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SPARROW MODELING—Enhancing Understanding of the Nation's Water Quality

The information provided here is intended to assist water-resources managers with interpretation of the U.S. Geological Survey (USGS) SPARROW model and its products. SPARROW models can be used to explain spatial patterns in monitored stream-water quality in relation to human activities and natural processes as defined by detailed geospatial information. Previous SPARROW applications have identified the sources and transport of nutrients in the Mississippi River basin, Chesapeake Bay watershed, and other major drainages of the United States. New SPARROW models with improved accuracy and interpretability are now being developed by the USGS National Water Quality Assessment (NAWQA) Program for six major regions of the conterminous United States. These new SPARROW models are based on updated geospatial data and stream-monitoring records from local, State, and other federal agencies.

Benefits of Integrated Monitoring and Modeling

Successful management of our Nation's water resources requires an integrated approach to environmental assessment that includes both monitoring and modeling. Monitoring provides direct observations, often over time, of water-quality properties and characteristics, whereas models are tools for interpreting these observations. Modeling results can advance understanding of the relation of water quality to human activities and natural processes that affect spatial variations in quality.

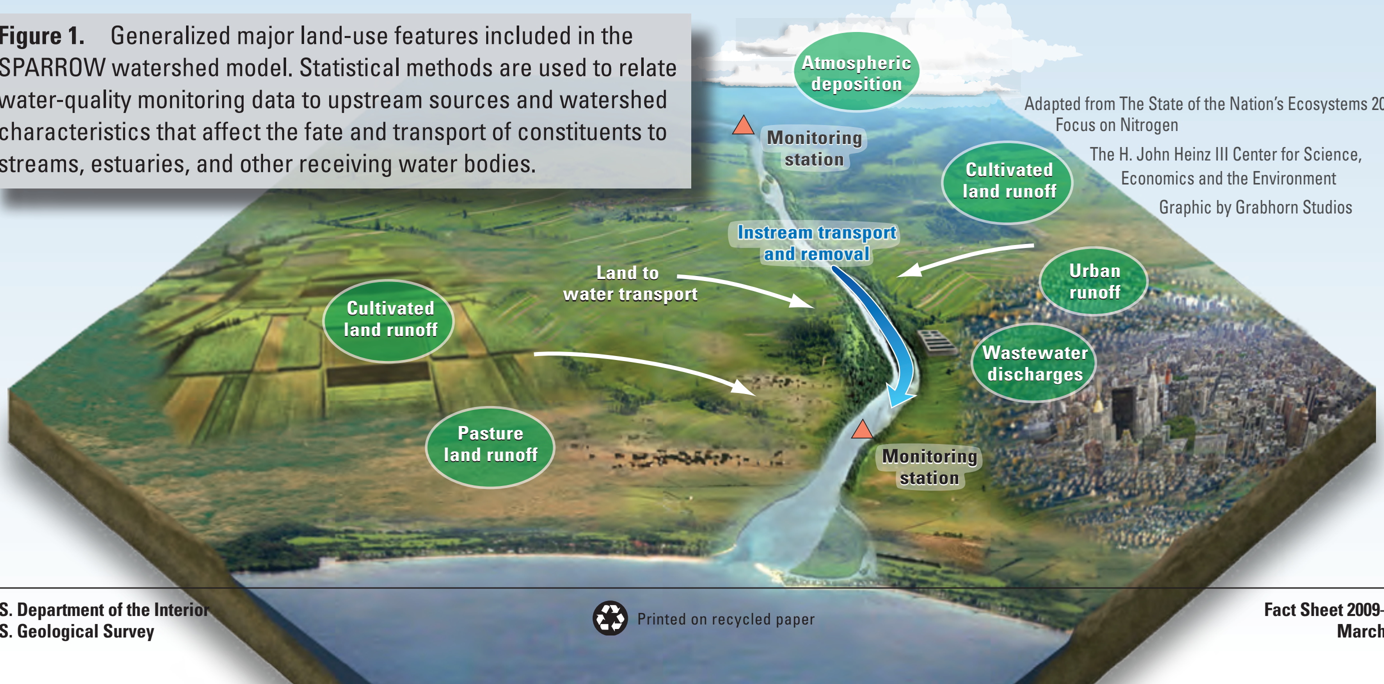
Specifically, models can be used to (1) establish links between water quality and constituent sources; (2) track the transport of constituents to streams and downstream receiving waters, such as estuaries; (3) assess the natural processes that attenuate constituents as they are transported from land and downstream; and (4) predict changes in water quality that may result from management actions or changes in land use.

Continued integration of monitoring and modeling is key to our future understanding and management of the Nation's water quality. Modeling results can help in a variety of management decisions, including those related to contaminant-reduction and protection strategies across broad regions and decisions about future monitoring and assessments of streams that are highly vulnerable to environmental degradation. Modeling can help in meeting regulatory requirements, such as those related to nutrient-management strategies and the development of total maximum daily loads (TMDLs). Finally, modeling can help in identifying gaps and priorities in monitoring; including identifying monitoring that might be redundant or unnecessary.

SPARROW Modeling

To support the need for water-quality modeling, USGS scientists developed a model that integrates monitoring data with landscape information. This model, known as SPARROW (SPAtially-Referenced Regression On Watershed attributes), is watershed based and designed for use in predicting long-term average values of water characteristics, such as concentrations and amounts of selected constituents that are delivered to downstream receiving waters. Statistical methods are used in SPARROW modeling to explain in-stream measurements of water quality (constituent mass or load) in relation to upstream sources and watershed properties (soil characteristics, precipitation amounts, and land cover) that influence the transport of constituents to streams and their delivery to receiving water bodies, including estuaries (fig. 1).

Figure 1. Generalized major land-use features included in the SPARROW watershed model. Statistical methods are used to relate water-quality monitoring data to upstream sources and watershed characteristics that affect the fate and transport of constituents to streams, estuaries, and other receiving water bodies.



Adapted from The State of the Nation's Ecosystems 2008: Focus on Nitrogen
The H. John Heinz III Center for Science, Economics and the Environment
Graphic by Grabhorn Studios

SPARROW models can be used to predict water-quality levels in streams across spatial scales ranging from small-sized watersheds (tens to hundreds of square kilometers [km^2]) to large river drainages (several million km^2). Simulation results can be used to identify atmospheric and land-based sources of constituents that affect water quality over large spatial scales or to estimate the origin and fate of constituents in streams and receiving bodies. In all cases, model estimates can be illustrated through detailed maps that provide information about constituent loadings at multiple scales for specific watersheds or geographic areas, especially in unmonitored areas.

SPARROW models integrate two data components—water-quality and streamflow data collected at numerous monitoring sites. These data are used to estimate the mass (annual load) of a constituent that is transported by the stream at each site. Geospatial data sets then are used to relate land-use features with load estimates, which provide information on constituent sources and natural factors that can affect constituent fate and transport (fig. 2).

Constituent sources for the purpose of SPARROW modeling include estimates of nitrogen mass in atmospheric deposition, nutrients (nitrogen and phosphorus) in commercial fertilizer applied to agricultural land, and nutrients in runoff from urban and other land uses. Watershed characteristics that affect land-to-water delivery of nutrients include soil permeability, wetland area, land-surface slope, and mean annual climatic factors, such as precipitation and temperature.

Geospatial data sets continually advance and change as new geographic information becomes available or as spatial resolution improves. Consequently, published SPARROW models have improved over time as updated and refined data have been used. In some cases, special geospatial data sets reflect unique local and regional characteristics in SPARROW models. One such example is a geospatial data set that characterizes the phosphate content of surficial geologic materials; this information is useful in quantifying natural sources of phosphorus to streams, particularly in the southeastern United States.

The spatial framework for SPARROW modeling is provided by a digital network of stream and reservoir-reach segments that are linked to contributing watersheds that were delineated using a digital-elevation model. For each stream segment, average watershed characteristics, constituent-source estimates, and monitoring-site locations are referenced to this digital network. Digital referencing links load estimates at monitoring sites to upstream watershed characteristics. It also links individual constituent sources to the river network, so that the source contribution to stream loads can be tracked and evaluated as the constituent attenuates during transport downstream. Finally, using the spatial framework, SPARROW model estimates can be illustrated through detailed maps that provide information about constituent loads at multiple scales, from single stream basins to larger geographic areas, including estimates for areas where little or no monitoring information is available.

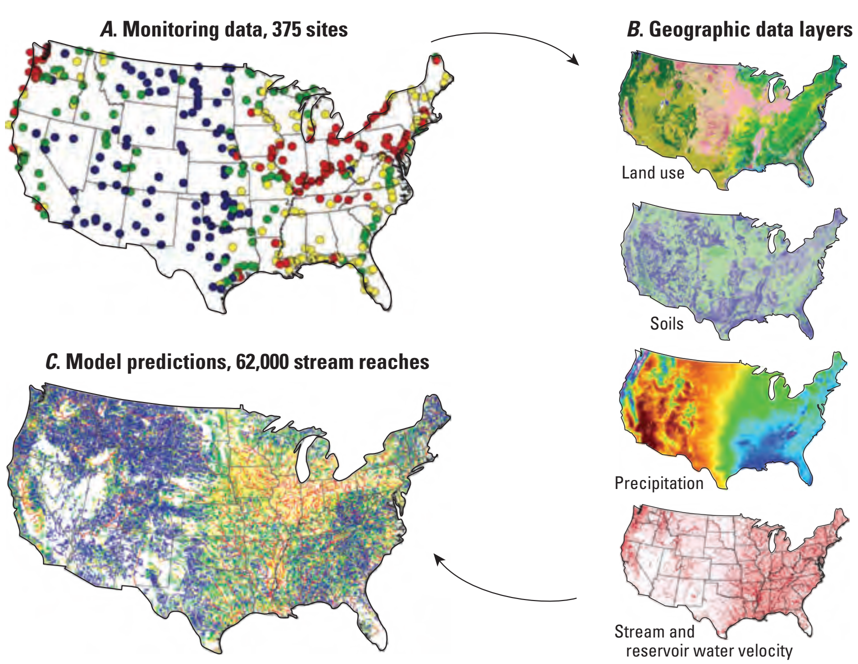


Figure 2. SPARROW models define spatial patterns in water quality, based on data collected at numerous monitoring sites *(A)*. Estimates of constituent loads at these sites are related to constituent sources, land use, and other factors that affect water quality (soils, precipitation), as well as stream characteristics (channel, velocity) *(B)*. Based on these relations, the model is used to predict water quality in unmonitored stream reaches for an entire region *(C)*.

Calibration and Uncertainty

SPARROW models are calibrated by using a statistical procedure that estimates model coefficient values to minimize the error between predicted and observed values of annual constituent loads at fixed monitoring sites. The calibrated model includes only the explanatory variables that show statistically significant relations to spatial patterns in annual constituent loads. This feature of the model provides an objective means of evaluating the relative importance of various watershed characteristics and sources of constituents (soil type, geology, animal manure) as predictors of water-quality and constituent loads in streams, which helps to show, for instance, whether discharges from point sources, such as wastewater-treatment plants, are a stronger predictor of water quality and load than nonpoint-source loads, such as runoff from farm lands.

Statistical model calibration also provides a means for quantifying a level of certainty (or margin of error) in load estimates for streams. The level of certainty depends on the number of monitoring sites and the resolution of the spatial data used to calibrate the model, but the level of certainty generally increases as monitoring networks and the accuracy and resolution of geospatial data sets improve.

All models, including SPARROW, are imperfect representations of reality; thus, simulation results reflect uncertainties in the available spatial and monitoring data sets. Knowledge of model uncertainty is important in making environmental-management decisions, and the statistical basis of SPARROW provides a means of quantifying uncertainty (Robertson and others, 2009).

Knowledge of model uncertainties can be used to prioritize future monitoring and assessment activities. For example, under or over predictions of nutrient loads in a watershed may indicate that additional monitoring and assessment are needed to improve models and clarify local management strategies.

> ***"The Kansas Department of Health and Environment (KDHE) utilized the results of the SPARROW model for Mississippi watershed nitrogen transport as the unifying theme behind the state's Nutrient Reduction Plan. The visual output of the model is a powerful tool for explaining nitrogen impacts on a watershed-by-watershed basis in Kansas as well as all Mississippi River watershed states. We look forward to continued refinement of the SPARROW modeling efforts to identify high priority watersheds for mitigation of nitrogen and other pollutants. We are unaware of any similar projects that have been as valuable in helping to identify nitrogen contributions to the Gulf of Mexico, and upstream states on a watershed-by-watershed basis."***
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> Michael B. Tate, P.E., Chief Bureau of Water, Technical Services Section, Kansas Department of Health and Environment, 2005

Understanding SPARROW Predictions

Several characteristics of the SPARROW model must be taken into account when applying the model results to management decisions and water-quality assessments. Important among these are that the SPARROW model (1) focuses on spatial rather than temporal detail; (2) integrates long-term discharge and water-quality records to calculate annual stream-load values used for calibration; (3) includes only the water-quality factors that are represented in available geospatial data and correlated statistically with stream load; and (4) favors water-quality comparisons across broad regions as opposed to within single catchments.

How are stream-load measurements that vary over time used to calculate a mean annual load for SPARROW models?

The mean annual stream-load calculation integrates long-term discharge and water-quality data to estimate a value that is representative of the water-quality conditions during a base year and normalized to average hydrologic conditions (Schwarz and others, 2006). The adjustment of the load to a base year accounts for differences in monitoring record lengths and sample sizes, and ensures that a contemporaneous period is used among all sites being considered. Normalizing to average hydrologic conditions ensures that spatial patterns in rainfall in any single year do not interfere with identifying the environmental factors that affect water quality over longer periods. Based on this approach, the stream-load values used to calibrate SPARROW models can be interpreted as the mean annual load that would have occurred in a specified base year if mean annual-flow conditions, based on long-term flow data, had prevailed during that year. Emphasis on long-term mean annual hydrology enhances the capability of the model to identify major constituent sources and watershed processes that affect the long-term supply, transport, and fate of water-quality constituents in watersheds.

How is a base year selected for SPARROW models?

Two factors are considered in selecting the base year. First, the base year typically falls within the period of greatest overlap in the water-quality and discharge monitoring records. This overlap helps to ensure temporal consistency in the mean annual load calculations at the calibration monitoring sites. Second, the base year is selected for consistency with the available national and regional geospatial data sets. Major effort is required to produce the geospatial data at high spatial resolutions; thus, the data are limited to specific years and reported only periodically. For example, national land-use and land-cover data suitable for large-scale SPARROW modeling were produced by the USGS only for 1992 and 2002. Agricultural data on animal nutrients and crop land area and production are available only every 5 years (for example, 1992, 1997, 2002) from the U.S. Department of Agriculture census. Thus, the selected base years for past and current SPARROW models typically have reflected the availability of the most critical geospatial data sets.

Do the mean annual load values used to calibrate SPARROW models adequately account for brief high-flow periods that can carry most of the annual load of a chemical constituent?

Measurements of concentration and discharge collected at each site throughout the year and across many years are used to calculate mean load in the SPARROW model. In these calculations, measurements from annual high-flow periods, such as spring runoff months, typically receive greater weight because of their large magnitude. Thus, the SPARROW mean load is disproportionately influenced by high-flow data. SPARROW load predictions, therefore, generally are more indicative of the spatial variability in stream load that occurs during high-flow periods than during other periods of the year. This is supported by the generally close agreement observed between SPARROW mean annual loads and mean spring (March to May) loads.

Why don't some SPARROW models account for factors I consider to be important in my watershed?

Some watershed characteristics that may be critical in understanding water-quality conditions are not well documented for large watersheds that cover multistate regions, such as those typically modeled with SPARROW. Examples include land-management or conservation practices, manure applications during recent years, and the effects of urban-contaminant sources, such as combined sewer overflows. Because data on many of these characteristics are not currently available for use in SPARROW modeling, the role of these data in determining constituent loads cannot be explicitly evaluated by the model. The effects of such characteristics, however, can be evaluated by extension through other variables with which they are correlated spatially (for example, effects of combined sewer overflows as reflected by urban land cover), or explored indirectly by evaluating model uncertainty. In general, if these variables are not correlated spatially with other variables already in a SPARROW model, then their influence will be reflected in the margin of error associated with the SPARROW predictions.

Why are the SPARROW model predictions for the stream on my property different than expected?

Inconsistency in levels of detail and other scaling issues commonly associated with geospatial data sets can affect model construction and performance. Geospatial data often are available only at the county level or even coarser scales. In these instances, conditions in relatively small streams that are affected by local environmental conditions or human activities may not be represented well by the model. The performance of the model also can be limited by the scale or relative density of the monitoring network used for calibration. Small watersheds, especially first-order headwater streams, are monitored relatively infrequently and may be underrepresented in calibration data sets. Thus, model estimates for stream reaches draining small watersheds likely have higher levels of uncertainty than the statistics reported by the model. Because of this, model estimates frequently are summarized and reported only for larger watersheds that consist of multiple stream reaches (Alexander and others, 2008; Robertson and others, 2009). In general, SPARROW models illustrate the broad spatial patterns of water quality well, but may be less accurate for a single stream because of limitations in the underlying data sets.

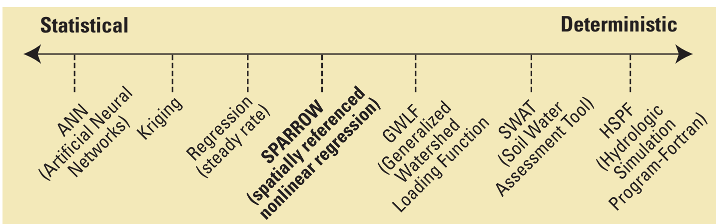
SPARROW Models—Current and Future

The SPARROW modeling approach originally was developed and applied to assess nutrient-source contributions, transport, and water-quality conditions at the national scale for the base year 1987 (Smith and others, 1997). Subsequently, refined national models were developed to simulate nitrogen and phosphorus loading for the year 1992, and these models have been used to estimate nutrient sources and transport in the Mississippi River basin (Alexander and others, 2008; Robertson and others, 2009).

SPARROW models also have been developed for other regions across the country, including nutrient models for the Chesapeake Bay watershed (Preston and Brakebill, 1999), selected North Carolina coastal drainages (McMahon and others, 2003), and the New England region (Moore and others, 2004). In addition, a salinity model of the Southwest was developed to estimate the spatial distribution of total dissolved solids and natural and human factors controlling salinity throughout the region (Anning and others, 2007).

These regional models provide a more detailed focus on the factors that influence water quality locally but may not be important factors everywhere in the country. Regional models also provide more intensive water-quality data compilation, which often includes more monitoring sites, thus leading to enhanced calibration and greater precision in model predictions than can be achieved at larger scales.

How does SPARROW compare with other water-quality models?



Water-quality models are considered either deterministic or statistical in basic form and approach and vary in temporal and spatial scale, and process detail and complexity (Singh, 1995). Deterministic models generally estimate water-quality conditions by balancing mass or energy for explicit physical environmental processes. Because of underlying computational and structural complexity, these models usually are limited in application to small sites or single stream reaches and do not account directly for uncertainty or error. The Hydrologic Simulation Program-Fortran (HSPF) and Soil and Water Assessment Tool (SWAT) represent some of the more clearly deterministic approaches, although these models can include statistical components. These models commonly are used by managers to simulate temporal variations in water quality by simulating rainfall-runoff processes and estimating contaminant transport from watersheds to individual monitoring sites.

Statistical models tend to be less complex in structure and estimate water-quality conditions by relating field observations to causative environmental factors. As such, statistical models quantify and attempt to minimize uncertainty over a specified region. These models may be based on a variety of underlying forms, including artificial neural networks (Conrads and Roehl, 2007) and simple–multiple or linear–nonlinear regression models (Helsel and Hirsch, 2002).

Models at either end of this spectrum are valuable in assessing water quality. Deterministic models can offer insight into the role of key environmental processes, such as denitrification, and can help to evaluate the effectiveness of proposed conservation practices or policies. Statistical models can improve understanding of the relation of water quality to various environmental factors and are amenable to broad regional comparisons, uncertainty analysis, and risk assessment.

SPARROW modeling is a relatively new approach to water-quality modeling and has some attributes of both deterministic and statistical models (Schwarz and others, 2006). SPARROW models are deterministic in nature in that they incorporate nonlinear physically-based functions, mass-balance requirements, and simulations of certain physical processes (attenuation). SPARROW models are statistical in nature in the way they are calibrated—using established statistical procedures designed to optimize model fit by minimizing error between model predictions and measured water-quality data. Although purely deterministic models can be calibrated by using these same statistical procedures, the task generally is more challenging than with SPARROW because of the differences in complexity (number of coefficients and processes). Because calibration of deterministic models becomes increasingly difficult for large watersheds, such as the Mississippi River basin and its major tributaries, these models rarely are applied at such scales.

The NAWQA Program has adopted SPARROW modeling to assess nutrient conditions in six large regions across the Nation for the base year 2002 (fig. 3 on p. 6). The findings from these regional models are used to compare nutrient sources and watersheds that contribute elevated nutrient loads to estuaries and other receiving waters, such as the South Atlantic and Gulf of Mexico, inland and coastal waters of the Northeast, the Upper Mississippi and Great Lakes, and Puget Sound. These models will be useful in evaluating stream-water quality for management or regulatory objectives. The 2002 regional models include nutrient-monitoring data from local, State, and other federal agencies, which substantially increases the number of model-calibration sites. For instance, the South Atlantic–Gulf model includes data from 321 monitoring sites, which is 233 sites more than were used in the national model (based on USGS monitoring only) for the same region. By including more sites, preliminary regional models generally display a lower degree of uncertainty.

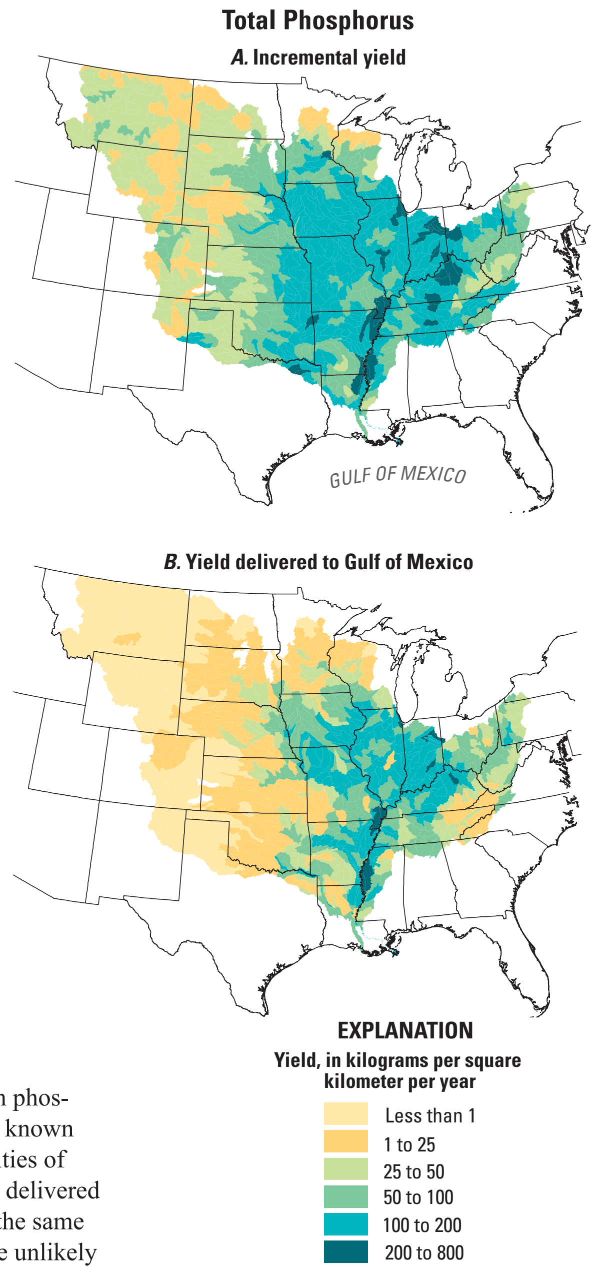
For the regional SPARROW models, 2002 base-year data are used to describe atmospheric deposition, commercial fertilizer applied to agricultural land, animal-manure production, point-source discharges, population density, and land cover (urban, agricultural, and forested). The data describing many of these nutrient sources and watershed characteristics have been refined since earlier SPARROW models. The combination of more calibration sites and refined geospatial data provides significant improvement over previous models in prediction accuracy and the identification of regional nutrient sources and transport factors.

SPARROW: Estimating Water-Quality Conditions at National and Regional Scales

SPARROW models are developed and applied to assess a variety of water-quality constituents over a range of spatial scales, including the national scale. For example, SPARROW nutrient models developed at the national scale provide estimates of the delivery of loads from 62,000 stream reaches contributing to the Nation's major rivers and estuaries (fig. 2; Smith and others, 1997; Alexander and others, 2008). These models improve understanding of sources, transport, and delivery of nutrients to downstream reservoirs and estuaries and provide additional insight in many areas, including the role of headwater streams in downstream water quality, natural background concentrations of nutrients in streams, atmospheric sources of nitrogen to major estuaries, and the effect of stream-channel size on nitrogen delivery to the Gulf of Mexico.

A recently developed national-scale SPARROW model (Alexander and others, 2008) provides estimates of nutrient sources and transport in the 3-million-km^2 Mississippi River basin and estimates of nutrient transport and delivery from the Nation's largest watershed to the Gulf of Mexico. Findings from this model indicate that agriculture is the predominant nutrient source to the Gulf. About 52 percent of the nitrogen entering the Gulf from the Mississippi River basin is from lands cultivated in corn and soybeans. Animal manure on pasture and rangelands combined with commercial fertilizer applied to crops are the largest contributors of phosphorus. Nonagricultural sources are also important contributors of nutrients to the Gulf of Mexico. About 30 percent of the nitrogen delivered to the Gulf is from regional atmospheric deposition and various urban sources that may include nitrogen from wastewater discharges, septic systems, and emissions from power plants and vehicles.

SPARROW models can be used to track nutrient delivery *(A)* locally to the outlets of inland watersheds (incremental yield) and *(B)* regionally over longer distances to downstream water bodies. This example illustrates the use of a national SPARROW model to map delivery of phosphorus yields *(A)* locally and *(B)* regionally to the Gulf of Mexico. Differences in the spatial patterns of phosphorus yield are attributable to differences in phosphorus removal during transport to downstream receiving waters. In certain regions, the maps highlight watersheds in which sources are likely to have a greater effect on local water-quality conditions than on hypoxia in the Gulf. For example, although phosphorus inputs from watersheds above reservoirs in the Tennessee Valley are known to create water-quality concerns in some of the reservoirs, only small quantities of phosphorus are delivered from these watersheds to the Gulf of Mexico. The delivered yields of watersheds in these areas in map *B* are smaller than the yields for the same watersheds in map *A*. Therefore, phosphorus sources in these watersheds are unlikely to influence Gulf hypoxia.



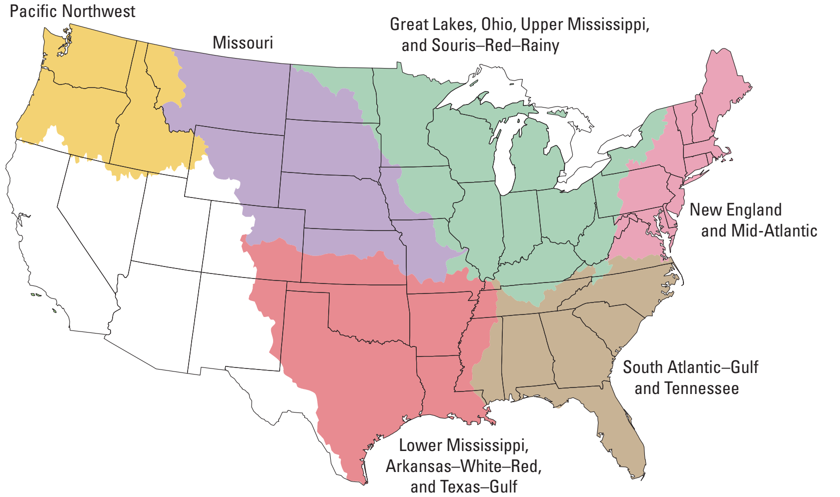


Figure 3. The SPARROW modeling approach is being applied to assess nutrient conditions in 2002 in six large regions across the Nation.

Although development of SPARROW models has advanced the understanding of water-quality conditions, considerable room for improvement still exists. Ongoing refinements of geospatial data sets will improve the precision of future models. Also, improvements in the modeling infrastructure will allow insights to be gained by the development of multiyear and seasonal models. Finally, the distributions of many important constituents remain to be considered in a SPARROW analysis.

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Information on SPARROW modeling applications, data, and documentation can be accessed at *http://water.usgs.gov/nawqa/sparrow/*