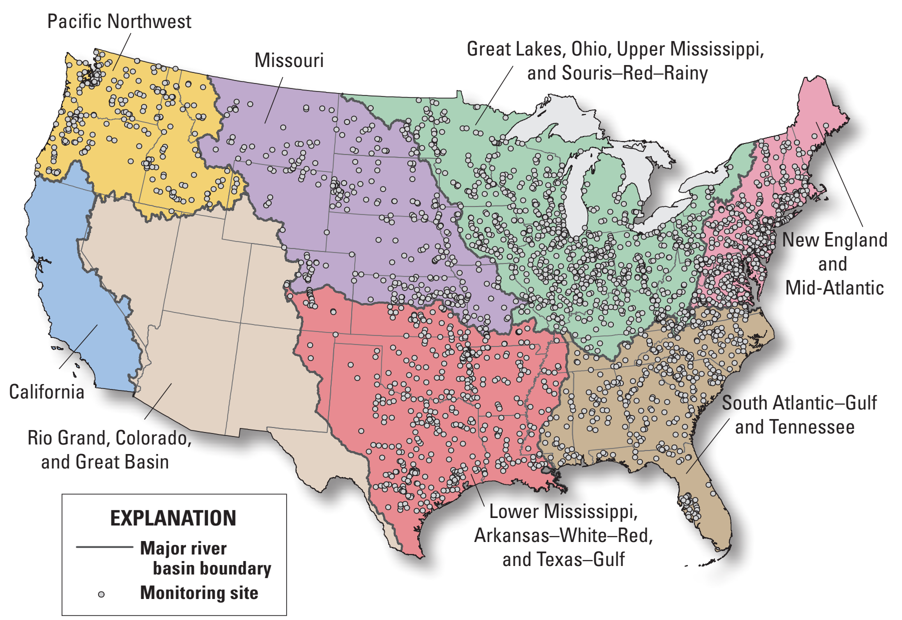


Figure 4. Stream water-quality data obtained from 73 local, state, and federal agencies at 2,700 monitoring sites were used to calibrate the six regional nutrient SPARROW models. A model of dissolved solids was developed for the Rio Grande, Colorado, and Great Basin region, where stream salinity is a major water-quality concern, and nutrient models are currently under development for the California region.

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