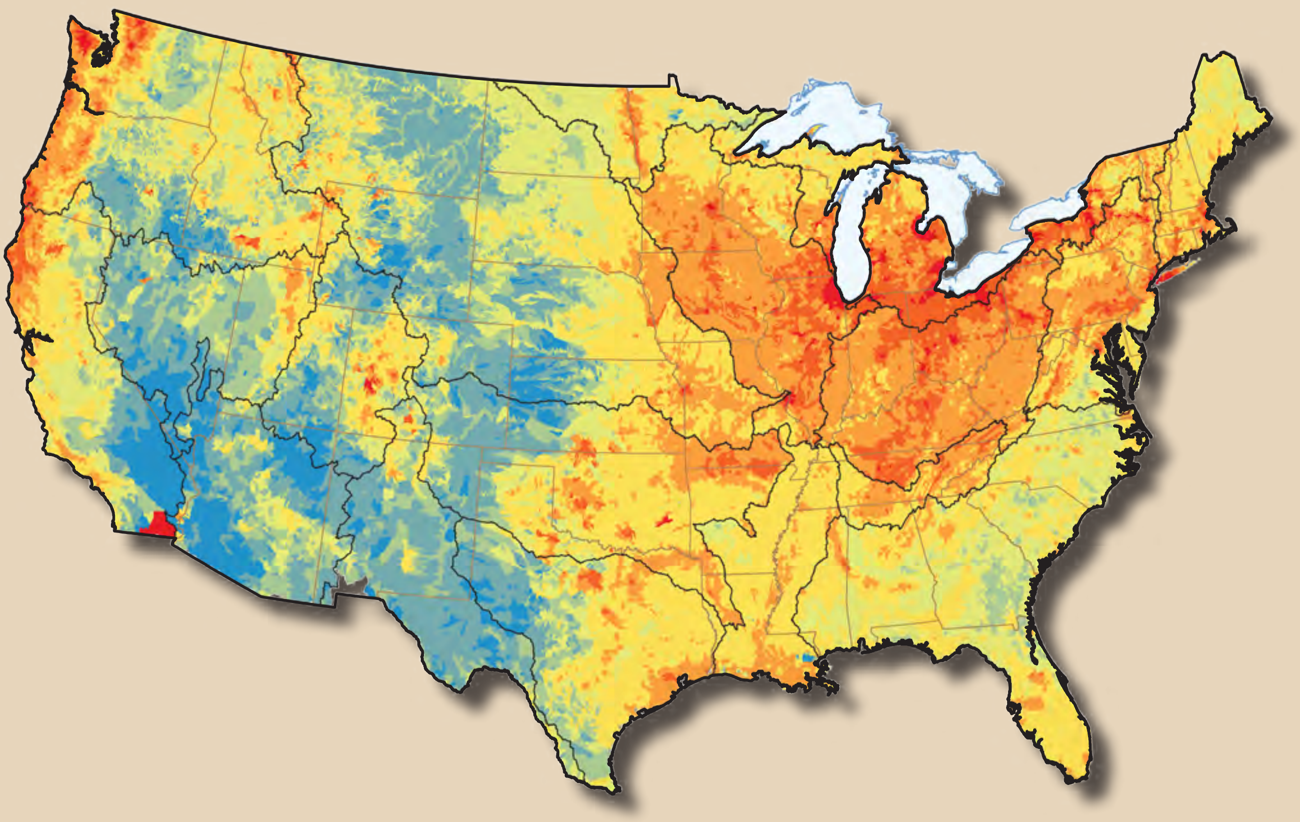
National Water Quality Assessment Program

Dissolved-Solids Sources, Loads, Yields, and Concentrations in Streams of the Conterminous United States



Scientific Investigations Report 2014–5012

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

Cover. Map of the conterminous United States, showing long-term mean annual incremental-catchment yield of dissolved solids from all sources considered in this report, as predicted by the national SPARROW model of dissolved solids transport (from figure 9 on p. 42).

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By David W. Anning and Marilyn E. Flynn

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SALLY JEWELL, Secretary

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

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FOREWORD

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (*http://www.usgs.gov/*). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (*http://water.usgs.gov/nawqa*). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and groundwater? How are conditions changing over time? How do natural features and human activities affect the quality of streams and groundwater, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (*http://water.usgs.gov/nawqa/studies/study_units.html*).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and groundwater. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between *sources* of contaminants, the *transport* of those contaminants through the hydrologic system, and the potential *effects* of contaminants on humans and aquatic ecosystems. Included are studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

William H. Werkheiser
USGS Associate Director for Water

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
cubic hectometer per year (hm^3/yr)	811.03	acre-foot per year (acre-ft/yr)
cubic meter per second per square kilometer [$(m^3/s)/km^2$]	91.49	cubic foot per second per square mile [$(ft^3/s)/mi^2$]
liter per second (L/s)	15.85	gallon per minute (gal/min)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
Metric ton (Mt)	1.102	ton, short (2,000 lb)
Metric ton (Mt)	0.9842	ton, long (2,240 lb)
megagram per day per square kilometer [$(Mg/d)/km^2$]	2.8547	ton per day per square mile [$(ton/d)/mi^2$]
Metric ton per year (Mt/yr)	1.102	ton per year (ton/yr)
Metric ton per year per square kilometer $(Mt/yr)/km^2$	2.8547	ton per year per square mile (ton/yr)

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

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).

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of dissolved solids in water are given in milligrams per liter (mg/L).

Dissolved-Solids Sources, Loads, Yields, and Concentrations in Streams of the Conterminous United States

By David W. Anning and Marilyn E. Flynn

Abstract

Recent studies have shown that excessive dissolved-solids concentrations in water can have adverse effects on the environment and on agricultural, domestic, municipal, and industrial water users. Such effects motivated the U.S. Geological Survey's National Water Quality Assessment Program to develop a SPAtially-Referenced Regression on Watershed Attributes (SPARROW) model that has improved the understanding of sources, loads, yields, and concentrations of dissolved solids in streams of the conterminous United States.

Using the SPARROW model, long-term mean annual dissolved-solids loads from 2,560 water-quality monitoring stations were statistically related to several spatial datasets that are surrogates for dissolved-solids sources and land-to-water delivery processes. Specifically, sources in the model included variables representing geologic materials, road deicers, urban lands, cultivated lands, and pasture lands. Transport of dissolved solids from these sources was modulated by land-to-water delivery variables that represent precipitation, streamflow, soil, vegetation, terrain, population, irrigation, and artificial drainage characteristics. Where appropriate, the load estimates, source variables, and transport variables were statistically adjusted to represent conditions for the base year 2000. The nonlinear least-squares estimated SPARROW model was used to predict long-term mean annual conditions for dissolved-solids sources, loads, yields, and concentrations in a digital hydrologic network representing nearly 66,000 stream reaches and their corresponding incremental catchments that drain the Nation.

Nationwide, the predominant source of dissolved solids yielded from incremental catchments and delivered to local streams is geologic materials in 89 percent of the catchments, road deicers in 5 percent of the catchments, pasture lands in 3 percent of the catchments, urban lands in 2 percent of the catchments, and cultivated lands in 1 percent of the catchments. Whereas incremental catchments with dissolved solids that originated predominantly from geologic sources or from urban lands are found across much of the Nation, incremental catchments with dissolved solids yields that originated predominantly from road deicers are largely found in the Northeast, and incremental catchments with dissolved solids that originated predominantly from cultivated or pasture lands are largely found in the West. The total amount of dissolved solids delivered to the Nation's streams is 271.9 million metric tons (Mt) annually, of which 194.2 million Mt (71.4%) come from geologic sources, 37.7 million Mt (13.9%) come from road deicers, 18.2 million Mt (6.7%) come from pasture lands, 13.9 million Mt (5.1%) come from urban lands, and 7.9 million Mt (2.9%) come from cultivated lands.

Nationwide, the median incremental-catchment yield delivered to local streams is 26 metric tons per year per square kilometer [(Mt/yr)/km^2]. Ten percent of the incremental catchments yield less than 4 (Mt/yr)/km^2, and 10 percent yield more than 90 (Mt/yr)/km^2. Incremental-catchment yields greater than 50 (Mt/yr)/km^2 mostly occur along the northern part of the West Coast and in a crescent shaped band south of the Great Lakes. For example, the median incremental-catchment yield is 81 (Mt/yr)/km^2 for the Great Lakes, 78 (Mt/yr)/km^2 for the Ohio, and 74 (Mt/yr)/km^2 for the Upper Mississippi water-resources regions. Incremental-catchment yields less than 10 (Mt/yr)/km^2 mostly occur in a wide band across the arid lowland of the interior West that excludes areas along the coast and the extensive, higher mountain ranges. For example, the median incremental-catchment yield is 3 (Mt/yr)/km^2 for the Lower Colorado, 5 (Mt/yr)/km^2 for the Rio Grande, and 8 (Mt/yr)/km^2 for the Great Basin water-resources regions.

Predicted incremental loads were cascaded down through the reach network, with loads accumulating from reach to reach. For most stream reaches, the entire incremental load of dissolved solids delivered to the reach was transported to either the ocean or to one of the large streams flowing along the U.S. international boundary without losses occurring along the way. The exceptions to this include streams in the southwestern part of the country, such as the Colorado River, Rio Grande, and streams of internally drained drainages in the Great Basin, where dissolved-solids loads decreased through streamflow diversion for off-stream use, or by infiltration through the streambed.

Long-term mean annual flow-weighted concentrations were derived from the predicted accumulated-load

and stream-discharge data. Widespread low concentrations, generally less than 100 milligrams per liter (mg/L), occur in many reaches of the New England, South Atlantic-Gulf, and Pacific Northwest water-resources regions as a result of moderate dissolved-solids yields and high runoff rates. Widespread moderate concentrations, generally between 100 and 500 mg/L, occur in many reaches of the Great Lakes, Ohio, and Upper Mississippi River water-resources regions. Whereas dissolved-solids yields are generally high in these regions, runoff rates are also high, which helps moderate concentrations in these regions. Widespread higher concentrations, generally greater than 500 mg/L, occur across a belt of reaches that extends almost continuously from Canada to Mexico in the Midwest, cutting through the Souris-Red-Rainy, Missouri, Arkansas-White-Red, Texas-Gulf, and Rio Grande water-resources regions. Although dissolved-solids yields are moderate to low in these areas, low runoff rates result in the high concentrations for these areas.

In 12.6 percent of the Nation's stream reaches, predicted concentrations of dissolved solids exceed 500 mg/L, the U.S. Environmental Protection Agency's secondary, nonenforceable drinking water standard. While this standard provides a metric for evaluating predicted concentrations in the context of drinking-water supplies, it should be noted that it only applies to drinking water actually served to customers by water utilities, and it does not apply to all stream reaches in the Nation nor does it apply during times when water is not being withdrawn for use. Exceedance of 500 mg/L is more pronounced in certain water-resources regions than others. For example, about half of the reaches in the Souris-Red-Rainy region have concentrations predicted to exceed 500 mg/L, and between 25 and 37 percent of the reaches in the Missouri, Arkansas-White-Red, Texas-Gulf, Rio Grande, and Lower Colorado regions are predicted to exceed 500 mg/L.

Development of stream-load data for use in the SPARROW model also provided long-term temporal trend information in dissolved-solids concentrations at the monitoring stations for their period of record, which was constrained between 1980 and 2009. For the 2,560 monitoring stations used in this study, long-term trends in flow-adjusted dissolved-solids concentrations increased over time at 23 percent of the stations, decreased at 18 percent of the stations, and did not change over time at 59 percent of the stations. Long-term trends show a strong regional spatial pattern where from the western parts of the Great Plains to the West Coast, concentrations mostly either did not change or decreased over time, and from the eastern parts of the Great Plains to the East Coast, concentrations mostly either did not change or increased over time.

Results from the trend analysis and from the SPARROW model indicate that, compared to monitoring stations with no trends or decreasing trends, stations with increasing trends are associated with a smaller percentage of the predicted dissolved-solids load originating from geologic sources, and a larger percentage originating from urban lands and road deicers. Conversely, compared to stations with increasing trends or no trends, stations with decreasing trends have a larger percentage of the predicted dissolved-solids load originating from geologic sources and a smaller percentage originating from urban lands and road deicers. Stations with decreasing trends also have larger percentages of predicted dissolved-solids load originating from cultivated lands and pasture lands, compared to stations with increasing trends or no trends.

Introduction

All water naturally contains dissolved solids as a result of weathering processes in rocks and soils. Certain human activities can increase dissolved-solids concentrations above natural levels. Major ions, such as bicarbonate, calcium, chloride, magnesium, potassium, silica, sodium, and sulfate constitute most of the dissolved solids in water and are an indicator of salinity. Some amount of dissolved solids is necessary for agricultural, domestic, and industrial water uses and for plant and animal growth. Many of the major ions are essential to life and provide vital nutritional functions. Dissolved solids are also fundamental in numerous products and processes, such as nutritional supplements, water conditioning, food seasoning and production, cleaning products, fertilizers, road deicers, and in the manufacturing, chemical, and electronics industries. Excessive dissolved-solids concentrations in water, however, can have adverse effects on the environment and on agricultural, domestic, municipal, and industrial water users. These adverse effects provide motivation for expanding the understanding of dissolved-solids conditions in water resources.

Ramakrishna and Viraraghavan (2005) reviewed the effects of road deicers on the environment, including streams, lakes, and aquatic ecosystems. Their 2005 review discussed the following adverse effects on surface waters owing to the influx of runoff affected by deicer (sodium chloride) application:

- increased chloride concentrations, with the larger increases occurring more frequently in smaller drainage basins than in larger drainage basins;
- change in the density gradient of lakes, which alters the physical and ecological characteristics of the lake;
- deicer induced stratification, which can disrupt the seasonal mixing of lake water that is essential to maintain plant and animal life in a lake; and
- deicer stimulation of algal growth, where sodium can increase the growth of blue-green algae and thereby stimulate a nuisance algal bloom.

Kaushal and others (2005) investigated increases in chloride concentrations of freshwater in the northeastern United States that were found to result from human activities in suburban and urban watersheds. Their 2005 study found that chloride concentrations near Baltimore, Maryland, were high enough to induce several effects on aquatic and terrestrial ecosystems. These effects included

- acidification of streams,
- mobilization of toxic metals through ion exchange or impurities in road deicers,
- increased mortality rates of aquatic plants and animals,
- changes to reproductive processes and systems of aquatic plants and animals,
- alteration of community composition of plants in riparian areas and wetlands,
- facilitation of invasion of saltwater species into previously freshwater ecosystems,
- interference with the natural mixing of lakes,
- alteration of microbial community structure, and
- inhibition of denitrification, a process critical for removing nitrate.

In aquatic ecosystems, plant and animal species vary in their ability to tolerate dissolved solids, and elevated concentrations can be stressful for some plants and animals because of changing osmotic conditions. Chapman and others (2000), for example, reported that benthic macroinvertebrates were significantly affected when dissolved-solids concentrations in mine effluent were greater than 1,100 milligrams per liter (mg/L) (equivalent to parts per million), whereas trout were tolerant to dissolved-solids concentrations greater than 2,000 mg/L in mine effluent. Synthetic effluents that matched the overall chemical characteristics of dissolved solids in effluents discharged from mines were used in the toxicity tests, but metals were not included because the objective was to characterize the potential effects of dissolved solids. Increased levels of some ions were found to be more toxic to aquatic organisms than other ions (Chapman and others, 2000; Scannell and Jacobs, 2001). With increased concentrations of dissolved solids or particular ions, less tolerant plant species may be replaced by more tolerant species, and animal communities may change as the specific plant community to which they are adapted changes. Overall community structure may change with the introduction of salt-tolerant species.

Elevated dissolved solids can also affect human uses of water. For example, elevated dissolved-solids concentrations in irrigation water and soils can lead to decreased crop production or crop death and, thus, decreases in economic returns, altered crop patterns, greater soil leaching and drainage requirements, degraded soil structure, and higher management costs. In extreme cases, agricultural land may be removed from production. Cordy and Bouwer (1999) note that the salinization of soil and water in agricultural areas is not a new concern. Civilizations in ancient Mesopotamia (present-day Iraq) declined in part because food production on agricultural lands in the floodplain of the Tigris and Euphrates Rivers, known as the Fertile Crescent, could not be sustained owing to salinization of the land over time.

The Food and Agriculture Organization of the United Nations has reported guidelines for the use of irrigation water regarding dissolved solids. Depending on soil condition and type of vegetation, there is no restriction for irrigation-water use when dissolved-solids concentrations are less than 700 mg/L, slight to moderate restrictions for irrigation-water use when dissolved-solids concentrations are between 700 and 2,000 mg/L, and severe restrictions for irrigation-water use when dissolved-solids concentrations are greater than 2,000 mg/L (Ayers and Westcot, 1994). With increased dissolved-solids concentrations in irrigation water, crops with low-salinity tolerance, such as beans, may need to be replaced by crops with moderate- or high-salinity tolerance, such as corn or peppers and barley or beets, respectively.

For livestock production, high concentrations of dissolved solids and specific ions, particularly magnesium, in drinking water can negatively affect animal health and cause death. The National Academy of Sciences and National Academy of Engineering (1972) reported that a dissolved-solids concentration of 5,000 mg/L or less in drinking water for livestock is satisfactory. The suitability of any particular water, however, should be evaluated in terms of local conditions and the availability of alternate supplies, water source, seasonal changes in water quality, age and condition of the animal, and animal species (Ayers and Westcot, 1994).

The effects of high concentrations of dissolved solids in water on domestic, municipal, and industrial users include objectionable taste to drinking water; greater water-treatment costs; increased use of detergents and soaps; encrustation or corrosion of metallic surfaces that result in reduced lifespan of domestic, municipal, and industrial equipment; restricted use for landscape irrigation; and interference with chemical processes. Recommended limits for some industrial processes include pulp and paper, 200 mg/L (for fine paper); canning or freezing, 850 mg/L; brewing, 500 mg/L (light beer), and 1,100 mg/L (dark beer) (Sherrard and others, 1987). The U.S. Environmental Protection Agency (EPA) has established nonenforceable secondary drinking water regulations for dissolved solids and selected ions related to esthetic qualities of water, such as taste. For chloride and sulfate, the standard is 250 mg/L each, and the standard for total dissolved solids is 500 mg/L (U.S. Environmental Protection Agency, 2012). Individual states may have similar regulations or standards.

Damages from elevated dissolved-solids concentrations in water can have substantial economic costs. For the Nation, the losses in agricultural revenue that result from dissolved-solids loads in irrigation water and accumulation in cultivated lands amount to about $2.8 billion annually during recent years, with about $2.55 billion in damages for Western States (Sabo and others, 2010). In the Colorado River Basin, the cost to agricultural, municipal, and industrial users of water high in dissolved-solids concentrations was about $383 million for 2009 (U.S. Department of Interior, 2011). Such past damages led to public laws enacted in 1974 and 1984 that authorized the planning and construction of numerous salinity-control projects to improve or prevent further degradation in the quality of Colorado River water for use by the United States and Mexico (U.S. Department of Interior, 2011). These salinity-control projects have included canal lining, lateral piping, on-farm irrigation control, irrigation drainage, pumping of groundwater, well plugging, vegetation management, and land retirement. Salinity-control programs operated in 2010 by the Bureau of Reclamation, U.S. Department of Agriculture, and Bureau of Land Management are reported to have reduced dissolved-solids loading to the Colorado River by about 1,192,000 tons annually (U.S. Department of Interior, 2011). In some areas where salinity-control projects have not been implemented, concentrations in brackish water supplies have been reduced through water-treatment processes, such as reverse osmosis.

Purpose and Scope

This purpose of this report is to provide an understanding of dissolved-solids conditions in streams of the conterminous United States. Specifically, this includes a characterization of the spatial patterns of dissolved-solids sources, loads, yields, and concentrations, as well as an understanding of the natural and human factors affecting these conditions.

The scope of this report is topically limited to the investigation of dissolved solids, spatially limited to streams of the conterminous United States, and temporally limited to the years 1980 through 2009. The streams included in this study generally drain more than about 120 km^2 and most have perennial flow, except in more arid regions where flow in many cases is intermittent or ephemeral. Given the spatial scope of this study, results are typically presented for the nation as a whole, and for each water-resources region (fig. 1; Seaber and others, 1987) to provide a summary of conditions in different parts of the conterminous United States (hereafter, Nation, despite the exclusion of Alaska, Hawaii, and offshore territories and possessions).

It should be recognized that a general limitation to this and other national-scale water-quality studies is that the analysis was designed to evaluate variables influencing dissolved-solids conditions across a broad region. Inevitably, there are some factors that have significant effects on dissolved solids for specific localized areas that either were not considered in this study or were included but found to be of lesser importance because these local characteristics were masked by larger regional influences.

Acknowledgments

The authors would like to thank all the local, state, and Federal agencies who provided support for water-quality and streamflow monitoring programs over several years that produced the data that made this study possible, and we thank all the dedicated employees who spent countless hours collecting and publishing those data.

Modeling Approach

This study used a GIS-based nonlinear regression model that integrates water-quality monitoring data for streams with landscape information, known as SPARROW (SPAtially Referenced Regression on Watershed Attributes; Smith and others, 1997; Preston and others, 2009) to improve the understanding of dissolved-solids occurrence, sources, and transport in streams of the conterminous United States. Statistical methods are used in SPARROW modeling to explain long-term average values of in-stream measurements of water quality (constituent mass or load) in relation to upstream sources and watershed properties such as soil characteristics, precipitation amounts, land cover, and other factors that influence the transport of constituents to streams and their delivery to downstream receiving water bodies. The major components of the SPARROW model infrastructure include (1) a hydrologic network of stream reaches and associated catchments through which constituent loads are routed from stream headwaters to their outlets, (2) spatial datasets of watershed attributes that represent dissolved-solids sources, land-to-water delivery processes, and stream-loss processes and are used in the model to determine the constituent load in each reach of the hydrologic network, and (3) long-term mean annual dissolved-solids load estimates at monitoring stations, which are the observations used to estimate the model.

Smith and others (1997) developed the SPARROW modeling technique and applied it to build an understanding of nitrogen and phosphorus sources and transport in streams of the conterminous United States. Subsequent efforts that have developed SPARROW models include but are not limited to nitrogen and phosphorus sources and transport for streams in specific major river basins of the United States (Preston, Alexander, and Wolock, 2011; Preston, Alexander, Schwarz, and Crawford, 2011), dissolved-solids sources and transport in streams of the Upper Colorado River Basin (Kenney and others, 2009), and dissolved-solids sources and transport in streams of the southwestern United States (Anning and others, 2007; Anning, 2011). SPARROW models have been used to (1) extrapolate known water-quality conditions in monitored reaches to estimate conditions in unmonitored reaches; (2) establish links between water quality and constituent sources; (3) track the transport of constituents to streams and downstream receiving waters, such as estuaries; (4) assess the natural processes that attenuate constituents as they are transported from land and downstream; and (5) predict changes in water quality that may result from management actions or changes in land use.

For this study, development of the national SPARROW model of dissolved-solids transport began with a hypothesis of the major sources, land-to-water delivery processes, and loss processes that affect dissolved-solids transport in streams. With this hypothesis in mind, a hydrologic network was selected, watershed-attribute data were obtained or developed, and long-term mean annual constituent loads were computed. A base year for the model was selected on the basis of

Figure 1. Map showing water-resources regions and selected streams in the conterminous United States.

modeling objectives and data availability, and the watershed-attribute data and constituent loads were statistically adjusted to this year where possible. With the main model components ready, a strategy was created for development and selection of the final model. This modeling approach is summarized below; for further detail on SPARROW modeling theory and methods, see Schwarz and others (2006).

Hypothesis

SPARROW model development began with a hypothesis of the major (1) sources, (2) land-to-water transport processes, and (3) loss processes for dissolved solids that occur in the study area. Each of these three components of the hypothesis is expressed mathematically in the nonlinear regression equation for the SPARROW model (Smith and others, 1997; Schwarz and others, 2006). For streams in the conterminous United States, dissolved solids come from both natural and human sources, and several factors affect transport from sources across the landscape to streams (fig. 2). For many streams, dissolved-solids concentrations and loads generally increase from their headwaters to their outlets; however, in some areas certain processes lead to decreases in loads.

Precipitation contains dissolved solids, including sulfate, nitrate, ammonium, chloride, and base cations like calcium, magnesium, potassium, and sodium (National Atmospheric Deposition Program, 1999). The ocean is an important source for several solutes in the precipitation, especially sodium and chloride. Consequently, concentrations of these ions in precipitation are generally higher near coasts and decrease inland. Fossil fuel emissions can elevate concentrations of sulfate and nitrate in precipitation above natural levels. Similarly, livestock operations and fertilizer application increase nitrate and ammonium concentrations in the atmosphere above natural levels.

Precipitation contains carbonic and other acids, which help to chemically weather minerals in soils and rocks and release dissolved solids to runoff that flows to streams or that infiltrates the land surface and percolates down to the aquifers. Comparison of results from several studies indicates that the general relative order of increasing dissolved-solids yields for rocks is crystalline (plutonic or metamorphic) rocks, volcanic rocks, and sedimentary rocks (Anning, 2011). Of the

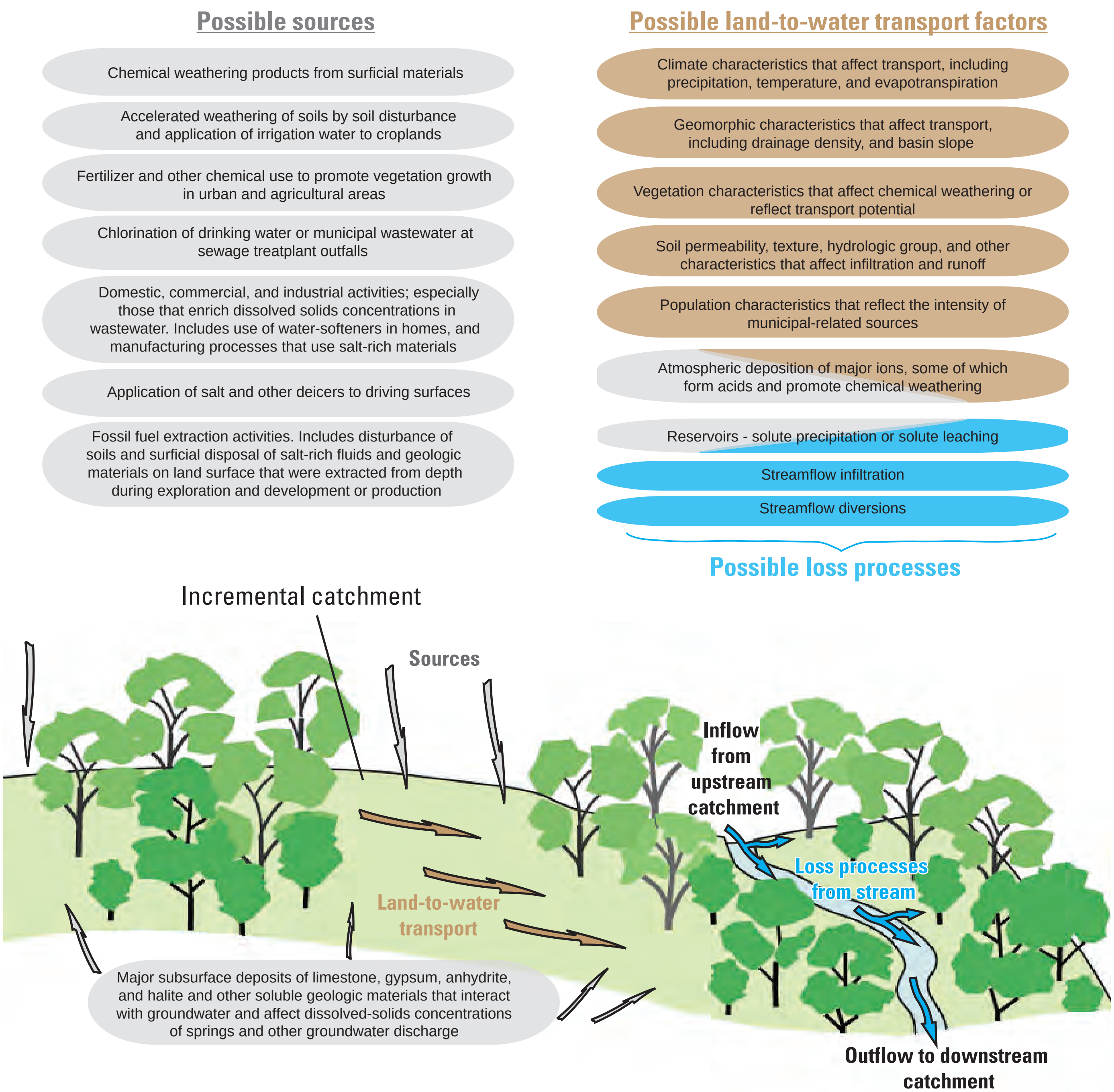


Figure 2. Chart and schematic drawing showing hypothesis of the primary possible sources, land-to-water transport factors, and loss processes affecting dissolved solids in streams and incremental catchments of the conterminous United States.

sedimentary rocks, sands, sandstones, and quartzite are generally the least susceptible to weathering, and they can have smaller relative yields than crystalline rocks. Relative yields for shales are generally greater than those of sandstones, but less than those of carbonate rocks. Relative yields for carbonate rocks are larger than sandstones and shales, and they can be as much as 35 times greater than yields from crystalline rocks. Dissolved solids from weathering processes can be delivered to streams in runoff or can infiltrate with recharge water to aquifers. Dissolved solids in aquifers eventually are delivered to streams through groundwater discharge, and concentrations can be high where groundwater has interacted with particularly soluble geologic materials such as carbonate rocks or subsurface salt deposits such as gypsum, anhydrite, or halite.

Irrigation of soils for crop cultivation or in urban landscapes accelerates the weathering process by providing additional water that can expedite weathering processes and flush solutes from the soils to surface water or groundwater (Gates and others, 2012; Liebermann and others, 1989; Iorns and others, 1965). Agricultural chemicals, such as fertilizers, pesticides, and soil amendments, are often manufactured as a salt to facilitate transportation to the farm, field application, and plant or soil interaction with the compound. Nationally in year 2000, for example, 7.11 million metric tons of sulfur was used in phosphatic fertilizers, 0.213 million metric tons was used in nitrogenous fertilizers, 0.014 million metric tons was used in pesticides, and 1.29 million metric tons was used in other agricultural chemicals (Ober, 2000). Similarly, 1.92 million metric tons of gypsum was used for primarily agricultural purposes in the year 2000 (Olsen, 2000).

Besides irrigation and crop production, other human activities increase dissolved solids in streams. Surface disturbances from activities, such as off-road vehicle use, grazing, and development have the potential to increase dissolved solids in water through soil erosion and dissolution of dissolved solids in sediments. Water delivered for public supply and water released from wastewater-treatment plants is treated to reduce risks from aquatic-borne disease, commonly by chlorination. Many domestic, commercial, or industrial activities, such as cleaning with detergents, softening water, and manufacturing, add solutes to water that is sent through sewerage systems, treated, and then released to streams. Although such uses occur over a wide area, release of the dissolved solids through the wastewater treatment plant discharges makes them a point source. In contrast, application of salts to roads for deicing and subsequent transport to streams through runoff processes represents a nonpoint source. For several of these human activities, the amount of dissolved solids delivered to streams may be greater where human populations are denser. This is partly because there may be more source material in such areas, and partly because transport is generally enhanced by the impervious surfaces and conveyance systems associated with densely populated areas.

Annual salt (sodium chloride) usage estimates provide an indication of the potential loading to the landscape from several of the aforementioned human activities. Historically, the Nation's annual salt use from 1790 to 1940 was low compared to recent years—less than 10 million metric tons per year (Mt/yr; fig. 3*A*; Kostick, 1992). Since that period, however, the Nation's annual salt use has grown to exceed 50 million Mt annually. In year 2000, about 53.4 million Mt of salt were used for different end uses (fig. 4; Kostick, 1993–2009). The primary end uses were for deicing and for manufacturing chemicals—about 19.7 million Mt (37 percent) was used for deicing, and about 22.4 million Mt (42 percent) of salt was used for manufacturing chemicals, such as chlorine, sodium hydroxide, sodium hypochlorite, and sodium chlorate. In addition, about 11.3 million Mt (21 percent) were used for water treatment, agricultural uses (especially for feed), general industrial uses, food processing, and distribution to other end users. Although the Nation's annual use of salt for water treatment, agricultural uses, general industrial uses, food processing, distribution, and manufacturing chemicals was generally steady for 1993–2009, annual use of salt for deicing fluctuated as a result of snowfall variation, but has steadily increased since 1940 (figs. 3*B* and 4; Kostick, 1992 and 1993–2009).

Subsurface disturbance through fossil fuel exploration and extraction makes dissolved solids available for surface transport to streams when soils are disturbed and when salt-rich fluids and (or) geologic materials are extracted from depth and brought to the land surface (Nuccio, 2000; Soeder and Kappel, 2009; Buto and others, 2010). In a conventional oil or gas reservoir, for example, gas lies on top of oil, which, in turn, lies on top of water. An oil or gas well ideally draws only from the petroleum without producing a large volume of water. Coalbeds, however, are often saturated with water and its pressure traps methane within the coal (Nuccio, 2000). To produce methane from coalbeds they must first be dewatered, which lowers the pressure so that methane can flow out of the coal and into the well bore. Produced water, whether from oil, gas, or coalbed methane, is commonly saline and must be disposed of in an environmentally sensitive manner. Most frequently, water is reinjected into subsurface rock formations, but in some cases, the water is allowed to flow into surficial drainages or is put into evaporation ponds. In cold regions, it is possible to freeze the water in the winter, collect the salts that separate out, and dispose of or utilize them independently of the water, which can then be discharged. In unconventional reservoirs, such as shale plays, water and chemical additives are injected into host formations to hydraulically fracture it and improve natural gas recovery. The injected fluids may come into contact with brines and other subsurface solute sources before the fluids are recovered and disposed of. In Pennsylvania, recovered fluids from hydraulic fracturing of the Marcellus Shale were disposed of by processing them through wastewater treatment plants, whereas in Texas fluids from the Barnett Shale were reinjected back into the ground or put into a tank for evaporation (Soeder and Kappel, 2009; Kargbro and others, 2010).

Several watershed characteristics that affect runoff processes likewise affect transport of dissolved solids from sources across the landscape to streams (fig. 2). These include climate characteristics such as precipitation, air temperature, and evapotranspiration; geomorphic characteristics such as land-surface slope and drainage density; vegetation cover that affects precipitation interception and evapotranspiration; and soil characteristics that affect infiltration and runoff, such as permeability and texture. Several of these factors affect weathering rates as well as surface-water runoff rates. Most of these factors were used in one or more SPARROW models of dissolved solids, nitrogen, or phosphorus transport constructed for selected parts of the Nation (Anning and others, 2007; Kenney and others, 2009; Preston, Alexander, Schwarz, and Crawford, 2011).

Whereas individual ions may sorb and desorb from streambed and other materials, as a summary measurement of the major ions, dissolved solids within streams overall are generally chemically conservative and loads of dissolved solids typically remain the same or increase downstream. Although

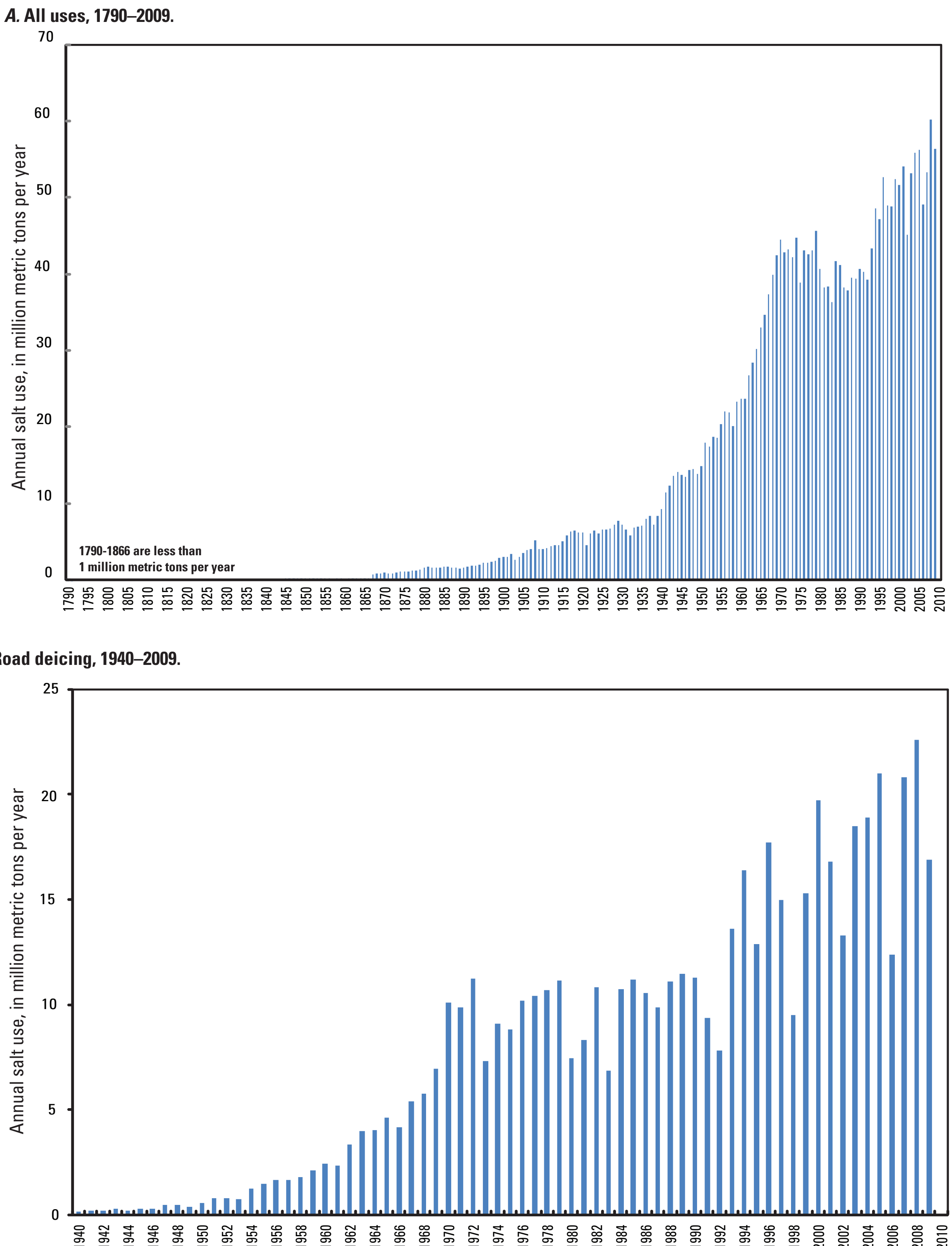


Figure 3. Histograms of annual use of salt (sodium chloride) in the United States. *A*, All uses, 1790–2009. *B*, Road deicing, 1940–2009. Data are from Kostick (1992) and Kostick (1993–2009).

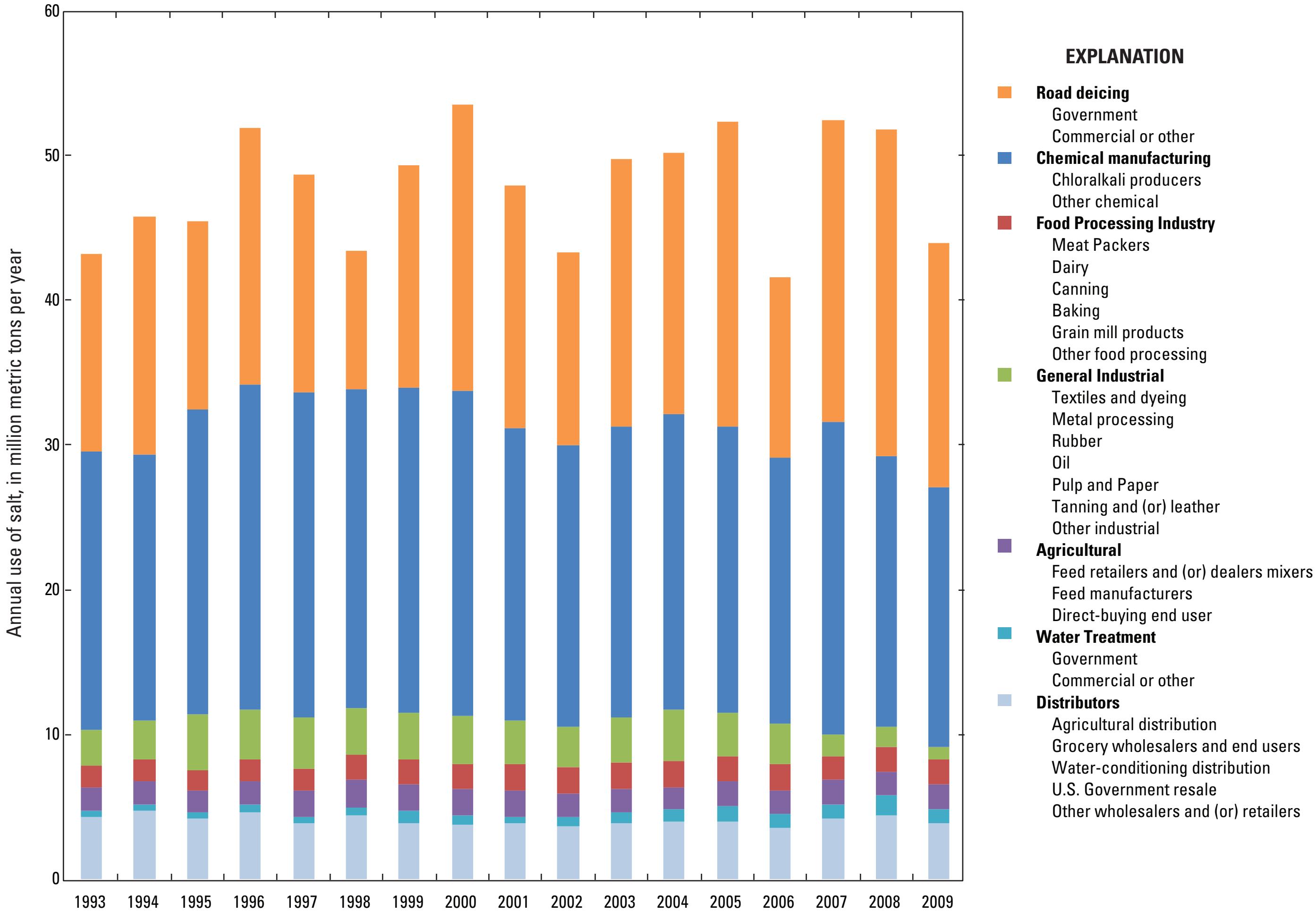


Figure 4. Histogram of annual use of salt (sodium chloride) in the United States by use. Data are from Kostick (1993–2009).

evaporative processes can remove water, solutes remain in solution and consequently the concentration of dissolved solids increases but the load remains unchanged. Inflow from tributary streams or nonnatural water sources to a receiving stream contains dissolved solids, and therefore loads increase downstream from their confluence. If the inflow is of a lower concentration than the receiving stream, concentrations will be diluted (decrease) downstream of their confluence.

Dissolved-solids loads are reduced in streams when flow infiltrates through the streambed and percolates to the aquifer, or when flow is diverted into canals, pipes, or other conveyance structures for offstream uses (fig. 2). In the case of streamflow infiltration, some (or all) of the removed dissolved-solids load may eventually return to the stream or another surface-water body through groundwater discharge. In the case of streamflow diversions, some (or all) of the removed dissolved-solids load may be returned to the stream or another surface-water body through irrigation return flows or releases of treated municipal wastewater.

Within reservoirs, solutes can be added to the water through dissolution of salts in soils and geologic deposits lining the reservoir bottom. For example, Liebermann and others (1989) found dissolved-solids loads in the Green River increased from gypsum dissolution of bank material in the Flaming Gorge Reservoir of Wyoming and Utah. Alternatively, certain geochemical conditions could cause solutes to precipitate and line the reservoir bottom with salts. Consequently, reservoirs can behave either as a dissolved-solids source or as an area where losses occur.

Hydrologic Network

The hydrologic network used in SPARROW models is a digital representation of the major streams in the United States and consists of individual reaches and their corresponding incremental catchments. Whereas the network describes the linear connection and direction of flow in surface-water pathways, the incremental catchments defined by the area drained by each individual reach provide the ability to spatially reference data representing dissolved-solids sources, land-to-water delivery processes, and loss processes.

The national SPARROW model of dissolved-solids transport was developed using the MRB_E2RF1 hydrologic network (Brakebill and others, 2011; Brakebill and Terziotti 2011a, 2011b), which contains 65,540 stream reaches in the conterminous United States. Minor coding changes, largely corrections, were made to three of the network attributes and are listed in appendix 4. Stream reaches were digitized at the 1:500,000 scale for this network and incremental catchments were delineated from 100-m digital elevation models. The average incremental catchment area is about 118 km^2, although this varies by water-resources region (table 1). On average, incremental catchment areas are smaller in the eastern water-resources regions than in most western water-resources regions. For example, the average incremental catchment area for New England is 66 km^2, whereas the average incremental catchment area for the Great Basin is 363 km^2 (table 1).

The MRB_E2RF1 network is an enhanced version of the original RF1 network. The most notable change is that many of the original reaches were broken into two reaches at USGS stream-monitoring stations so that (1) the area represented by loads for monitoring stations and the area represented by watershed attributes would have improved spatial alignment, and (2) more monitoring stations could be used for SPARROW model estimation where multiple stations occur on a single original RF1 reach.

Base Year

An important aspect to SPARROW modeling is that load data and the explanatory source, land-to-water delivery, and loss data should generally represent long-term mean conditions for the same timeframe, and this is accomplished by statistically adjusting model input data to represent a base year where possible. Such adjustments are necessary because the model input data, especially that for monitoring sites, often have different periods of record and exhibit long-term trends, which, when combined, can affect the representativeness of a mean value estimate if these factors are not accounted for. Schwarz and others (2006) discussed details for the methods used to account for such trends and different periods of record in estimates of long-term mean annual dissolved-solids loads, and our appendix 5 outlines methods used in estimates of selected watershed attributes. The values resulting from such adjustments are often referred to as “detrended.”

For the national SPARROW model of dissolved-solids transport, the base year 2000 was selected because (1) its relatively recent so that study results are relevant to current (2013) conditions; (2) data exploration indicated a general decline

Table 1. Summary of areal extent, incremental catchments, and water-quality monitoring stations in water-resources regions in the conterminous United States.

[Incremental catchments are from the MRB_E2RF1 digital hydrologic network (Brakebill and Terziotti, 2011b)]

Water-resources region		Areal extent, square kilometers	Incremental catchments		Monitoring stations[1]	
Code	Name		Count	Average area, square kilometers	Count	Density in region, count per square kilometer x10^6
1	New England	154,824	2,339	66	88	568
2	Mid-Atlantic	271,479	2,610	104	175	645
3	South Atlantic-Gulf	691,551	6,945	100	314	454
4	Great Lakes	303,049	2,415	125	62	205
5	Ohio	421,932	4,832	87	104	246
6	Tennessee	105,911	1,471	72	44	415
7	Upper Mississippi	491,830	3,629	136	200	407
8	Lower Mississippi	261,980	1,722	152	46	176
9	Souris-Red-Rainy	151,955	653	233	61	401
10	Missouri	1,323,778	12,482	106	502	379
11	Arkansas-White-Red	642,654	3,792	169	257	400
12	Texas-Gulf	463,748	2,854	162	125	270
13	Rio Grande	333,597	982	340	40	120
14	Upper Colorado	294,057	1,986	148	186	633
15	Lower Colorado	368,479	1,336	276	47	128
16	Great Basin	358,816	988	363	82	229
17	Pacific Northwest	709,716	12,034	59	193	272
18	California	416,156	2,470	168	34	82
Conterminous United States		7,765,514	65,540	118	2,560	330

[1]Includes only those used in the national dissolved-solids SPARROW model.

in the amount of available monitoring data over time, and the year 2000 had a relatively high number of potential stations compared to later years; (3) many of the explanatory variables had data for year 2000 or another year not temporally distant from it.

Water-Quality Monitoring Station Data

Estimated long-term mean annual dissolved-solids loads for monitoring stations used to estimate the national SPARROW model of dissolved-solids transport were determined on the basis of daily streamflow data at USGS gaging stations available from the USGS National Water Information System database (NWIS; USGS, 2010) and stream-chemistry samples analyzed for specific conductance (SC), residue on evaporation at 180 °C (ROE), or the sum of the dissolved constituents (SUM) and available from NWIS or from the USEPA STOrage and RETreval database (STORET; U.S. Environmental Protection Agency, 2011). The parameters SC, ROE, and SUM represent different measures of dissolved solids, and so mean annual loads were computed for each of these parameters at a given station. The program "Fluxmaster" (Schwarz and others, 2006) was used to estimate the mean annual loads, which were detrended to the year 2000 to give an estimate of the load that would have occurred during 2000 under long-term mean hydrologic conditions (Schwarz and others, 2006). Details of the station selection and load determination process are further explained below.

The following criteria were used for selecting monitoring stations and identifying samples for use in load estimation:

- Water-quality and streamflow monitoring stations must be either colocated or located on the same stream without significant inflows occurring in between.
- Stations must be located on the reaches of the MRB_E2RF1 network. For reaches with multiple stations, the station farthest downstream was retained and the upstream station(s) were removed from the study.
- Stations on the coast must not be included if stream water chemistry was influenced by mixing with ocean water.
- Samples and streamflow data must be between water years 1980 and 2009 so as to represent relatively recent water-quality conditions.
- A minimum of 25 samples must be available for a given parameter (SC, ROE, or SUM) at a station so as to represent different flow conditions and seasonal variation over the period of data collection.
- Samples and streamflow data must span a minimum of 5 years to represent various hydrologic conditions and for trend detection.
- One or more samples and one or more years of streamflow data must be available prior to water year 2003 and after water year 1997 so that load estimates were not extrapolated distant in time to the 2000 base year.

Samples less than 10 µS/cm (microsiemens per centimeter) or 10 mg/L were deemed suspect and discarded unless data for other samples for the same station and parameter indicated that dissolved solids were typically at that low level. Samples deemed suspect typically were two or three orders of magnitude lower than either (1) other samples at the same station or (2) other measures of dissolved solids for the same sample; both of these reasons suggested the suspect data may have resulted from data entry errors.

Long-term mean annual loads were estimated at each monitoring station using the Fluxmaster program (Schwarz and others, 2006). In this program, log-transformed instantaneous dissolved-solids concentrations (SC, ROE, or SUM) were related to log-transformed mean daily streamflow using a bias-corrected log-linear regression model with maximum likelihood estimation (Cohn, 2005). Five different regression models were estimated for each water-quality station; the models varied by the terms contained in them as follows:

- Intercept
- Intercept and long-term trend
- Intercept, long-term trend, and seasonal pattern
- Intercept, long-term trend, seasonal pattern, and log of flow
- Intercept, long-term trend, seasonal pattern, log of flow, and squared log of flow

Seasonal patterns in concentration were represented in the regression model by a second-order harmonic of the sine and cosine of decimal time, and the long-term trend term was represented by a linear function of decimal time. A companion model of daily streamflow was also estimated for each water-quality station. The streamflow model relates the logarithm of daily streamflow to a second-order harmonic of the sine and cosine of decimal time, a linear time-trend term, and a 10-day autoregression term in the residuals to account for serial correlation in the daily values. The streamflow model was then used to predict long-term mean streamflow for each day during the base year 2000. These streamflow estimates were then input to the water-quality model to predict dissolved-solids concentrations (SC, ROE, and SUM) for each day during the base year 2000. The predicted streamflow and dissolved-solids concentrations were then multiplied together to obtain daily loads, which were summed together for an estimate of the long-term mean annual load detrended to base year 2000.

For each parameter (SC, ROE, and SUM) available for a given water-quality station, the long-term annual load estimate was chosen from the five models based on two criteria. The first criterion was the 'observed/expected ratio,' which is part of the Fluxmaster output and represents a weighted average ratio of the observed daily load divided by a weighted predicted daily load for monitored days. This value will be greater than 1 if load is under-predicted, and less than 1, but positive, if load is overpredicted. The weights were intended to account for over- or underrepresentation of the observation days in terms of conditions that dictate the determination of load—principally streamflow, but also time trend and seasonal factors. Models were discarded from selection where the expected value exceeded 30 percent difference from the observed value, and therefore resulted in an observed/expected ratio that was either less than 0.77 or greater than 1.43. The second criterion used for selecting the long-term load estimate from the possible five models was the Akaike information criterion with a correction for finite sample sizes, referred to as the AICc. The load estimate from the model with the lowest AICc was selected as the long-term load estimate for each parameter for a given station.

Long-term annual load estimates for SC, ROE, and SUM (L_{SC}, L_{ROE}, and L_{SUM}, respectively) for a given water-quality monitoring station were evaluated to select the value to represent the dissolved-solids load (L_D), which is used to estimate the national SPARROW model of dissolved-solids transport. First, an average ratio of SUM to SC values, $R_{SUM/SC}$, was determined for each station using data for individual samples. For all stations where such average ratios could be computed, the average for these stations was 0.616. Likewise, an average ratio of SUM to ROE values was determined, $R_{SUM/ROE}$, and for all stations where such average rates could be determined, the average for these stations was 0.931. Next, to convert the L_{SC} load estimates to equivalent L_{SUM} load estimates, L_{DSC}, the L_{SC} load estimates were multiplied by the station-specific ratio $R_{SUM/SC,}$ where available, or the average value of 0.616 if such ratios were unavailable. Likewise, L_{ROE} was multiplied by $R_{SUM/ROE}$ ratio to obtain the estimated dissolved-solids load based on ROE data, L_{DROE}. The variances (S^2_{SC} and S^2_{ROE}) of the load estimates (L_{SC} and L) were also converted to equivalent SUM variances by multiplying them by the ratios $R_{SUM/SC}$ and $R_{SUM/ROE}$. Multiplication of the original loads by the ratios $R_{SUM/SC}$ and $R_{SUM/ROE}$ increases the uncertainty of those estimates because the ratios themselves contain uncertainty, and thus variances of the load estimates were increased by adding them to the variance of the ratio estimates. To combine the variance from the ratio with the variance from the load estimate, each of which has different units, the variances were first converted to squared percent errors, then added together, and then multiplied by the square of the load estimate. In the final step of the load evaluation, the variances of the L_{DSC}, L_{DROE}, and L_{SUM} estimates for a given station were compared, and the estimate with the smallest variance was selected to represent the dissolved-solids load (L_D) that was used to estimate the national SPARROW dissolved-solids model. Where the station was not located at the downstream end of a reach in the MRB_E2RF1 network, L_D was multiplied by the ratio of the upstream drainage area for the reach to the upstream drainage area for the station.

Altogether, long-term mean annual loads were determined for 2,560 monitoring stations and used to estimate the national SPARROW model of dissolved-solids transport (appendix 1). This represents an average nationwide density of 330 stations per million km^2; however the density varies spatially (table 1). For example, the New England, Mid-Atlantic, and Upper Colorado River water-resources regions have monitoring-station densities greater than 500 stations per million km^2, whereas the Lower Mississippi, Rio Grande, Lower Colorado, and California water-resources regions have monitoring-station densities less than 200 stations per million km^2 (table 1). In general, a greater monitoring-station density allows the model to more accurately reflect dissolved-solids sources and transport processes and results in a lower uncertainty of model predictions.

Comparison of estimated long-term mean annual load data is facilitated by normalizing estimates with respect to drainage area (yields) or to annual discharge (flow-weighted concentrations). Maps of the estimated long-term mean annual yield and flow-weighted concentrations show the presence of regional patterns, and that spatial changes in values among nearby stations are small relative to the range of values observed for the Nation as a whole (figs. 5 and 6). These two observations suggest that the predominant sources, land-to-water delivery, and stream losses of dissolved solids vary more at the regional scale rather than at local scale.

Nationwide, the median long-term mean annual yield for monitoring stations is 26 (Mt/yr)/km^2 (table 2); however, the yields have a range of almost 4 orders of magnitude. The minimum and maximum long-term mean annual yields are 0.1 (Mt/yr)/km^2 and 714 (Mt/yr)/km^2, respectively. Median long-term mean annual yields for stations within water-resources regions are greater than 60 (Mt/yr)/km^2 in the Great Lakes, Ohio, Tennessee, and Upper Mississippi regions, and less than 10 (Mt/yr)/km^2 in the Rio Grande and Lower Colorado regions.

Nationwide, the median long-term mean annual flow-weighted concentration for monitoring stations is 187 mg/L (table 3). Like yield, concentrations also have a wide range; the minimum and maximum long-term mean annual flow-weighted concentrations are 9 mg/L and 10,769 mg/L, respectively. Median long-term mean annual flow-weighted concentrations within water-resources regions were greater than 350 mg/L in the Souris-Red-Rainy, Missouri, and Lower Colorado regions, and less than 70 mg/L in the New England, South Atlantic-Gulf, and Lower Mississippi regions.

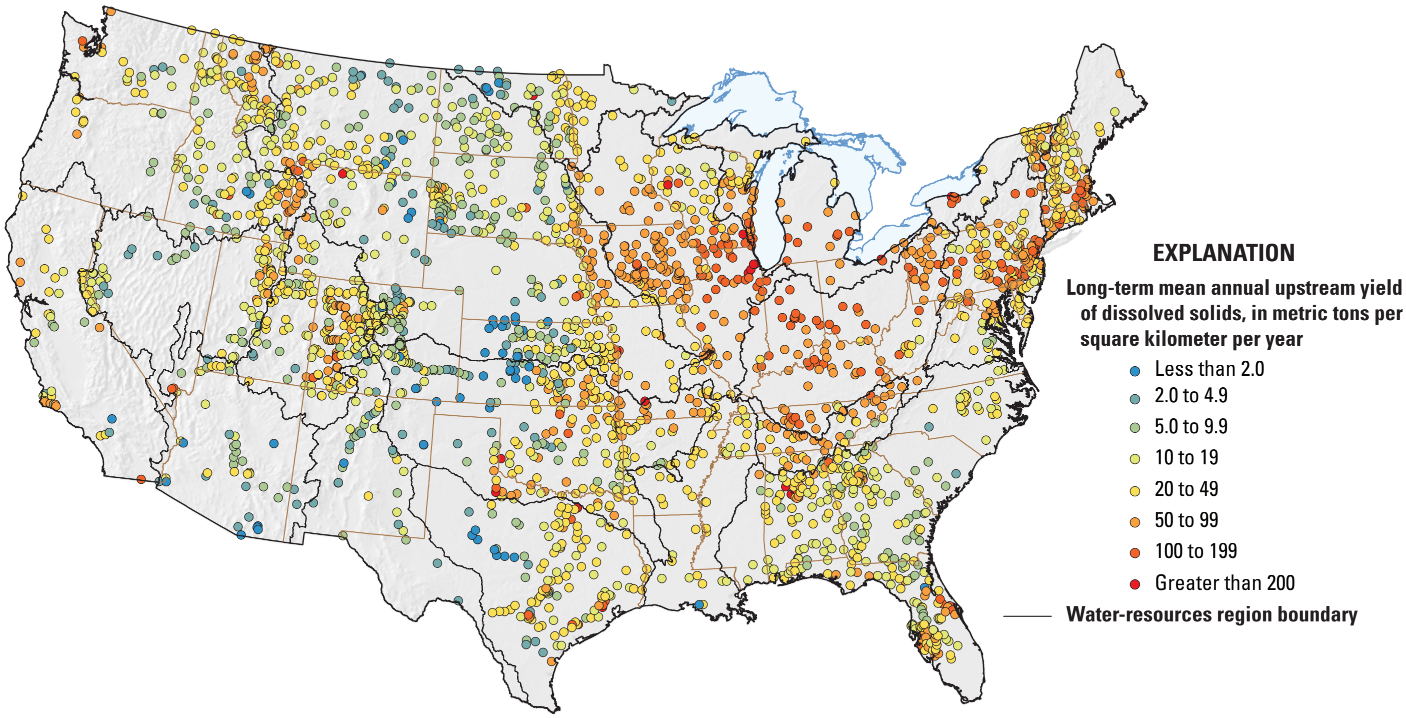


Figure 5. Map of conterminous U.S. showing long-term mean annual yield of dissolved solids at 2,560 water-quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport.

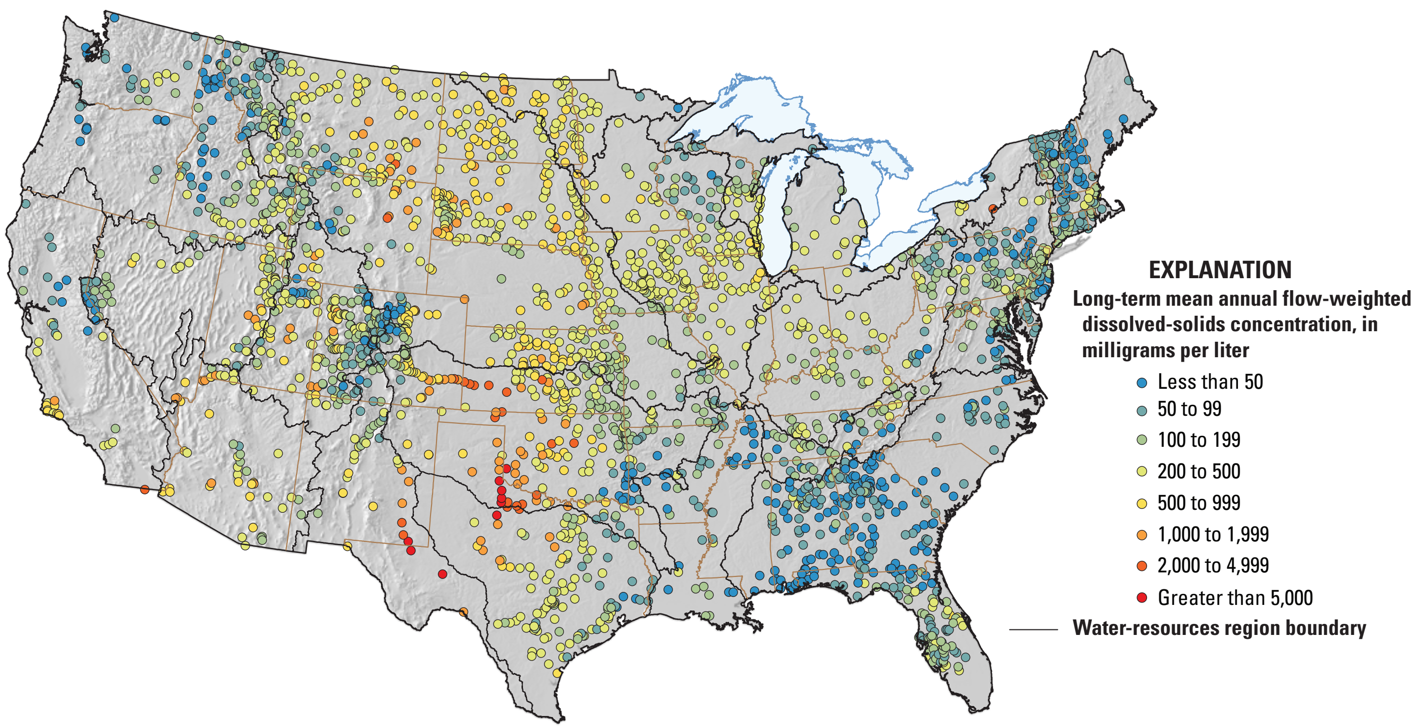


Figure 6. Map of conterminous U.S. showing long-term mean annual flow-weighted concentration of dissolved solids at 2,560 water-quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport.

Table 2. Percentile statistics of long-term mean annual yields of dissolved-solids at 2,560 water-quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport, tabulated by water-resources regions of the conterminous United States.

Water-resources region		Percentile statistic for estimated long-term mean annual yield at monitoring stations, metric tons per year per square kilometer						
Code	**Name**	**Minimum**	**10th**	**25th**	**Median**	**75th**	**90th**	**Maximum**
1	New England	11.5	19	26	42	75	107	152
2	Mid-Atlantic	7.2	20	30	53	81	115	244
3	South Atlantic-Gulf	1.9	9	13	19	33	60	282
4	Great Lakes	17.7	32	47	72	114	175	282
5	Ohio	13.7	50	66	92	115	135	183
6	Tennessee	9.2	23	42	64	77	94	111
7	Upper Mississippi	15.1	28	49	79	94	115	714
8	Lower Mississippi	0.1	13	20	27	33	47	88
9	Souris-Red-Rainy	0.3	3	9	19	27	34	379
10	Missouri	0.1	4	8	15	34	60	319
11	Arkansas-White-Red	0.1	4	10	29	48	62	381
12	Texas-Gulf	0.4	4	15	24	39	57	436
13	Rio Grande	1.0	3	4	6	12	20	33
14	Upper Colorado	1.5	9	14	23	41	68	213
15	Lower Colorado	0.2	1	3	7	19	34	170
16	Great Basin	2.4	5	11	16	32	47	100
17	Pacific Northwest	0.6	6	14	22	41	61	157
18	California	1.2	7	10	25	48	82	131
Conterminous United States		0.1	6	13	26	54	91	714

Table 3. Percentile statistics of long-term mean annual flow-weighted concentrations of dissolved-solids at 2,560 water quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport, tabulated by water-resources regions of the conterminous United States.

Water-resources region		Percentile statistic for estimated long-term mean annual flow-weighted concentrations at monitoring stations, milligrams per liter						
Code	**Name**	**Minimum**	**10th**	**25th**	**Median**	**75th**	**90th**	**Maximum**
1	New England	11	23	38	58	109	153	233
2	Mid-Atlantic	14	36	60	105	154	207	367
3	South Atlantic-Gulf	9	25	36	57	91	159	747
4	Great Lakes	53	105	168	272	380	448	2,325
5	Ohio	16	84	117	185	250	311	424
6	Tennessee	13	33	66	113	164	214	250
7	Upper Mississippi	44	110	218	305	366	427	691
8	Lower Mississippi	15	31	40	69	110	190	206
9	Souris-Red-Rainy	21	272	350	465	555	638	2,531
10	Missouri	13	136	202	351	536	774	3,347
11	Arkansas-White-Red	9	66	145	257	695	1,652	9,879
12	Texas-Gulf	34	84	167	229	301	635	7,902
13	Rio Grande	40	70	166	214	812	2,852	10,769
14	Upper Colorado	12	51	90	183	342	669	2,311
15	Lower Colorado	88	131	212	416	763	1,406	1,534
16	Great Basin	21	66	109	200	295	487	1,115
17	Pacific Northwest	11	30	55	103	185	263	498
18	California	12	48	82	242	492	590	4,163
Conterminous United States		9	43	83	187	352	600	10,769

Watershed-Attribute Data

Watershed-attribute data for the hydrologic network were developed to represent the major dissolved-solids sources, land-to-water delivery processes, and loss processes that were hypothesized to occur in streams of the Nation (appendix 2). The watershed attributes were derived from existing spatial datasets using geospatial analysis techniques. Several of the attributes were available from previously published SPARROW models of nutrient transport and, therefore, were already attributed for each incremental catchment of the MRB_E2RF1 network. Other attributes that were more specific to dissolved-solids transport, however, were not already available and therefore were developed as part of this investigation.

Attributes developed as part of this investigation include surficial lithology, subsurface evaporite deposits, presence of saline groundwater, fossil-fuel extraction, road deicers, atmospheric deposition of dissolved solids, detrending correction factors for climate conditions, vegetation growth, and water-use variables. Source data formats for these attributes include text files with point information, digital maps, raster images, and point, line, and polygon GIS (geographic informatoin system) layers. Source datasets were processed to enable the use of overlay statistical tools to calculate an attribute count, total area, or average value per catchment polygon.

The attributes that represented sources in exploratory or final SPARROW models include:

- atmospheric deposition
- surficial lithology
- bedrock geology
- subsurface evaporite deposits
- presence of saline groundwater
- fossil-fuel extraction
- road deicers
- land use and land cover
- fertilizer use

Attributes that represented factors affecting land-to-water delivery in exploratory or final SPARROW models include:

- climate conditions
- basin characteristics
- streamflow and runoff conditions
- vegetation growth
- soil conditions
- irrigation and drainage practices
- water use
- population density

Some of the streamflow and runoff conditions were also used to represent stream losses of dissolved solids in the model, and selected information associated with the digital hydrologic network was used to represent attenuation processes that can occur in streams, reservoirs, or lakes. Some attributes could be used to represent either sources or land-to-water transport. For example, ions in atmospheric deposition are a source of dissolved solids; however, some are also acids that promote chemical weathering of geologic materials and therefore also affect land-to-water transport. A short description of each attribute, including its name, definition, units, and whether it was used in the final model is provided in table 4, along with information regarding whether the attribute was developed as part of this study or whether it was developed by previous SPARROW model investigations.

The Watershed-Attribute Portfolio (appendix 5) contains descriptions for the most important watershed attributes investigated in development of the national SPARROW model of dissolved-solids transport—those that were developed as part of this study and those used in the final model. Each attribute or set of attributes is highlighted in the portfolio and includes a definition, units, the source of the data used to develop the attribute and the URL from which the digital data were obtained, a synopsis of the processing steps used to develop the attribute from the source data, and a map showing the spatial distribution of the attribute. In some cases the map is used to show the distribution of the original source data. For example, the spatial extent of surficial lithology units are shown in a single map rather than illustrating the value for area of each unit (km^2) occurring in the incremental catchments in multiple maps.

Strategy

The SPARROW modeling methodology is relatively flexible and different modelers could take somewhat different approaches to model development. This section provides more insight and overview of the SPARROW model, but more importantly, it provides a discussion on the strategy and logic behind the decisions made in developing the national SPARROW model of dissolved-solids transport. A brief and generalized description of the SPARROW modeling methodology as applied to the development of the national SPARROW model of dissolved-solids transport is described here; for a more detailed discussion of the equations and statistical methods used in the SPARROW modeling approach, see Smith and others (1997) and Schwarz and others (2006).

In the SPARROW model, the load leaving a reach in the stream network is considered to be the sum of two components (see equation 1.27 in Schwarz and others, 2006):

1. The load originating within the reach's incremental watershed and delivered to the reach segment, and
2. The load generated within upstream reaches and transported to the reach through the stream network.

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Digital hydrologic network The MRB_E2RF1 digital hydrologic network and associated attribute data were developed by Brakebill and Terziotti (2011).				
MRB_ID	Unique reach identification number for this dataset; used to relate monitoring station data and watershed-attribute data.	NA	Yes	No
FNODE	Internal node number for the beginning of an arc (from-node)	NA	Yes	No
TNODE	Internal node number for the end of an arc (to-node)	NA	Yes	No
HYDSEQ	Hydrologic sequence number for use in sorting the file in downstream order to perform network operations	NA	Yes	No
PNAME	Name of the reach defined in River Reach File 1.0	NA	Yes	No
FRAC	Fractional diversion of load for reaches that share to-nodes	Range of 0 to 1	Yes	No
RCHTYPE	Code determining reservoir or nonreservoir reach	0, nonreservoir; 1, interior reservoir; 2, outlet reservoir reach	No	No
TERMFLAG	Code determining termination of transport	0, transport reach; 1, terminal; 2, nonconnected, closed basin, of drainage to Canada; 3, shoreline reach; 4 Canadian Boundary reach	Yes	No
HEADFLAG	Headwater reach flag	0, nonheadwater reach; 1, headwater reach	Yes	No
CANADIAN	Flag identifying Canadian reaches	NA	No	No
STATE1	State Federal Information Processing Standard	2-digits	No	No
MRB	U.S. Geological Survey National Water Quality Assessment Program Major River Basin code	NA	No	No
HUC2	2-digit U.S. Geological Survey hydrologic cataloging unit	NA	Yes	No
HUC4	4-digit U.S. Geological Survey hydrologic cataloging unit	NA	Yes	No
HUC6	6-digit U.S. Geological Survey hydrologic cataloging unit	NA	Yes	No
HUC8	8-digit U.S. Geological Survey hydrologic cataloging unit	NA	No	No
DEMIAREA	Incremental drainage area for a given reach	km^2	Yes	No
DEMTAREA	Total drainage areas upstream summed for a given reach	km^2	Yes	No
LENGTH	Length of feature in internal units	NP	No	No
MEANQ_RF1	Mean streamflow for reach, from RF1 network	ft^3/s	No	No
MEANV_RF1	Velocity corresponding to mean streamflow for reach, from RF1 network	ft/s	No	No
HLOAD	Hydraulic load from RF1 network	NP	No	No
RCHTOT	Reach time of travel; calculated from MEANV_RF1 and LENGTH	Days	No	No
RESTOT	Time of travel through reservoir	Days	No	No

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Water-quality monitoring data Attribute data were developed as part of this study on the basis of streamflow and stream-chemistry monitoring data in U.S. Geological Survey and U.S. Environmental Protection Agency databases (U.S. Geological Survey, 2010; U.S. Environmental Protection Agency, 2011).				
STATION_ID	Monitoring station identifier	NA	No	No
STATION_NAME	Monitoring station name	NA	No	No
LATITUDE	Monitoring station latitude, referenced to North American Datum of 1983	Decimal degrees	No	No
LONGITUDE	Monitoring station longitude, referenced to North American Datum of 1983	Decimal degrees	No	No
STATION_LOAD	Estimated long-term mean annual dissolved solids load for monitoring station, detrended to year 2000	kg/yr	No	No
LOAD_ERROR	Error for long-term mean annual dissolved-solids load estimate	Percent	No	No
REACH_LOAD	Long-term mean annual load detrended to year 2000 and adjusted to downstream end of reach based on monitoring station yield; this value was used for model estimation	kg/yr	Yes	No
Country and boundary conditions Attribute data were developed as part of this study on the basis of published digital spatial data that delineate political boundaries.				
AREA_CANADA	Area of catchment in Canada	km^2	No	No
AREA_MEXICO	Area of catchment in Mexico	km^2	No	No
AREA_USA	Area of catchment in the United States	km^2	No	No
NON_US_INFLOW_AREA	Area of accumulated drainage outside the United States for boundary reaches with inflow only; zero elsewhere	km^2	Yes	No
NON_US_YIELD	Estimated dissolved-solids yield for area outside United States for boundary reaches with inflow only; zero elsewhere	$(kg/yr)/km^2$	Yes	No
NON_US_INFLOW	Estimated dissolved-solids load entering United States for boundary reaches with inflow only; zero elsewhere	kg/yr	Yes	No
NOMINAL_INPUT	1-kilogram dissolved-solids source material in incremental catchment to ensure nonzero source deliveries for catchment	kg/yr	Yes	No
Surficial lithology Attribute data were developed as part of this study on the basis of published digital spatial data that delineates the lithology of surficial deposits in the United States (Cress and others, 2010).				
L_RMC	Carbonate residual material	km^2	Yes	Yes
L_RMNC	Noncarbonate residual material	km^2	Yes	Yes
L_VRIA	Alkaline intrusive volcanic rocks	km^2	Yes	Yes
L_RMS	Silicic residual material	km^2	Yes	Yes

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Surficial lithology Attribute data were developed as part of this study on the basis of published digital spatial data that delineates the lithology of surficial deposits in the United States (Cress and others, 2010).—Continued				
L_VRE	Extrusive volcanic rock	km^2	Yes	Yes
L_CS	Colluvial sediment	km^2	Yes	Yes
L_GTC	Glacial till, clayey	km^2	Yes	Yes
L_GTL	Glacial till, loamy	km^2	Yes	Yes
L_GTCT	Glacial till, coarse textured	km^2	Yes	Yes
L_GLCT	Glacial outwash and glacial lake sediment, coarse textured	km^2	Yes	Yes
L_GLFT	Glacial lake sediment, fine textured	km^2	Yes	Yes
L_ESCT	Eolian sediment, coarse textured (sand dunes)	km^2	Yes	Yes
L_ESFT	Eolian sediment, fine textured (glacial loess)	km^2	Yes	Yes
L_SLS	Saline lake sediment	km^2	Yes	Yes
L_SFT	Alluvium and fine-textured coastal zone sediment	km^2	Yes	Yes
L_SCT	Coastal zone sediment, coarse textured	km^2	Yes	Yes
L_HYDRIL	Hydric soils, peat and muck	km^2	Yes	Yes
L_WATER	Water (undifferentiated submerged lithologies)	km^2	Yes	Yes
Bedrock geology Attribute data were available from Wieczorek and LaMotte (2010f), who developed them on the basis of digital spatial data delineating the major bedrock types in the United States.				
G_Q_S	Bedrock geology, area underlain by Quaternary sediments	km^2	No	No
G_T_S	Bedrock geology, area underlain by Tertiary sedimentary rocks	km^2	No	No
G_MK_S	Bedrock geology, area underlain by Cretaceous sedimentary rocks	km^2	No	No
G_MZJT_S	Bedrock geology, area underlain by Jurassic and Triassic sedimentary rocks	km^2	No	No
G_PZP_S	Bedrock geology, area underlain by Permian sedimentary rocks	km^2	No	No
G_PZPP_S	Bedrock geology, area underlain by Pensylvanian sedimentary rocks	km^2	No	No
G_PZM_S	Bedrock geology, area underlain by Mississippian sedimentary rocks	km^2	No	No
G_PZD_S	Bedrock geology, Devonian sedimentary rocks	km^2	No	No
G_PZS_S	Bedrock geology, area underlain by Cambrian sedimentary rocks	km^2	No	No
G_PZO_S	Bedrock geology, area underlain by Ordovician sedimentary rocks	km^2	No	No
G_PZC_S	Bedrock geology, area underlain by Cambrian sedimentary rocks	km^2	No	No
G_PC_S	Bedrock geology, area underlain by Precambrian sedimentary rocks	km^2	No	No

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Bedrock geology Attribute data were available from Wieczorek and LaMotte (2010f), who developed them on the basis of digital spatial data delineating the major bedrock types in the United States.—Continued				
G_ALL_C	Bedrock geology, area underlain by continental deposits	km^2	No	No
G_ALL_E	Bedrock geology, area underlain by eugeosynclinal deposits	km^2	No	No
G_ALL_VF	Bedrock geology, area underlain by felsic volcanic rocks	km^2	No	No
G_ALL_V	Bedrock geology, area underlain by other volcanic rocks	km^2	No	No
G_ALL_P	Bedrock geology, area underlain by plutonic rocks	km^2	No	No
G_ALL_M	Bedrock geology, area underlain by metamorphic rocks	km^2	No	No
Subsurface evaporite deposits Attribute data were developed as part of this study on the basis of published maps that delineate major gypsum (or anhydrite) and halite deposits of the United States (Johnson, 2008).				
GYPANHYD	Area of catchment underlain by gypsum (or anhydrite)	km^2	No	Yes
HALGYPANHYD	Area of catchment underlain by halite and gypsum (or anhydrite)	km^2	No	Yes
Presence of saline groundwater Attribute data were developed as part of this study on the basis of published maps that delineate the depth to known saline groundwater where known in the United States (Alley, 2003).				
SALINE_GW_All	Area of catchment underlain by groundwater greater than 1,000 mg/L and less than 500 feet below the land surface	km^2	No	Yes
Fossil fuel extraction Attribute data including oil and gas wells, coalbed-methane, and shale-gas plays were developed as part of this study on the basis of data from the U.S. Energy Information Administration (Biewick, 2008 and U.S. Energy Administration, 2011).				
1900s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1900s	km^2	No	Yes
1910s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1910s	km^2	No	Yes
1920s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1920s	km^2	No	Yes
1930s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1930s	km^2	No	Yes
1940s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1940s	km^2	No	Yes
1950s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1950s	km^2	No	Yes
1960s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1960s	km^2	No	Yes
1970s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1970s	km^2	No	Yes
1980s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1980s	km^2	No	Yes
1990s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 1990s	km^2	No	Yes

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Fossil fuel extraction Attribute data including oil and gas wells, coalbed-methane, and shale-gas plays were developed as part of this study on the basis of data from the U.S. Energy Information Administration.—Continued				
2000s_OILGAS	Number of 1 square-kilometer grid cells in catchment with one or more oil or gas wells, 2000s	km^2	No	Yes
COALFIELDAREA	Area of catchment with coal-bed methane fields	km^2	No	Yes
COUNTGASSYMINES	Number of top 100 mines that produce coalbed-methane in catchment	Count	No	Yes
SHALE_PLAYS_AREA	Area of catchment with shale-gas plays	km^2	No	Yes
Land use and land cover Attribute data were available from Wieczorek and LaMotte (2010e,g), who developed them using the National Land Cover dataset.				
URBAN	Area of urban lands, codes 21,22,23,24 (year 2001)	km^2	Yes	Yes
CULTIVATED	Area of cultivated lands (Orchards, vineyards, row crops, small grains, fallow), code 82 (year 2001)	km^2	Yes	Yes
PASTURE	Area of pasture lands, code 81 (year 2001)	km^2	Yes	Yes
FORESTED	Area of land with forest cover, codes 41, 42, 43 (year 2001)	km^2	Yes	Yes
SHRUB	Area of land with shrub cover, code 52 (year 2001)	km^2	No	Yes
GRASSLAND	Area of land with grass cover, code 71 (year 2001)	km^2	No	Yes
WETLAND	Area of land with grass cover, codes 90, 95 (year 2001)	km^2	No	Yes
CANOPY	Mean percent tree canopy cover (year 2001)	Percent	No	No
Road deicers Attribute data were developed as part of this study on the basis of published digital spatial climate and transportation data, as well as tabular state and national road-salt usage data. (Kostick, 1993–2009, National Climatic Data Center, 2010)				
TOTAL_ROAD_LENGTH	Total length of major highways and roads in catchment	km	Yes	Yes
SNOW_DAYS	Road-length weighted average number days with snowfall equal to or greater than 1 inch for catchment, 1961–90	Days	Yes	Yes
DEICER_WT	State-specific deicer application weight	kg of salt per (road km* snow day)	Yes	Yes
Atmospheric deposition of dissolved solids Attribute data were developed as part of this study on the basis of published National Atmospheric Deposition Program monitoring data (National Atmospheric Deposition Program, 2010).				
ATM_DEP_2000	Atmospheric deposition of dissolved solids, detrended to year 2000, yield, yield for incremental catchment	$(kg/yr)km^2$	No	Yes
ATM	Atmospheric deposition of dissolved solids, detrended to year 2000, load to incremental catchment	kg/yr	Yes	No

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Climate conditions Precipitation and temperature attribute data were available from Wieczorek and LaMotte (2010j, m, n). Detrending correction factors for precipitation and temperature data were developed as part of this study on the basis of climate monitoring data available from the United States Historical Climatology Network (Menne and others, 2012). Potential evapotranspiration was developed as part of this study based on available digital spatial data (Wolock, 2003a).				
PPT1971_2000	Average precipitation, 1971–2000	m/yr	Yes	Yes
PPT_2000_COR	A correction coefficient that converts PPT1971_2000 to a mean annual precipitation rate detrended to year 2000	Dimensionless	Yes	Yes
TMAX1971_2000	Average maximum daily air temperature, 1971–2000	Degrees Celcius	No	No
TMIN1971_2000	Average minimum daily air temperature, 1971–2000	Degrees Celcius	No	No
TAVE1971_2000	Average of average maximum and average minimum daily air temperature, 1971–2000	Degrees Celcius	Yes	Yes
TEMP_2000_COR	A correction coefficient that converts TAVE1971_2000 to a mean annual air temperature detrended to year 2000	Dimensionless	Yes	Yes
PET_MEAN	Mean potential evapotranspiration	in/yr	No	No
Basin characteristics Attribute data were available from Wieczorek and LaMotte (2010b), who developed them on the basis of digital elevation data and the digital data for the MRB_E2RF1 network.				
BSI	Basin Shape Index; catchment area divided by perimiter squared	Dimensionless	No	No
STRM_DENS	Stream density; reach length divided by catchment area	NP	No	No
SINUOUSITY	Reach length divided by straight line length	Dimensionless	No	No
ELEV_MEAN	Mean elevation	m	No	No
SLP_DEG	Mean slope	Degrees	Yes	Yes
SLP_PER	Mean slope	Percent rise	No	No
Streamflow and runoff characteristics Q_Reach was available from Wolock (2003b) and Q_CHANGE, Q_LOSS_PCT, AND Q_GAIN were derived from those data. The baseflow and overland flow data were available from Wieczorek and LaMotte (2010c, f, k).				
Q_REACH	Average annual discharge in reach for 1975–2007, extrapolated from U.S. Geological Survey stream monitoring data	ft^3/s	Yes	Yes
Q_CHANGE	Change in reach's annual discharge from upstream inflow(s)	ft^3/s	No	No
Q_LOSS_PCT	Decrease in reach's annual discharge, as a percentage of Q_reach. Zero if there was a gain	Percent	Yes	Yes
Q_GAIN_PCT	Increase in reach's annual discharge, as a percentage of Q_reach. Zero if there was a loss	Percent	No	No
BFI_MEAN	Average base-flow index for area	Percent	Yes	Yes
SAT_EOF	Average saturation excess-overland flow for catchment	Percent	No	No
INF_EOF	Average infiltration excess-overland flow for catchment	Percent	No	No

Table 4. Digital hydrologic network, water-quality monitoring station, and watershed-attribute data used in the development of the national SPARROW model of dissolved-solids transport.—Continued

[NA, not applicable; NP, not provided]

Name	Definition	Units	Used in final model	Presented in watershed-attribute portfolio
Vegetation growth Attribute data were developed as part of this study on the basis of published vegetation growth data available from the National Atlas (Center for Earth Resources Observation and Science, 2005–12).				
PVEG2000	Average peak vegetation growth for year 2000 as determined using the normalized difference vegetation index	Dimensionless	Yes	Yes
Soil conditions Attribute data were available from Wieczorek and LaMotte (2010l) except for soil salinity, which was unpublished but available from Wieczorek (written commun. May 6, 2011). The attribute data were developed on the basis of data from the State Soil Geographic Database (STATSGO).				
PERMAVE	Average value for permeability in soils	Percent	No	No
CLAYAVE	Average value of percent clay in soils	Percent	Yes	Yes
SILTAVE	Average value of percent silt in soils	Percent	No	No
SANDAVE	Average value of percent sand in soils	Percent	Yes	Yes
HGA	Percent of catchment with soil hydrologic group “A”	Percent	No	No
HGB	Percent of catchment with soil hydrologic group “B”	Percent	No	No
HGC	Percent of catchment with soil hydrologic group “C”	Percent	No	No
HGD	Percent of catchment with soil hydrologic group “D”	Percent	No	No
SOIL_SALINITY	Average value of soil salinity in catchment	Milllimhos per centimeter	No	Yes
Irrigation and drainage practices Attribute data were available from Wieczorek and LaMotte (2010a), who devloped them on the basis of National Resource Inventory data. Irrigation and drainage practice area data were divided by the catchment area with cultivated lands and pasture lands to express the data as percentages.				
PCT_IRRIG	Estimated area subject to the practice of irrigation, as a percent of cultivated lands and pasture lands	Percent	Yes	Yes
PCT_DITCHES	Estimated area subject to ditch drainage, as a percent of cultivated lands and pasture lands	Percent	Yes	Yes
PCT_TILES	Estimated area subject to tile drainage, as a percent of cultivated lands and pasture lands	Percent	Yes	Yes
Fertilizer use Attribute data were available from Wieczorek and LaMotte (2010h), who devloped them on the basis of published 2002 county-level fertilizer usage estimates.				
FARM_N	Sum total of nitrogen from farm areas	kg nitrogen	No	No
NOFARM_N	Sum total of nitrogen from non-farm areas	kg nitrogen	No	No
FARM_P	Sum total of phosphorus from farm areas	kg phosphorus	No	No
NOFARM_P	Sum total of phosphorus from non-farm areas	kg phosphorus	No	No
Water use Attribute data were developed as part of this study on the basis of data from the U.S. Geological Survey Water-Use Program (U.S. Geological Survey, 2011).				
IRRIG_WATER_USE	Water application rate per unit area of irrigated cropland, year 2000	m/yr	Yes	Yes
MUNI_WATER_USE	Municipal and industrial per-capita use rate, year 2000	m^3/yr per person	Yes	Yes
Population density Attribute data were available from Wieczorek and LaMotte (2010i), who developed them on the basis of U.S. Bureau of Census data.				
POP_2000	Population density for catchment, year 2000	Number of people per km^2 multiplied by 10	Yes	Yes

The first component of the load leaving a reach accounts for loads generated from sources within the incremental catchment and delivered to the reach. Several source-dependent processes affect the amount of contaminant load reaching the stream network. For source loads originating on the landscape, the processes affecting delivery from the source to the stream network are called land-to-water delivery processes, and they may reflect both surface and subsurface processes.

Sources and land-to-water delivery processes are represented by user-selected variables in the SPARROW model. Source variables are multiplied by source coefficients in the model to adjust source-input data so that it reflects the contaminant loading rate originating from that source. Source variables may be intensive, meaning a direct measure of contaminant mass, or extensive, meaning a surrogate measure of mass, such as an area or a count of a particular feature indicative of a contaminant source. Most source variables in the national SPARROW model of dissolved-solids transport were extensive variables.

The amount of dissolved solids from a given source, as determined by the product of the source variable and the source coefficient, is amplified or reduced by multiplying it by the land-to-water term. Flexibility of the SPARROW model allows users to specify which source variables are affected by each land-to-water delivery variable. The land-to-water delivery term consists of an exponential function of the land-to-water variable multiplied by a model coefficient. The mathematical relations within the exponential function are constructed so as to constrain the result to equal or exceed zero, which is important to ensure that the source term is never multiplied by a negative value representing the land-to-water delivery term (Schwarz and others, 2006). The value is between zero and one if representing a reducing process, and the value is greater than one if representing an amplifying process.

The second component of the load leaving a reach accounts for the accumulation of load from the drainage area upstream from the reach of interest, as well as any loss processes that occur within stream or reservoir segments of the reach network. Load accumulation through the network is a rather straightforward matter of accounting for loads entering the hydrologic network from adjoining reaches in the downstream direction. The load transported out of a given reach can be distributed among two or more downstream reaches, which most often occurs where the stream is braided or where there are significant streamflow diversions. In these cases, the FRAC variable of the reach network represents the fraction of the upstream load that is allocated to each of the downstream diverging reaches, and the SPARROW model routes the appropriate amount to each reach on the basis of this value.

Contaminant loss or attenuation processes can occur during stream and reservoir or lake transport. Where streamflow is diverted for off-stream use and does not return back to the main stem of the river, the load can be reduced from the reach using the FRAC variable to indicate the fraction of the load that remains in reach, and the fraction that is lost by diversion. If a canal is represented in the MRB_E2RF1 network, then the fraction lost from the reach using the FRAC variable is routed to that canal. In most cases, however, canals and other conveyance structures are not represented in the network and the FRAC variable effectively removes the diverted load from the network entirely.

Stream decay or reservoir decay terms can be used to represent attenuation of loads due to geochemical, biological, or settling processes. In the SPARROW model, the accumulated load is multiplied by the stream decay and reservoir decay terms with the purpose of maintaining or reducing the accumulated load in the reach of interest. Like the land-to-water delivery term, the stream decay and reservoir decay terms use an exponential function; however, they are mathematically constructed to constrain the result between zero and one (Schwarz and others, 2006). This calculation ensures that the accumulated load is either reduced or not affected, but it is never increased by these terms.

Several exploratory models were constructed before arriving at the final national SPARROW model of dissolved-solids transport. Each exploratory model had different configurations of source, land-to-water delivery, and stream or reservoir decay variables. The general approach to building the model was to start simple and build a more complex model with additional variables under a goal of minimizing the root-mean-square error. Surficial lithology variables were added first, followed by the source variables of atmospheric deposition, subsurface evaporites, saline groundwater, land cover, and fossil-fuel extraction. Model development included selecting the land-to-water variables that should be applied to each source variable, which was largely determined on the basis of the root-mean-square error for the model and on the p-values for variable coefficients.

After testing all source variables for significance and assessing their inclusion in the model, maps of model residuals were visually examined for regional-scale spatial patterns indicative of model bias, namely areas with predominantly positive or negative residuals. The regional-scale patterns in residuals were largely considered the result of representing sources with extensive variables, especially the geologic sources, and only two intensive variables (atmospheric deposition and road deicers). Compared to intensive-source variables, which represent a direct measurement of mass, extensive-source variables represent a surrogate for contaminant mass that by its nature is more uncertain than a measurement of mass. The regional-scale spatial patterns in model residuals were visually compared to the spatial distribution of the watershed attributes to identify correspondences. In most cases, the spatial patterns of residuals corresponded best with geologic units compared to other source or land-to-water transport variables. Consequently, the bias in these cases was rectified by assuming that the errors resulted from a geologic unit source coefficient that was either too high or too low for the area of concern because of spatial differences in weathering potential within that geologic unit. With this assumption, the geologic unit variable was split into two variables, one applied for areas of high dissolved-solids yields, and the other applied to areas of low dissolved-solids yields. The high-yielding and low-yielding areas for geologic units were geographically assigned on the basis of their hydrologic unit code.

In general, source and land-to-water delivery variables with p-values less than 0.05 were retained in the final model. There were three exceptions to this rule, however. The first was that all surficial lithology variables with nonzero source coefficients were retained in the final model so that the entire area of the Nation was represented, regardless of the p-value for the source coefficient. Those surficial lithology variables with p-values greater than 0.05 are thought to be less significant in the model as a result of a lack of monitoring stations in areas where those sources are prevalent rather than a lack of importance of the source to dissolved-solids loads. The second exception was implemented in recognition that the purpose of the model is to simulate the major sources and transport processes affecting dissolved solids in the Nation's streams. If predictions from exploratory models indicated that a given source did not contribute at least 0.5 percent of the total delivery of dissolved solids to the Nation's streams, as determined from model predictions, then that variable was deemed not significant at the national scale and removed from the model. The third exception occurred during development of the very last set of exploratory models, where parsimony was sought for the final model. In this last stage of obtaining the final model, the model complexity was reduced by removing individual variables from the model if such removal only increased the root-mean-square error by 1 percent or less.

Model boundary conditions require that each incremental catchment must have a nonzero, nonnegative amount of dissolved solids delivered. To achieve this, all source coefficients were restricted to be greater than or equal to zero. Also, for some small catchments (less than 1 km^2) all of the watershed-attribute data for sources were zero; consequently a nominal source input of 0.01 kg was added to ensure this requirement was met for each reach. Another model boundary condition occurs where dissolved-solids loads enter the United States across international borders. Dissolved solids in streams entering from Canada or Mexico were accounted for in the SPARROW model by creating a source variable equal to the Canadian or Mexican land area in each incremental catchment, which was then multiplied by an estimated yield for that catchment. The yields were estimated on the basis of yields estimated for monitoring stations or predicted yields from exploratory models for neighboring areas in the United States.

For model estimation, estimated long-term mean annual loads for monitoring stations were weighted on the basis of the intervening drainage area between the monitoring station of interest and other monitoring stations that occurred upstream, if any. SPARROW model estimation is performed based on the differences in load entering and leaving this intervening area, and on the watershed attributes for this intervening area. This approach removes correlation in observations of load that is otherwise present in nested monitoring stations. Weights for each observation of load were computed as the log-transformed intervening area for the monitoring station of interest, divided by the average log-transformed intervening area for all monitoring stations. For model estimation, this provided more weight to stations with larger intervening areas and less weight to stations with smaller intervening areas. Compared to monitoring stations with large intervening areas, monitoring stations with smaller intervening areas were considered to likely have a greater percentage of error in the estimates of the difference between long-term mean annual loads and a greater percentage of error in the watershed-attribute data. Consequently, the approach for weight selection was intended to provide more weight to observations of load with lower uncertainty and less weight to observations of load with greater uncertainty.

Coefficients of the source, land-to-water delivery, and stream/reservoir decay terms in the SPARROW model were estimated using nonlinear regression (Schwarz and others, 2006). Various model diagnostics were used to assess the changes in model goodness-of-fit that occurred with different configurations of variables in the exploratory models, and for selection of the final model. The primary diagnostics included:

- Overall statistics, including R-squared, yield R-squared, and the root-mean-squared error for the residuals. Changes in these statistics were noted between different exploratory models to determine whether a general improvement in the model occurred as a result of the new specification in the source and land-to-water variables.

- Statistics for individual variable coefficients including the students T statistics and significance (p-value) as well as the variance inflation factor, which is indicative of collinearity between the variable of interest and others in the specified model. As mentioned previously, these statistics were examined to determine the significance of individual variables coefficients in the specified model.

- Graphs of the observed versus predicted loads, observed verus predicted yields, residuals versus predicted load, and residuals versus predicted yield. These graphics provided additional information on the overall fit of predicted loads to the load estimates for monitoring stations.

- Summary statistics of residuals for water-resources regions and maps of model residuals. These provided information on spatial variation of random and bias errors in the model.

After the final model was selected based on the above diagnostics, a bootstrap analysis was performed as an additional assessment of the uncertainty of the model coefficients (Schwartz and others, 2006). In this analysis, observations of loads from monitoring stations were randomly selected with replacement, the model was re-estimated, and the resulting source and land-to-water delivery coefficients were recorded. This process was repeated 200 times, yielding a set of 200 observations of each model coefficient from which confidence intervals that contain the mean value (p=0.90) of the coefficient were determined.

Model Description

The national SPARROW model of dissolved-solids transport was successfully estimated using long-term mean annual loads for 2,560 monitoring stations, and it includes 31 geologic sources that are mediated by seven land-to-water delivery terms, and four other sources that are mediated by eight other land-to-water delivery terms. During model development, some watershed attributes were mathematically transformed while others were duplicated so that different responses of that variable could occur for different geographic regions (table 5). In this report section, an evaluation of the model diagnostics and assumptions is discussed, followed by further description of the major sources, land-to-water delivery processes, and attenuation and loss processes for dissolved solids, as indicated by the national SPARROW model.

Model diagnostics and other information indicate that random and bias errors associated with the model are acceptable and that model assumptions were met. The nonlinear least-squares estimation results for the national SPARROW model of dissolved-solids transport are summarized in table 6, and they include estimated coefficients and diagnostics for dissolved-solids source and land-to-water delivery variables, non-parametric bootstrap estimates for each coefficient, and several overall model diagnostic statistics.

The model explained 90.9 percent of the spatial variability in the log-transformed values of the long-term mean annual load (load R-squared; table 6). Load R-squared values are generally high because of the strong relation between drainage area and annual discharge, a significant determinant of stream load. With adjustment for drainage-area scaling affects in the loads for monitoring stations, the model explained about 70.5 percent of the observed variability (yield R-squared value of 0.705; table 6). The yield R-squared is a better measure of fit than load R-squared given that the basin sizes were variable for the monitoring stations. For comparison, the yield R-squared for six regional SPARROW models with similar monitoring station densities as that of this study ranged from 0.72 to 0.86 for nitrogen, and 0.60 to 0.80 for phosphorus (Preston, Alexander, Schwarz, and Crawford, 2011).

The root-mean-square error for the model was 0.605 log units, implying that on average the predicted dissolved-solids load or concentration in any given reach has an error of approximately 60.5 percent. For comparison, the root-mean-square error for six regional SPARROW models with similar monitoring station densities as that of this study ranged from 0.320 to 0.744 for nitrogen, and 0.493 to 1.010 for phosphorus (Preston, Alexander, Schwarz, and Crawford, 2011). The root-mean-square error of the other national SPARROW models was 0.45 for nitrogen transport and 0.71 for phosphorus transport (Smith and others, 1997).

The mean residual error was near zero for each water-resources region, which indicates the model is generally unbiased down to the regional scale for all parts of the Nation (table 7). The largest mean residual errors for water-resources regions were -0.15 for California, -0.08 for Rio Grande, 0.09 for Ohio, and 0.10 for Lower Colorado. The standard deviation of residual errors for water-resources regions was highest in three of those same regions—0.98 for Lower Colorado, 0.87 for California, and 0.75 for Rio Grande. Both bias and variance of residuals tends to be greater in the more arid and more densely monitored regions of the Nation than in the more humid and more densely monitored regions (table 1). The ratio of the mean residual to the standard error of the residuals within a water-resources region indicates the relative importance of bias error and random error in the model for each region. For most water-resources regions, this ratio is less than 11 percent (table 7). This ratio, however, is higher for the Ohio (24.7), Lower Mississippi (-15.1), and California (-17.1) regions and indicates that the relatively high amount of bias error compared to random error in these areas should be kept in mind when using predictions from these regions.

Table 5. Geographic restrictions and mathematical transformations applied to source and land-to-water delivery variables of the national SPARROW model of dissolved-solids transport.

[Water-resources regions, subregions, and accounting units are defined in Seaber and others, 1987]

Watershed attribute	Geographic restrictions or mathematical transformations applied within the SPARROW modeling environment
	Source variables
Carbonate residual material	High yielding in water-resources regions 2, 4, 7, and 8; low yielding elsewhere
Noncarbonate residual material	High yielding in water-resources regions 2, 13, 14, 15, 16, and 18; low yielding elsewhere
Alkaline intrusive volcanic rock	None
Silicic residual material	Low yielding in water-resources regions 2, 3, 6, and 12; high yielding elsewhere
Extrusive volcanic rock	None
Colluvial sediment	High yielding in water-resources subregions 1105, 1106, 1109, 1110, 1112, 1113, and 1206; moderate yielding in water-resources regions 2, 5, 6, and 7; low yielding elsewhere
Glacial till, clayey	None
Glacial till, loamy	High yielding in water-resources regions 4,5, and 7, and subregions 1017, 1023; low yielding elsewhere
Glacial till, coarse textured	High yielding in water-resources subregion 108; low yielding elsewhere
Glacial outwash and glacial lake sediment, coarse textured	High yielding in water-resources regions 2 and 7; low yielding elsewhere
Glacial lake sediment, fine textured	High yielding in water-resources accounting units 90201 and 90203; low yielding elsewhere
Eolian sediment, coarse textured (sand dunes)	None
Eolian sediment, fine textured (glacial loess)	High yielding in water-resources subregions 1023; low yielding in water-resources subregions 1025, 1026, 1103, 1104, and 1110; moderate yielding elsewhere
Saline lake sediment	None
Alluvium and fine-textured coastal zone sediment	Low yielding in water-resources regions 3, 6, and 8; high yielding elsewhere
Coastal zone sediment, coarse-textured	High yielding in water-resources subregions 310, 311, 312, 313, and 314; low yielding elsewhere
Hydric soils, peat and muck	None
Water (undifferentiated submerged lithologies)	None
Cultivated lands	None
Pasture lands	None
Urban lands	None
Road deicers	Calculated as: (road length) x (snow days) x (state-specific deicer application rate)
	Land-to-water delivery variables
Precipitation	Variable was duplicated, one to be applied to geologic sources and the other to be applied to cultivated lands and pasture lands. Both were log transformed
Atmospheric deposition	Log transformed
Slope	None
Clay	None

Table 5. Geographic restrictions and mathematical transformations applied to source and land-to-water delivery variables of the national SPARROW model of dissolved-solids transport.—Continued

[Water-resources regions, subregions, and accounting units are defined in Seaber and others, 1987]

Watershed attribute	Geographic restrictions or mathematical transformations applied within the SPARROW modeling environment
	Land-to-water delivery variables—Continued
Sand	None
Forested area	Assigned as "East" for water-resources regions 1-7, and "West" elsewhere; transformed to fraction of catchment area
Vegetation index	Values greater than 160 reassigned as equal to 160
Low streamflow index	If the vegetation index was less than 160 and streamflow was less than 50 cubic feet per second then values were computed as: (50-streamflow)/50 ; otherwise values were assigned as 0
Tiles	Transformed to percent area with cultivated lands and pasture lands
Ditches	Transformed to percent area with cultivated lands and pasture lands
Baseflow index	None
Irrigation application rate	None
Population density	Log transformed

Table 6. Summary of estimation results for the national SPARROW model of dissolved-solids transport.—(

[m, meter; km, kilometer; Mt, metric ton; –, not applicable]

Summary statistics			
Number of observations	2,560	Load R-squared	0.909
Root-mean squared error	0.605	Yield R-squared	0.705

Watershed attribute	Watershed attribute units	Coefficient units	Model coefficient	Standard error of the model coefficient	Probability level (p-value)	Variance inflation factor	90% Confidence interval for the model coefficient from bootstrap analysis		Mean coefficient estimate from bootstrap analysis)
							Low	High	
Geologic materials									
Carbonate residual material, high yielding	km^2	$(Mt/yr)/km^2$	30.2	6.0	<0.0001	1.13	23.0	36.4	30.4
Carbonate residual material, low yielding	km^2	$(Mt/yr)/km^2$	19.4	1.7	<0.0001	1.41	16.2	22.6	19.6
Noncarbonate residual material, high yielding	km^2	$(Mt/yr)/km^2$	23.1	2.1	<0.0001	1.64	19.4	27.4	23.4
Noncarbonate residual material, low yielding	km^2	$(Mt/yr)/km^2$	12.4	0.7	<0.0001	1.52	11.0	14.1	12.6
Alkaline intrusive volcanic rock	km^2	$(Mt/yr)/km^2$	95.2	26.6	0.000	1.16	32.5	147.6	88.0

Table 6. Summary of estimation results for the national SPARROW model of dissolved-solids transport.—Continued

[m, meter; km, kilometer; Mt, metric ton; –, not applicable]

Watershed attribute	Watershed attribute units	Coefficient units	Model coefficient	Standard error of the model coefficient	Probability level (p–value)	Variance inflation factor	90% Confidence interval for the model coefficient from bootstrap analysis		Mean coefficient estimate from bootstrap analysis)
							Low	High	
Silicic residual material, low yielding	km^2	$(Mt/yr)/km^2$	5.2	1.5	0.001	1.41	3.0	7.7	5.3
Extrusive volcanic rock	km^2	$(Mt/yr)/km^2$	5.3	6.1	0.383	1.08	–11.7	10.7	3.8
Colluvial sediment, high yielding	km^2	$(Mt/yr)/km^2$	81.4	12.0	<0.0001	1.13	48.9	109.0	82.1
Colluvial sediment, moderate yield-ing	km^2	$(Mt/yr)/km^2r$	25.1	3.2	<0.0001	1.88	20.1	30.9	25.3
Colluvial sediment, low yielding	km^2	$(Mt/yr)/km^2$	4.4	0.8	<0.0001	1.28	2.9	6.1	4.6
Glacial till, clayey	km^2	$(Mt/yr)/km^2$	28.7	8.9	0.001	1.12	20.4	39.5	29.3
Glacial till, loamy, high yielding	km^2	$(Mt/yr)/km^2$	28.9	2.8	<0.0001	1.67	23.5	33.3	28.8
Glacial till, loamy, low yielding	km^2	$(Mt/yr)/km^2$	13.4	1.7	<0.0001	1.53	9.8	16.8	13.4
Glacial till, coarse textured,high yielding	km^2	$(Mt/yr)/km^2$	27.7	5.8	<0.0001	1.23	18.2	34.8	27.2
Glacial till, coarse textured, low yielding	km^2	$(Mt/yr)/km^2$	22.1	3.7	<0.0001	1.29	13.6	28.6	21.8
Glacial outwash and glacial lake sediment, coarse textured, high yielding	km^2	$(Mt/yr)/km^2$	100.1	18.5	<0.0001	1.43	74.5	119.7	98.1
Glacial outwash and glacial lake sediment, coarse textured, low yielding	km^2	$(Mt/yr)/km^2$	7.2	3.2	0.024	1.15	2.8	12.4	7.4
Glacial lake sediment, fine textured, high yielding	km^2	$(Mt/yr)/km^2$	67.0	31.0	0.031	1.09	19.3	110.0	63.9
Glacial lake sediment, fine textured, low yielding	km^2	$(Mt/yr)/km^2$	18.2	8.0	0.024	1.12	6.4	28.9	17.4
Eolian sediment, coarse textured (sand dunes)	km^2	$(Mt/yr)/km^2$	11.2	3.6	0.002	1.21	–4.1	22.4	10.4

Table 6. Summary of estimation results for the national SPARROW model of dissolved-solids transport.—Continued

[m, meter; km, kilometer; Mt, metric ton; –, not applicable]

Watershed attribute	Watershed attribute units	Coefficient units	Model coefficient	Standard error of the model coefficient	Probability level (p–value)	Variance inflation factor	90% Confidence interval for the model coefficient from bootstrap analysis		Mean coefficient estimate from bootstrap analysis)
							Low	High	
Eolian sediment, fine textured (glacial loess), moderate yielding	km^2	$(Mt/yr)/km^2$	10.8	2.6	<0.0001	1.20	4.0	15.6	10.1
Eolian sediment, fine textured (glacial loess), nonyielding	km^2	$(Mt/yr)/km^2$	0.0	1.2	1.000	1.95	–4.3	0.0	–0.9
Saline lake sediment	km^2	$(Mt/yr)/km^2$	23.1	13.6	0.089	1.05	–11.8	46.2	21.9
Alluvium and fine textured coastal zone sediment, high yielding	km^2	$(Mt/yr)/km^2$	15.2	1.9	<0.0001	1.42	11.0	19.9	15.7
Alluvium and fine textured coastal zone sediment, low yielding	km^2	$(Mt/yr)/km^2$	7.9	1.2	<0.0001	1.38	6.5	9.6	8.1
Coastal zone sediment, coarse textured, high yielding	km^2	$(Mt/yr)/km^2$	47.4	10.2	<0.0001	1.75	19.4	67.3	45.4
Coastal zone sediment, coarse textured, low yielding	km^2	$(Mt/yr)/km^2$	21.5	9.1	0.018	1.25	–3.2	36.0	19.7
Hydric soils, peat and muck	km^2	$(Mt/yr)/km^2$	32.1	12.4	0.010	1.21	–1.7	50.7	28.0
Water (undifferentiated submerged lithologies)	km^2	$(Mt/yr)/km^2$	0.0	21.6	1.000	1.11	–34.6	0.0	–8.7
Other sources									
Road deicers	Mt/year	dimensionless	1.066	0.224	<0.0001	6.70	0.671	1.469	1.084
Urban lands	km^2	$(Mt/yr)/km^2$	12.8	4.4	0.004	8.11	1.7	20.4	12.4
Cultivated lands	km^2	$(Mt/yr)/km^2$	2.0	0.8	0.016	2.24	–0.8	3.9	2.0
Pasture lands	km^2	$(Mt/yr)/km^2$	15.1	4.7	0.001	6.70	4.2	23.2	14.1

Table 6. Summary of estimation results for the national SPARROW model of dissolved-solids transport.—Continued

[m, meter; km, kilometer; Mt, metric ton; –, not applicable]

Watershed attribute	Watershed attribute units	Coefficient units	Model coefficient	Standard error of the model coefficient	Probability level (p-value)	Variance inflation factor	90% confidence interval for the model coefficient from bootstrap analysis		Mean coefficient estimate from bootstrap analysis)
							Low	High	
Land-to-water delivery variables applied to geologic materials									
Atmospheric deposition	log(Mt/yr)	$[\log(Mt/yr)]^{-1}$	0.127	0.078	0.102	7.99	–0.015	0.313	0.134
Slope	degrees	per degree	0.072	0.007	<0.0001	5.61	0.059	0.085	0.072
Clay	percent	dimension-less	0.015	0.004	0.000	4.97	0.005	0.023	0.014
Sand	percent	dimension-less	–0.015	0.003	<0.0001	5.43	–0.020	–0.010	–0.015
Forested area, East	fraction of catchment	dimension-less	–1.218	0.135	<0.0001	3.71	–1.414	–0.992	–1.226
Forested area, West	fraction of catchment	dimension-less	–0.750	0.124	<0.0001	3.44	–0.963	–0.516	–0.754
Land-to-water delivery variables applied to geologic materials, road deicers, and urban lands, cultivated lands, and pasture lands									
Vegetation index	dimension-less	dimension-less	0.015	0.006	0.011	3.67	–0.007	0.033	0.016
Low streamflow index	dimension-less	dimension-less	–1.024	0.126	<0.0001	3.31	–1.450	–0.600	–1.012
Land-to-water delivery variables applied to cultivated lands and pasture lands									
Tiles	percent of catchment	dimension-less	0.032	0.006	<0.0001	1.54	0.014	0.044	0.030
Ditches	percent of catchment	dimension-less	0.032	0.005	<0.0001	1.82	0.025	0.049	0.035
Precipitation (cultivated lands and pasture lands)	log(m/yr)	$[\log(m/yr)]^{-1}$	–1.058	0.223	<0.0001	3.19	–1.467	–0.299	–0.990
Base-flow index	dimension-less	dimension-less	0.052	0.010	<0.0001	4.11	0.027	0.074	0.052
Irrigation application rate	m/yr	yr/m	0.412	0.132	0.002	1.91	0.192	0.654	0.420
Land-to-water delivery variables applied to road deicers and urban lands									
Population density	persons/ km^2 times 10	10 km^2/ person	0.219	0.053	<0.0001	12.45	0.106	0.311	0.208

Table 7. Summary statistics for weighted residuals from the national SPARROW model of dissolved-solids transport, tabulated by water-resources regions in the conterminous United States.

Water-resources region		Statistic for the weighted residuals, in natural log units					Mean/standard deviation, as a percent
Code	Name	Minimum	Median	Mean	Maximum	Standard deviation	
1	New England	–2.15	0.01	–0.03	1.14	0.52	–5.2
2	Mid-Atlantic	–1.67	0.05	0.02	1.43	0.44	4.9
3	South Atlantic-Gulf	–4.39	0.03	0.02	3.03	0.63	3.8
4	Great Lakes	–1.79	0.00	–0.01	0.65	0.40	–2.2
5	Ohio	–1.30	0.10	0.09	1.10	0.36	24.7
6	Tennessee	–1.53	0.04	–0.03	0.92	0.51	–4.9
7	Upper Mississippi	–0.84	0.01	–0.01	1.58	0.33	–2.2
8	Lower Mississippi	–0.84	–0.07	–0.05	0.98	0.35	–15.1
9	Souris-Red-Rainy	–3.54	0.04	–0.05	1.12	0.66	–8.1
10	Missouri	–4.22	0.06	0.06	3.25	0.66	8.5
11	Arkansas-White-Red	–3.29	–0.03	–0.04	2.58	0.73	–5.2
12	Texas-Gulf	–2.62	–0.04	–0.06	2.14	0.66	–9.7
13	Rio Grande	–1.59	–0.01	–0.08	1.68	0.75	–11.0
14	Upper Colorado	–2.44	0.00	0.01	1.79	0.56	0.9
15	Lower Colorado	–2.86	0.04	0.10	2.94	0.98	10.5
16	Great Basin	–1.56	–0.01	–0.06	0.93	0.53	–10.4
17	Pacific Northwest	–2.38	–0.02	–0.03	1.40	0.56	–5.3
18	California	–2.22	–0.16	–0.15	1.91	0.87	–17.1
Conterminous United States		–4.39	0.02	0.00	3.25	0.60	0.4

Visual inspection of the spatial distribution of the model residuals indicates that there are several areas much smaller than a water-resources region that have clusters of mostly positive or mostly negative residual errors (fig. 7). Such clusters indicate bias and that model predictions are likely overestimated in areas where residuals are mostly negative, or underestimated in areas where residuals are mostly positive.

The assumptions of the SPARROW model, based on nonlinear least-squares methodology, require the weighted residuals to be (1) independent across the range in load observations, (2) identically distributed (homoscedastic), and (3) uncorrelated with the explanatory variables (Schwarz and others, 2006). Examination of model diagnostic graphs indicates that these requirements are met. Figure 8*A* shows good correspondence between observed and predicted dissolved-solids load, as points are centered along the 1:1 line throughout the range of observations. The lack of systematic deviation in points from the 1:1 line, and the lack of serial correlation between adjacent points in figure 8*A* indicate that there is no evidence for dependence across the range in observations and, therefore, suggest that the first modeling assumption (listed above) is not violated.

The distance from the 1:1 line in figure 8*A* tapers as the magnitude of predicted and observed loads increase. This pattern is more clearly seen in the graph of weighted residuals against predicted load (fig. 8*C*). Initially this appears to suggest weighted residuals are heteroscedastic. The graphs of the observed yields and the weighted residuals against predicted yield, however, show that the weighted residuals are in fact homoscedastic when the differences in drainage area are accounted for. This difference in residual behavior between predicted loads and yields occurs because the SPARROW model is estimated on the basis of the load gained between nested monitoring stations and the watershed attributes for intervening drainage area between the monitoring stations, rather than on the basis of the load at the monitoring station and the watershed attributes for the entire upstream drainage area. Therefore, figures 8*C* and 8*D* provide no evidence for violating the second assumption listed above.

Correlation of the weighted model residuals with model predictors can cause points to systematically deviate from the 1:1 line in the graph of predicted versus observed load (fig. 8*A*). Such patterns are absent, and therefore provide no evidence for violation of assumption 3.

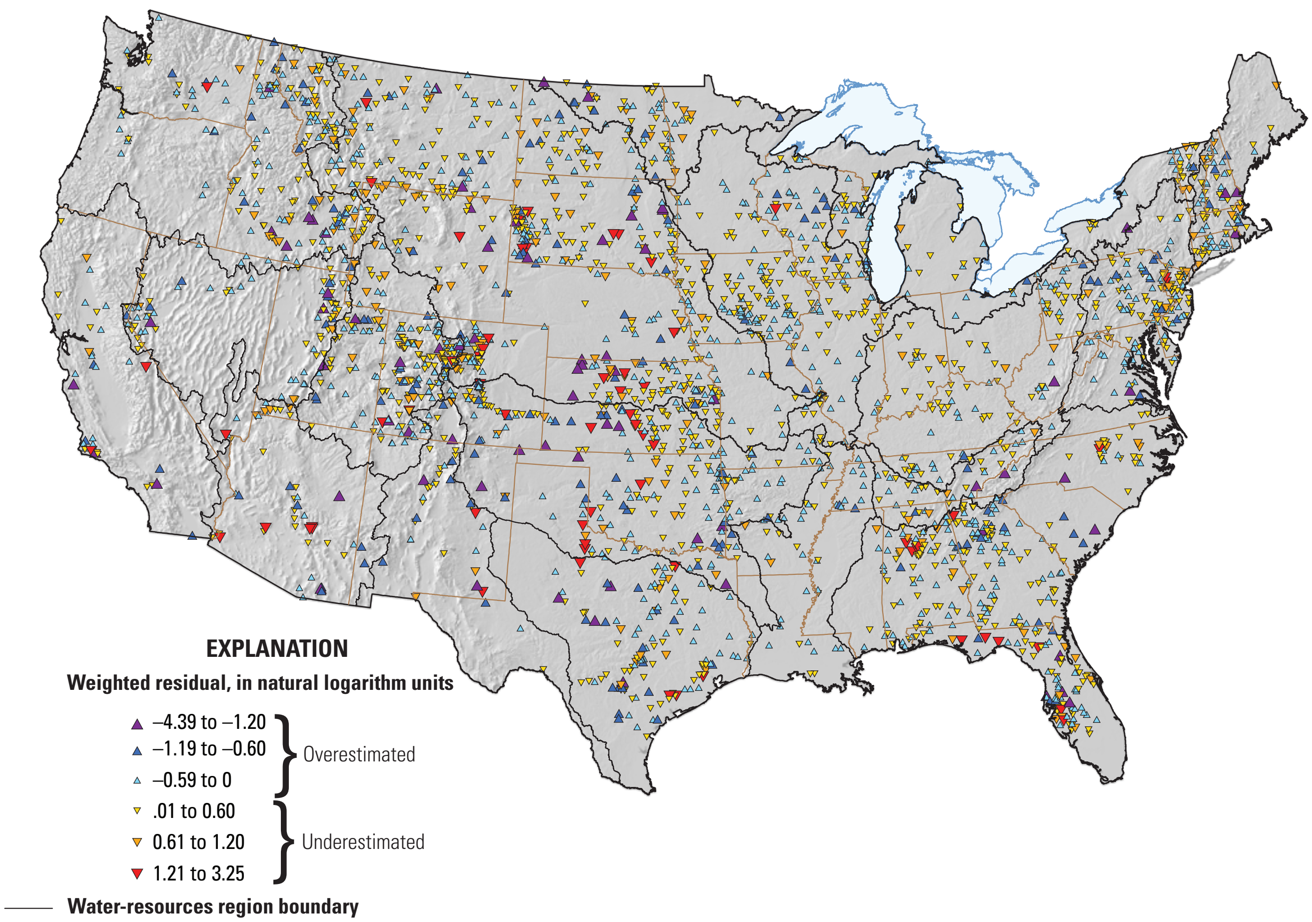


Figure 7. Map of the conterminous U.S. showing weighted residuals for 2,560 water-quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport.

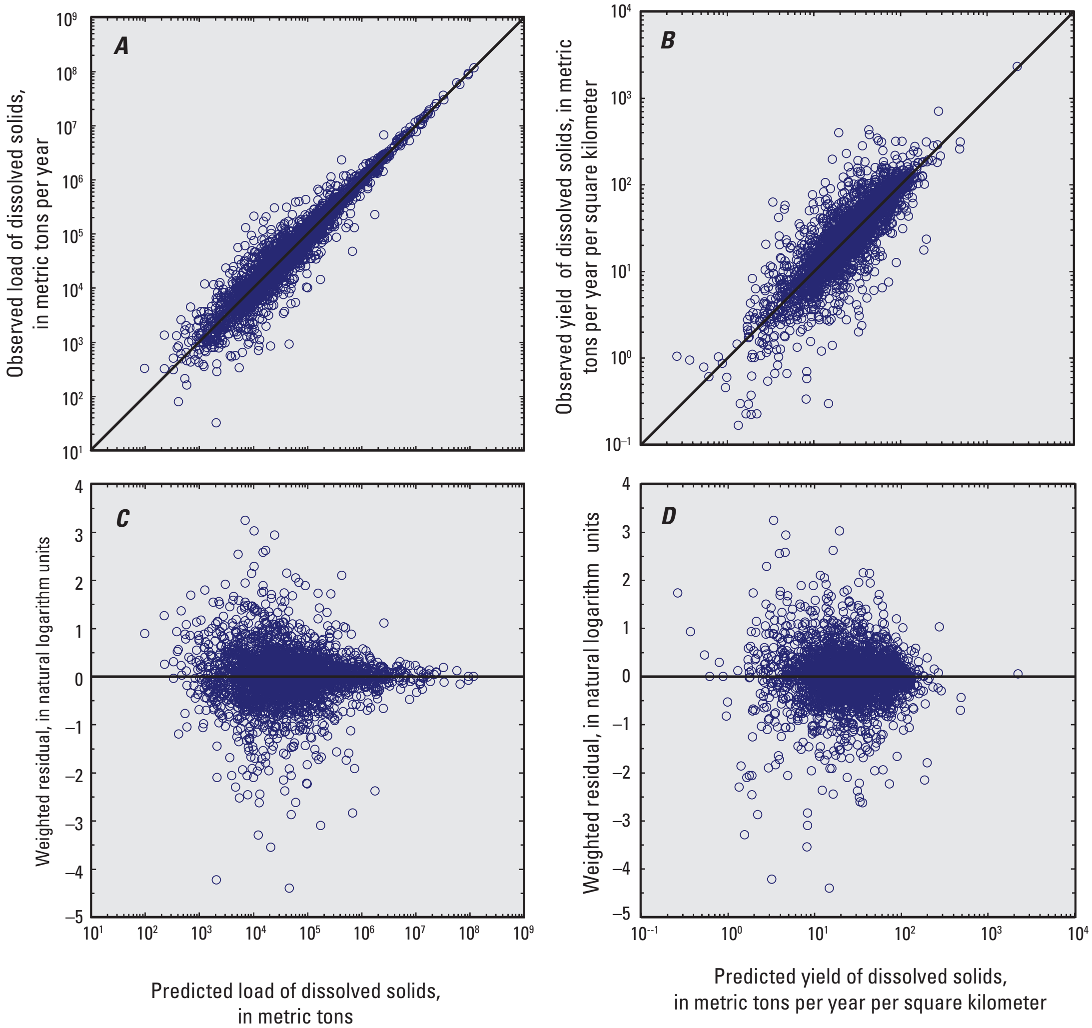


Figure 8. Diagnostic graphs for the national SPARROW model of dissolved-solids transport. *A*, Observed against predicted load. *B*, Observed against predicted yield. *C*, Weighted residuals against predicted load. *D*, Weighted residuals against predicted yield.

Sources

The national SPARROW model of dissolved-solids transport includes 31 variables representing geologic sources, and additional variables each representing road deicers, urban lands, cultivated lands, and pasture lands (table 6). For the most part, variables retained in the final model are statistically significant and are consistent with the hypothesis of major sources of dissolved solids presented in the section "Modeling Approach;" however, some sources in the hypothesis are not included in the final model.

Model development included testing several different combinations and configurations of the available geologic source variables in exploratory models. Although the exploratory models indicated that surficial lithology, bedrock geology, subsurface evaporite deposits, and presence of saline groundwater were significant sources of dissolved solids, large spatial bias in several water-resources regions was a significant issue in these models. The strategy that produced the least spatially biased residuals was to only use surficial lithology to represent geologic sources. This adjustment strategy suggests that representing geologic sources by surficial characteristics is better than representing them by subsurface characteristics and may reflect a dominance of surficial and near-surface dissolved-solids sources to streams over deeper subsurface sources.

Whereas surficial lithology may better represent geologic sources, spatial analysis of residuals still showed bias in some lithologic units in certain parts of the country. It was assumed that the bias largely resulted from spatial differences in the amount of dissolved solids yielded from the different areas where the lithologic unit occurs, including dissolved solids from both surficial and subsurface sources. To reduce the spatial bias in residuals, some of the surficial lithologic units were spatially divided into either two or three subunits, on the basis of varying dissolved-solids yields. Boundaries for each surficial-lithology subunit were defined using hydrologic unit codes, and reassignment of the surficial lithologic units into one of the subcategories performed within the SPARROW model control file for each reach in the hydrologic network (table 5). For example, carbonate residual material was spatially divided into two subunits—a high-yielding unit where it occurs in water-resources regions 2, 4, 7, and 8; and a low-yielding unit where it occurs elsewhere (table 5). The subdivision process was iterative, wherein, areas with the surficial lithology unit of interest were moved from one subunit to the other on the basis of spatial patterns in the residuals, the model was estimated, and residuals were re-examined for spatial bias. This process was repeated by trial-and-error by moving areas between subunits until the residuals generally lacked spatial bias at the water-resources region level. Although there are just 18 different units within the surficial lithology dataset, 9 were subdivided into a high-yielding unit and a low-yielding unit, and 2 were subdivided into a high-yielding unit, a medium-yielding unit, and a low-yielding unit. This subdivision process resulted in a total of 31 geologic source variables.

The surficial-lithology-based variables were given the overall categorical term of 'geologic materials' to indicate that they capture both surface and subsurface sources of dissolved solids. Whereas the geologic materials are based on surficial lithology, these variables also represent any subsurface sources of dissolved solids that are spatially correlated with the surficial lithology at the national scale. Groundwater carries the dissolved solids within the aquifer and releases them to the land surface in areas of discharge such as springs and gaining streams. In most of the high-yielding lithologic units, there are documented cases of saline groundwater that discharges from regional aquifers to springs and streams in the area. The surficial lithology-based sources used in the model, however, do not perfectly represent subsurface sources of dissolved solids. Some of the monitoring stations have large positive model residuals presumably because significant saline groundwater discharge was not completely captured by the surficial lithology variables.

Most p-values for the geologic materials were less than 0.0001, indicating a high level of significance for these sources as a whole. Mean coefficients from the bootstrap analysis were generally similar to and, therefore, verify the parametric estimates for each geologic source (table 6). Where surficial lithologic units were split into two or three subcategories, the bootstrap analysis results show that there is typically little or no overlap in the 90 percent confidence intervals for the low-, medium-, and high-yield source coefficients. The significant differences in the source coefficients support use of subcategorized lithologic units in the model.

Source coefficients for geologic materials with p-values greater than 0.05 are not significantly different than zero (at the 95-percent confidence interval), and they include those for extrusive volcanic rock, nonyielding fine-textured eolian sediment, saline lake sediment, and undifferentiated lithologies submerged underwater (table 6). It is possible that these are, in fact, significant sources of dissolved solids; however, there may not be sufficient monitoring-station data in these areas to capture their significance in the model. Alternatively, there may be significant loss processes like precipitation infiltration and soil or aquifer accumulation of salt that is associated with these lithologies such that there is no net gain in dissolved solids to streams from incremental catchments with these sources. Regardless of the significance of the coefficient, all geologic-material variables were retained in the model so that the entire modeled area would be represented by a geologic source.

Source coefficient values for the geologic materials ranged from 0.0 (Mt/yr)/km^2 for fine textured eolian sediment and undifferentiated lithologic units submerged underwater to 95.2 (Mt/yr)/km^2 for alkaline intrusive volcanic rock and 100.1 (Mt/yr)/km^2 for high-yielding coarse-textured glacial outwash and glacial lake sediment (table 6). Several areas with alkaline intrusive volcanic rock also have hydrothermal activity, which facilitates rock weathering and explains why its source coefficient is higher than those for most other geologic materials, especially extrusive volcanic rock [5.3 (Mt/yr)/km^2]. The high-yielding coarse-textured glacial outwash and glacial lake sediment is likely high partly because of its composition of physically weathered glacial materials, but also because it is underlain by aquifers with saline groundwater, which discharges to the glacial materials in some areas (Richter and Kreitler, 1991). This unit is also underlain by halite and gypsum deposits (see "Presence of saline groundwater" and "Subsurface evaporite deposits" in appendix 5, the Watershed-Attribute Portfolio). As a generalization, source coefficients for silicic residual material, eolian sediment, alluvium, and undifferentiated lithologies submerged underwater were lower than the source coefficients for glacial sediment, saline lake sediment, coarse-textured coastal zone sediment, carbonate residual material, hydric soils, and alkaline intrusive volcanic rock. This general comparison of dissolved-solids yields by lithology is less detailed but still consistent with the relative yields from rocks determined in other studies and compiled by Anning and others (2011) and discussed in the "Hypothesis" section of this report. Variation in source coefficients for the subcategories of a given surficial lithology makes it difficult to provide a more precise generalization on the relative yield for the 18 different lithologies used in this study. Development of a model that distinguishes groundwater and other subsurface sources of dissolved solids from surficial sources would likely provide clearer differences in yield characteristics from surficial lithologic units.

Other sources of dissolved solids in the model include road deicers as well as cultivated lands, pasture lands, and urban lands. The source coefficient for cultivated lands (2.0 [Mt/yr]/km^2) is substantially lower than that for pasture lands (15.1 [Mt/yr]/km^2). Despite having the same units, comparison of coefficients for cultivated lands and pasture lands to urban lands or to geologic sources cannot be made because each have different sets of land-to-water variables applied to them (table 6; Schwarz and others, 2006). The coefficient for urban lands of 12.8 (Mt/yr)/km^2 accounts for nonpoint sources of dissolved solids, such as urban runoff, and point sources such as treated municipal wastewater. Note that in the model application, a catchment with urban, cultivated, or pasture lands receives dissolved-solids from both the land-use source as well as geologic materials.

The amount of dissolved solids from road deicers was estimated as the product of three watershed attributes: (1) the total length of major highways and roads in the catchment, which has units of road km; (2) the mean number of snow days per year with greater than 1 inch of snowfall for the catchment, 1961–90, which has units of snow days; and (3) a state-specific deicer application weight, which has units of (kg salt / [road km × snow days]). The total length of major highways and roads provides an estimate of the length of roads likely to be deiced and excludes minor roads that are less likely to be deiced. The mean number of snow days per year (National Climate Data Center, 2010) provides a coarse estimate of how often deicers are applied to roads. The state-specific deicer application weight provides a means to convert road length and snow days to mass of deicer used. It was estimated based on the annual use of rock salt for a given state, less 25 percent because nationally about 25 percent of the rock salt was used for purposes other than deicing (Kostick, 1993–2009). The product of the road length times snow days was determined for all catchments in the state and summed together for a state total. The reduced average annual state rock salt usage was then divided by this state total of “road length-snow days” as an estimate of the state-specific deicer application weight. The strength of this approach is that it constrains the mass of salt applied to roads within a given state, and disaggregates it proportionally within the state on the basis of likely frequency and location of deicing. This adjustment to the model is particularly important for states with substantial snowfall that typically do not use rock salt as a deicer. It should be recognized, however, that the state-specific deicer application weight is not an actual application rate because it is based on likely roads to be deiced but not actual roads that are deiced, does not account for the number of road lanes, assumes a uniform frequency of application for all snowfall events with greater than 1 inch, and does not consider vehicle usage rates or the importance of the road for transport as relevant to determining whether deicers are to be applied due to a snowfall event. Illustrations of the spatial distribution and further information on the three variables used to compute the watershed attribute for road deicers are shown in appendix 5,Watershed-Attribute Portfolio.

The source coefficient for road deicers of 1.066 (dimensionless) suggests that about as much dissolved solids are predicted to enter streams from this source as are estimated to be applied to roads based on the watershed-attribute data. Whereas the bootstrapping analysis indicates the coefficient is not significantly different than 1.0, it is anticipated that the coefficient would be somewhat greater than 1.0. This is in part because the application estimates are only for sodium chloride; however, other salts such as magnesium chloride are sometimes applied to roads. In addition, sand applied for deicing purposes may weather and release dissolved solids to runoff. Other sources associated with roads could also yield salts. In North Carolina, for example, a mass balance approach was used to show that road deicers and sand application accounted for about two-thirds of the dissolved-solids load washed from a highway into local streams (Harned, 1988; Kobriger and others, 1982). The remaining one-third of the load delivered to local streams was found to come from deposition of particles from vehicles.

The sources retained in the model were consistent with the hypothesis developed for the SPARROW model of dissolved-solids transport (fig. 2); however, some sources anticipated to be significant were not included in the final model. As previously discussed, bedrock geology, subsurface evaporites, and saline groundwater are indirectly but incompletely accounted for in the model by the surficial lithology variables. Atmospheric deposition was significant in the model as either a source or as a land-to-water delivery variable. Atmospheric deposition is collinear with several variables in the model, and overall model diagnostics and variance inflation factors for the collinear variables were improved when the model was constructed with atmospheric deposition as a land-to-water delivery variable.

Fossil fuel extraction variables were anticipated to be significant dissolved-solids sources in the model (fig. 2). Coefficients for most of these sources, however, were not significant in any exploratory model and none of these sources were retained in the final model. Oil and gas extraction was represented by variables that reflected the amount of productive oil and gas wells in each incremental catchment for a given decade (see “Fossil fuel extraction, oil and gas wells,” in appendix 5, Watershed-Attribute Portfolio). Some of these variables were transformed to make new variables. For example, the three variables for oil and gas wells in the 2000s, 1990s, and 1980s were added together to reflect dissolved solids yielded from oil and gas extraction activities from 1980 through 2006. The coefficient for the resulting variable was not significant either, nor was the coefficient for a transformation of it to binary representation where data were coded as “0” if no wells were present, or “1” if one or more wells were present. It should be noted that the surficial lithology variables were not subset into low-, medium-, or high-yielding categories until after it was verified that the other source variables were not significant, including those representing oil and gas extraction variables. This order was maintained to ensure that sources deemed insignificant were indeed such and that the subcategorization of the surficial lithology variables did not render otherwise significant sources as insignificant in the model.

Buto and others (2010) explored the effects of oil and gas extraction on dissolved-solids loads in streams of the Upper Colorado River Basin using a SPARROW model. They found that the estimated land disturbance from oil and gas extraction was not statistically significant in explaining dissolved-solids loads. They concluded that lack of significance in their SPARROW model may be due to the amount of available monitoring data, the spatial distribution of monitoring stations with respect to land disturbance, or the overall quantity of land disturbance associated with oil and gas extraction basin wide. They also concluded that dissolved solids yielded from natural landscapes may be similar to that yielded from lands disturbed by oil and gas extraction. These explanations for the lack of significance in the Upper Colorado River SPARROW model also hold true for the national SPARROW model of dissolved-solids transport. An additional explanation is that the source variables for oil and gas extraction in the national model are not precise enough. These variables represent the number of quarter-mile cells with one or more producing oil or gas wells in them. An ideal variable would be the mass of dissolved solids brought up to the land surface of each incremental catchment from exploration, development, and production activities associated with oil and gas wells. Another explanation is that the amount of dissolved solids yielded from each well and transported to streams may decrease dramatically over time after the initial drilling—yields may behave as a pulse function rather than a steady-state function. In this case, a transient-type SPARROW model would perform better than the current model, which is reflects mean steady-state conditions for 1980–2009.

The coefficient for the source variable for shale plays, representing dissolved solids associated with development and extraction of natural gas from this unconventional reservoir, was not significant in the model. Reasons discussed above for the lack of significance of oil and gas wells also hold true for shale plays. In some cases where recovered drilling fluids associated with hydraulic fracturing of shale plays are disposed of through wastewater treatment plants, such as the Marcellus Shale in Pennsylvania, it is possible that dissolved solids from this source are accounted for by the urban lands source variable.

While the coefficient for the variable representing coalbed-methane fields was not significant in the model, the coefficient for the variable representing the top 100 coalbed-methane mines was significant (p-value less than 0.05) in several exploratory models. This variable was not retained in the final model, however, because predictions obtained from exploratory models that included the top 100 coalbed-methane mines indicated that less than 0.5 percent of the total load delivered to all of the Nation's streams was from this source. With such a small share of the total deliveries to the Nation's streams from all sources, dissolved-solids yields from the top 100 coalbed-methane mines were considered to be more of a locally important source and therefore was not included in the national model. See "Fossil fuel extraction (shale plays, coalbed-methane fields, and coalbed-methane mines)" in appendix 5, Watershed-Attribute Portfolio, for the location of the top 100 coalbed-methane mines.

Land-to-Water Delivery Processes

The national SPARROW model of dissolved-solids transport includes 15 land-to-water variables that amplify or reduce deliveries from dissolved-solids sources (table 6). The land-to-water delivery variables are grouped into four sets of variables, where each set affects different sets of source variables. As part of model development, each set of land-to-water delivery variables was applied to each set of source variables in exploratory model runs to ensure the best configuration of source and land-to-water delivery variables was obtained. In some cases, source variables or land-to-water delivery variables were moved to different variable sets. Alternate configurations were found viable; however, model diagnostics such as the t-test statistics for the land-to-water and source variables, the root-mean-square error, and the spatial distribution of model residuals indicate the configuration listed in table 6 is optimal. All land-to-water transport variables included in the model are significant ($p < 0.05$) when the variance inflation factor is considered. In addition, most 90-percent confidence intervals from the bootstrap analysis exclude zero, which further indicates their significance.

The first set of land-to-water delivery variables are only applied to geologic materials, and include precipitation, atmospheric deposition, slope, clay, sand, and forested area—one variable for the eastern part of the country and one for the western part of the country (tables 5 and 6). The coefficients for precipitation and atmospheric deposition are positive, indicating greater amounts of these two variables result in more dissolved solids being transported from geologic sources and delivered to streams. As land-to-water delivery variables, precipitation is a measure of the annual depth of rain and snow falling on a catchment and represents the potential for transport of dissolved solids from the source to the stream, and atmospheric deposition is a measure of the annual mass of dissolved solids falling on the catchment and represents the enhancement of rock weathering as a result of the acid content in the precipitation. While the atmospheric deposition variable is based only on wet deposition data, it likely performs as a surrogate for both wet and dry deposition of dissolved solids. The positive sign for the precipitation coefficient is consistent with those in other SPARROW models (for example, Preston and others, 2011, and Smith and others, 1997). The precipitation rate for a given catchment can have a significant effect on the delivery of dissolved solids to the stream reach. For example, with the precipitation coefficient of 1.029, a catchment with 2 meters of precipitation will have about 10 times as much dissolved solids delivered to the reach as an identical catchment but with 0.2 meters of precipitation. The p-value of 0.1016 for the atmospheric deposition coefficient is inflated due to collinearity with other variables. When accounting for the variance inflation factor of 7.99, the adjusted p-value for the coefficient becomes 0.0359 and indicates atmospheric deposition is significant in the model.

While precipitation and atmospheric deposition serve as proxies for the amount of water available to weather rocks and transport their mineral content to streams, the variables of slope, clay, sand, and forested land are factors likely affecting runoff processes. The steeper the slope, greater percent of clay, and lesser percent of sand promote less infiltration of runoff and greater dissolved-solids transport as evidenced by the sign of their coefficients—positive for slope and clay, and negative for sand. Forested land also affects dissolved-solids transport across the incremental catchments and delivery to streams—the greater the fraction of forested area, the lesser amount of dissolved solids delivered as indicated by the negative coefficients. Note that the coefficient is of greater magnitude for eastern catchments (–1.218 for water-resources regions 1–7) than for western catchments (–0.750 for water-resources regions 8–18). This difference in coefficients indicates that for identical watershed-attribute conditions, there is greater reduction of the land-to-water transport of dissolved solids in forested catchments of the eastern United States compared to forested catchments of the western United States. Further investigation is needed to determine whether differences in the land-to-water delivery coefficients resulted from overall differences in the vegetation species, structures, densities, or other factors such as climate or soil characteristics associated with runoff or weathering processes of forested lands in the eastern and western United States.

The second set of land-to-water delivery variables includes the vegetation index and the low-streamflow index, and are applied to geologic materials, road deicers, and urban lands, cultivated lands, and pasture lands (table 6). Both of these variables primarily modify transport and delivery of dissolved solids in the western part of the country where the climate is dry, vegetation is sparse, and ephemeral streams are common. The vegetation index is based on a normalized difference vegetation index (NDVI) that ranges in values from 100 for barren to 200 for highly vegetated areas. This index was recoded in the SPARROW modeling environment such that all values equal to or greater than 160 in the original data were reassigned as 160 (table 5), a value determined on the basis of spatial bias present in residuals that occurred in the western part of the country regardless of surficial lithology. The recoding made the index gradational for sparsely vegetated areas and constant for areas with substantial vegetation cover. The positive coefficient for the vegetation index indicates that the more vegetated the incremental catchment, the greater transport and delivery of dissolved solids. Conversely, the less vegetated the incremental catchment, the less transport and delivery.

The low-streamflow index is based on the stream discharge associated with the reach and is conditioned on the vegetation index. Coding of the index was performed within the SPARROW modeling environment (table 5). The default for the index was a value of zero unless the streamflow was less than 50 ft^3/sec, and the vegetation index was less than 160. Where these two conditions were met, the index was computed as (50 – streamflow)/50. This yielded values near zero for streamflow near 50 ft^3/s, and values near 1 for streamflow near 0 ft^3/s. The negative sign for the coefficient indicates that transport across the incremental catchment and delivery to streams is reduced for incremental catchments with minimal streamflow compared to that for reaches with substantial streamflow.

Coefficients for both the vegetation index and the low-streamflow index indicate dissolved-solids transport is impeded in areas of the western part of the country with drier climates that are characterized by sparse vegetation, lower streamflow rates, and predominance of ephemeral streams. Besides having a lack of precipitation to drive transport processes in such areas, dry antecedent conditions on the landscape prior to precipitation events promotes infiltration rather than runoff, thereby impeding transport. In addition, streambeds in these areas are typically unsaturated with water, which also promotes infiltration rather than runoff, and further detains dissolved solids from transport.

The third set of land-to-water delivery variables is only applied to cultivated lands and pasture lands and includes tiles, ditches, precipitation, base-flow index, and irrigation application rate (table 6). The positive coefficients for tiles and ditches indicate that agricultural lands with these drainage enhancements has greater dissolved-solids transport across incremental catchments and delivery to streams as compared to agricultural lands without them. The precipitation variable applied to both cultivated lands and pasture lands is a duplicate of the precipitation variable used for geologic sources, but using a separate variable for cultivated and pasture lands allows for a different, in fact opposite, response from these sources to precipitation. The negative sign for the precipitation coefficient indicates that transport across incremental catchments and delivery of dissolved solids to streams is greater in drier climates and lesser in wetter climates. In this case, precipitation is likely a surrogate for the potential to transport accumulated salt from soils in drier climates to streams, with areas in drier climates having more intensive irrigation than areas in wetter climates. The positive sign for the irrigation application rate coefficient indicates greater transport and delivery to streams with larger application rates, which tend to be those in drier climates. Thus both the precipitation and irrigation application rate are consistent. The positive coefficient for the base-flow index indicates that transport and delivery of dissolved solids to streams is greater where the base-flow component comprises a larger fraction of the total streamflow than does runoff.

The last set of land-to-water delivery variables consists of population density, which is applied to urban lands and road deicers. The positive coefficient for this variable indicates that transport and delivery of dissolved solids from both urban lands and road deicers is enhanced in the more densely populated areas. For urban lands, this is likely a result of a larger human population in the incremental catchment and a corresponding amount of dissolved solids associated with their activities. For road deicers, transport and delivery may be greater because of a greater density of roads in more populated areas. For both sources, the positive coefficient is likely to also result from a larger fraction of impermeable surfaces in the incremental catchment, and other enhanced drainage features such as storm sewers that are more likely to occur in more densely populated areas.

Attenuation and Loss Processes

Exploratory models examined attenuation and loss of loads within stream reaches and within reservoir and lake reaches; however, the final model did not include any terms for attenuation or loss processes. None of the exploratory models showed evidence for load attenuation owing to chemical precipitation within lakes or reservoirs. Loss of loads due to stream diversion or streambed infiltration was examined by constructing a stream decay term that contained the variable representing the decrease in a reach's discharge. The stream decay term was significant in the exploratory models; however, examination of predictions from those models indicated that problems resulted from using that term. For example, there are many sets of reaches of Missouri, Arkansas-Red-White, Texas-Gulf, and Upper Colorado water-resources regions where streamflow (and therefore loads) was locally diminished—likely through off-stream diversions or by streambed infiltration. Examination of load data for monitoring stations, however, indicated that diminishment of the load was spatially restricted to a limited number of reaches, where after the load that was diminished upstream eventually returned to the river in a downstream reach (or gradually over multiple reaches). For the Arkansas River, a local-scale study confirmed this diminishment and recovery of the dissolved-solids load (Gates and others, 2010). The use of the stream decay term resulted in permanent removal of dissolved solids in too many reaches for its use nationally. Identification of this problem was not immediately apparent in the model diagnostics because the model estimation is based on watershed-attribute data for the intervening area between monitoring stations and on differences in the loads for those stations.

Whereas the analysis of loads for monitoring stations and of predictions from exploratory models indicated that dissolved-solids loads generally are not affected by attenuation or loss processes in most streams, there were some exceptions. Such exceptions included several reaches along the lower Colorado River and several of its tributaries in Arizona and California, and along the main stem of the Rio Grande in Colorado and in New Mexico. In these areas, the losses were largely due to diversions that are conveyed long distances to areas where return of the water and dissolved-solids load back to streams is insignificant or nonexistent. Losses of accumulated dissolved-solids loads for these stream reaches were accounted for by adjusting the FRAC variable in the reach network on the basis of streamflow losses indicated by the reach discharge information in the MRB_E2RF1 network (appendix 4). After these modifications were made to the FRAC variable as part of this study, there were 398 reaches (excluding those representing shorelines; appendix 3) in the network with FRAC values less than one, indicating some loss of dissolved-solids load in those reaches. Losses due to diversions and streambed infiltration likely occur along other stream reaches in the arid Southwest; however, there are not sufficient monitoring data to identify these. The monitoring data are needed to confirm losses in the accumulated load as the decreases in the discharge may result from evaporative processes. Reaches that have losses due to streamflow diversion or streambed infiltration, which are not accounted for in the model, are likely to have overestimated load predictions. Future SPARROW models could be improved through better representation of streamflow diversions from the hydrologic network, especially where the diverted water and constituents are unlikely to return to the stream of origin.

Model Predictions

Watershed attributes for each incremental catchment and parametric estimates for the source and land-to-water transport coefficients (table 6) were used in the national SPARROW model of dissolved-solids transport to predict dissolved-solids conditions in each stream reach of the hydrologic network (appendix 3). Predictions of dissolved-solids mass for stream reaches include the load (mass per time), yield (mass per unit area per time), concentration (mass per unit water volume), and source-share contributions (percentage of the load for each source). In this report the stream load and yield are reported for two spatial domains: (1) total upstream accumulated drainage area, and (2) the incremental catchment's drainage area. The predicted incremental catchment and accumulated loads and yields represent long-term (1980–2009) mean annual conditions for dissolved solids, detrended to the year 2000. To avoid lengthy cumbersome terminology, however, this discussion text will refrain from prefacing the predictions with the descriptor "long-term mean annual."

Predicted yields less than 0.5 (Mt/yr)/km^2 or greater than 1,000 (Mt/yr)/km^2 occurred for 1.1 percent of the network reaches and are censored to constrain reported values from this analysis to values approximately within the range observed in the data for monitoring stations (table 2). Predicted values outside this range should be considered to have a higher degree of uncertainty than values within the observed range because they were not represented during model estimation. Similarly, predicted concentrations less than 10 mg/L or greater than 15,000 mg/L occurred for 1.6 percent of the network reaches and are censored to constrain reported values from this analysis to values approximately within the range observed in the data for monitoring stations (table 3).

Model predictions for areas outside the United States were only used in cases where needed to provide estimates of loads entering the country. Model predictions for such reaches are otherwise outside the scope of this report and, therefore, are not reported. Likewise, predicted loads are not reported for stream reaches that form an international boundary and do not enter the interior of the United States, such as those on the Rainy River, the Great Lakes and St. Lawrence River, and the lower Rio Grande downstream from El Paso, Texas.

Incremental-Catchment Sources and Yields

Nationwide, predicted incremental-catchment yields range from less than 0.5 (Mt/yr)/km^2 to greater than 1,000 (Mt/yr)/km^2 (table 8). Whereas the median predicted incremental-catchment yield is 26 (Mt/yr)/km^2, 10 percent of the incremental catchments yield less than 4 (Mt/yr)/km^2, and 10 percent yield more than 90 (Mt/yr)/km^2. Both incremental-catchment yields and source-share contributions show considerable regional variation (fig. 9).

The larger incremental-catchment yields, those greater than 50 (Mt/yr)/km^2, generally occur along the northern part of the west coast, or in a crescent shaped band south of the Great Lakes (fig. 9). For example, the median incremental-catchment yield is 81 (Mt/yr)/km^2 for the Great Lakes, 78 (Mt/yr)/km^2 for the Ohio, and 74 (Mt/yr)/km^2 for the Upper Mississippi water-resources regions (table 8). Incremental-catchment yields greater than 50 (Mt/yr)/km^2 south of the Great Lakes are high for several reasons. The geologic sources are high yielding, such as clayey glacial till (source coefficient of 28.7 (Mt /yr)/km^2), high-yielding loamy glacial till (source coefficient of 28.9 (Mt/yr)/km^2), and high-yielding coarse textured glacial outwash and glacial lake sediment (source coefficient of 100.1 (Mt /yr)/km^2). In addition, many catchments also yield dissolved solids from road deicers, cultivated lands, and pasture lands. Also, precipitation and atmospheric deposition are relatively high in these catchments, which enhance transport as land-to-water delivery factors. Incremental-catchment yields are high along the northern part of the west coast largely because of the high precipitation rates and steep slopes in that region.

The smaller incremental-catchment yields, those less than 10 (Mt/yr)/km^2, generally occur in a wide band across the lowlands of the interior West that excludes areas along the coast and the extensive, higher mountain ranges such as the Sierra Nevada (fig. 9). For example, the median incremental-catchment yield is 3 (Mt/yr)/km^2 for the Lower Colorado, 5 (Mt/yr)/km^2 for the Rio Grande, and 8 (Mt/yr)/km^2 for the Great Basin water-resources regions (table 8). Incremental-catchment yields less than 10 (Mt/yr)/km^2 in the lowlands of the interior West are low for a few reasons. Geologic sources generally have moderate to low yields in this area, especially low-yielding alluvium and fine-textured coastal zone sediment (7.9 (Mt/yr)/km^2). In addition, precipitation rates are low, the vegetation and low-streamflow indices are low, and the percentages of sand are high in these catchments; such conditions result in impeded land-to-water delivery from the low-yielding sources.

The Missouri, Arkansas-Red-White, and Texas-Gulf water-resources regions show considerable longitudinal variation in incremental-catchment yields (fig. 9). The incremental-catchment yields are largest in the eastern parts

Table 8. Percentile statistics of long-term mean annual incremental-catchment yields predicted by the national SPARROW model of dissolved-solids transport, tabulated by water-resources regions of the conterminous United States.

[Censored values of <0.5 and >1,000 are applied to predictions to constrain them within values near the minimum and maximum values of long-term mean annual yield observed for the monitoring stations.]

Water-resources region		Percentile statistic for estimated long-term mean annual yield at monitoring stations, metric tons per year per square kilometer						
Code	**Name**	**Minimum**	**10th**	**25th**	**Median**	**75th**	**90th**	**Maximum**
1	New England	<0.5	14	18	27	43	74	632
2	Mid-Atlantic	<0.5	17	28	47	73	120	>1,000
3	South Atlantic-Gulf	<0.5	10	14	19	28	42	139
4	Great Lakes	<0.5	23	41	81	136	249	>1,000
5	Ohio	9	48	61	78	102	139	>1,000
6	Tennessee	<0.5	25	36	52	72	91	324
7	Upper Mississippi	<0.5	29	51	74	98	134	>1,000
8	Lower Mississippi	<0.5	20	26	33	44	56	174
9	Souris-Red-Rainy	<0.5	9	12	20	41	84	249
10	Missouri	<0.5	3	5	12	26	49	463
11	Arkansas-White-Red	<0.5	5	20	37	53	81	351
12	Texas-Gulf	<0.5	5	12	28	44	64	167
13	Rio Grande	1	2	3	5	10	22	150
14	Upper Colorado	<0.5	2	4	12	32	49	>1,000
15	Lower Colorado	<0.5	1	2	3	7	13	81
16	Great Basin	<0.5	2	4	8	23	49	196
17	Pacific Northwest	<0.5	5	11	23	48	82	>1,000
18	California	<0.5	5	13	25	47	78	668
Conterminous United States		<0.5	4	11	26	54	90	>1,000

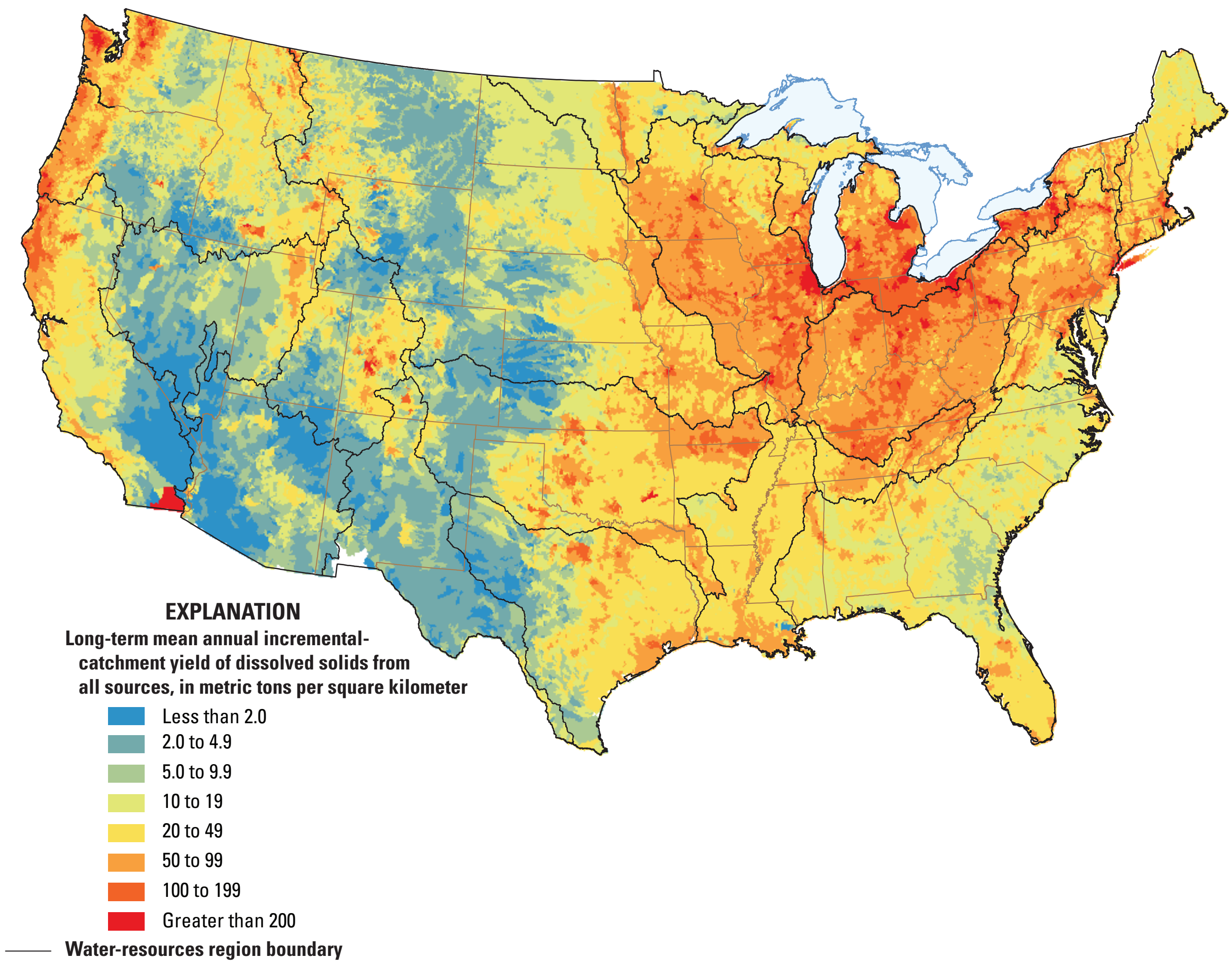


Figure 9. Map of conterminous U.S. showing long-term mean annual incremental-catchment yield of dissolved solids from all sources, predicted from the national SPARROW model of dissolved-solids transport.

of these regions where the climate is wetter, typically greater than 20 (Mt/yr)/km^2. The incremental-catchment yields are smallest in the western parts of these regions where the climate is drier, typically less than 5 (Mt/yr)/km^2. Although the longitudinal variation is largely a result of the gradient in precipitation, there are also east-to-west decreasing trends in the vegetation and low-streamflow indices that contribute to the longitudinal variation.

Analysis of model predictions shows that the source share of the incremental catchment yields has considerable variation across the nation, and that the magnitude of the yields from a given source also varies spatially. The following summaries highlight the results for each modeled source:

Geologic materials.—For simplification, yields from the 31 geologic materials variables were combined and discussed hereafter as a lump sum from geologic materials. The predominant source of dissolved-solids yields in 89 percent of the incremental catchments in the Nation is geologic materials (table 9; fig. 10). Whereas other sources may contribute significantly in these catchments, geologic materials deliver more dissolved solids to their reach than any of the other sources.

The median yield is 24 (Mt/yr)/km^2 for all incremental catchments in the Nation where geologic materials are the predominant source, which is 2 (Mt/yr)/km^2 less than the nationwide median incremental-catchment yield of 26 (Mt/yr)/km^2 (table 9). The spatial distribution of the incremental-catchment yield from geologic materials is very similar to the yield from all sources (fig. 11*A*). This is not surprising given that geologic materials are the predominant source in such a large percentage of the incremental catchments. Geologic materials provide 71.4 percent of the total amount of dissolved solids delivered the Nation's streams (table 10), and they contribute over 90 percent of incremental-catchment yield in the overwhelming majority of catchments (fig. 11*B*).

Road deicers.—New England, Mid-Atlantic, and Great Lakes are the only water-resources regions where geologic materials are not the predominant source of dissolved solids in more than 80 percent of the incremental catchments. In these three regions, road deicers are the next most important source. In fact, road deicers are the predominant source in more than 20 percent of their incremental catchments (table 9; fig. 10). Road deicers are also the predominant source in 10 percent of the incremental catchments in the Ohio and 9 percent of the incremental catchments in the Upper Mississippi water-resources regions.

Table 9. Median long-term mean annual dissolved-solids yield for all incremental catchments and for those grouped by predominant source, as predicted by the national SPARROW model of dissolved-solids transport, tabulated by water-resources regions of the conterminous United States.

[Predictions are from the national SPARROW model of dissolved-solids transport. %, percent of incremental catchments in water-resources region; –, less than 0.5 percent of the incremental catchments in the water-resources region have this predominant source]

Water-resources region		Median predicted long-term mean annual incremental-catchment yield of dissolved solids, in metric tons per year per square kilometer (percentage of catchments where source is predominant)										
			Incremental catchments grouped by predominant source									
		All catchments	Geologic materials		Road deicers		Urban lands		Cultivated lands		Pasture lands	
Code	Name		Yield	%	Yield	%	Yield	%	Yield	%	Yield	%
1	New England	27	23	(78)	67	(21)	50	(1)	–	(0)	–	(0)
2	Mid-Atlantic	47	36	(68)	78	(29)	74	(3)	–	(0)	–	(0)
3	South Atlantic-Gulf	19	18	(92)	–	(0)	40	(6)	–	(0)	31	(2)
4	Great Lakes	81	59	(65)	151	(31)	35	(1)	210	(1)	158	(3)
5	Ohio	78	74	(90)	156	(10)	–	(0)	–	(0)	–	(0)
6	Tennessee	52	52	(97)	92	(2)	40	(1)	–	(0)	–	(0)
7	Upper Mississippi	74	71	(91)	160	(9)	–	(0)	153	(1)	–	(0)
8	Lower Mississippi	33	33	(99)	66	(1)	83	(1)	–	(0)	–	(0)
9	Souris-Red-Rainy	20	20	(89)	71	(4)	78	(1)	19	(0)	25	(6)
10	Missouri	12	12	(89)	36	(1)	33	(1)	9	(3)	30	(6)
11	Arkansas-White-Red	37	37	(98)	5	(1)	37	(1)	–	(0)	–	(0)
12	Texas-Gulf	28	28	(97)	–	(0)	68	(3)	–	(0)	–	(0)
13	Rio Grande	5	5	(96)	–	(0)	15	(1)	–	(0)	23	(3)
14	Upper Colorado	12	10	(87)	–	(0)	15	(1)	–	(0)	37	(12)
15	Lower Colorado	3	3	(96)	–	(0)	9	(2)	–	(0)	12	(2)
16	Great Basin	8	7	(85)	–	(0)	–	(0)	–	(0)	31	(14)
17	Pacific Northwest	23	22	(90)	–	(0)	44	(2)	17	(2)	30	(6)
18	California	25	25	(90)	–	(0)	32	(7)	–	(0)	26	(2)
Conterminous United States		26	24	(89)	108	(5)	41	(2)	12	(1)	31	(3)

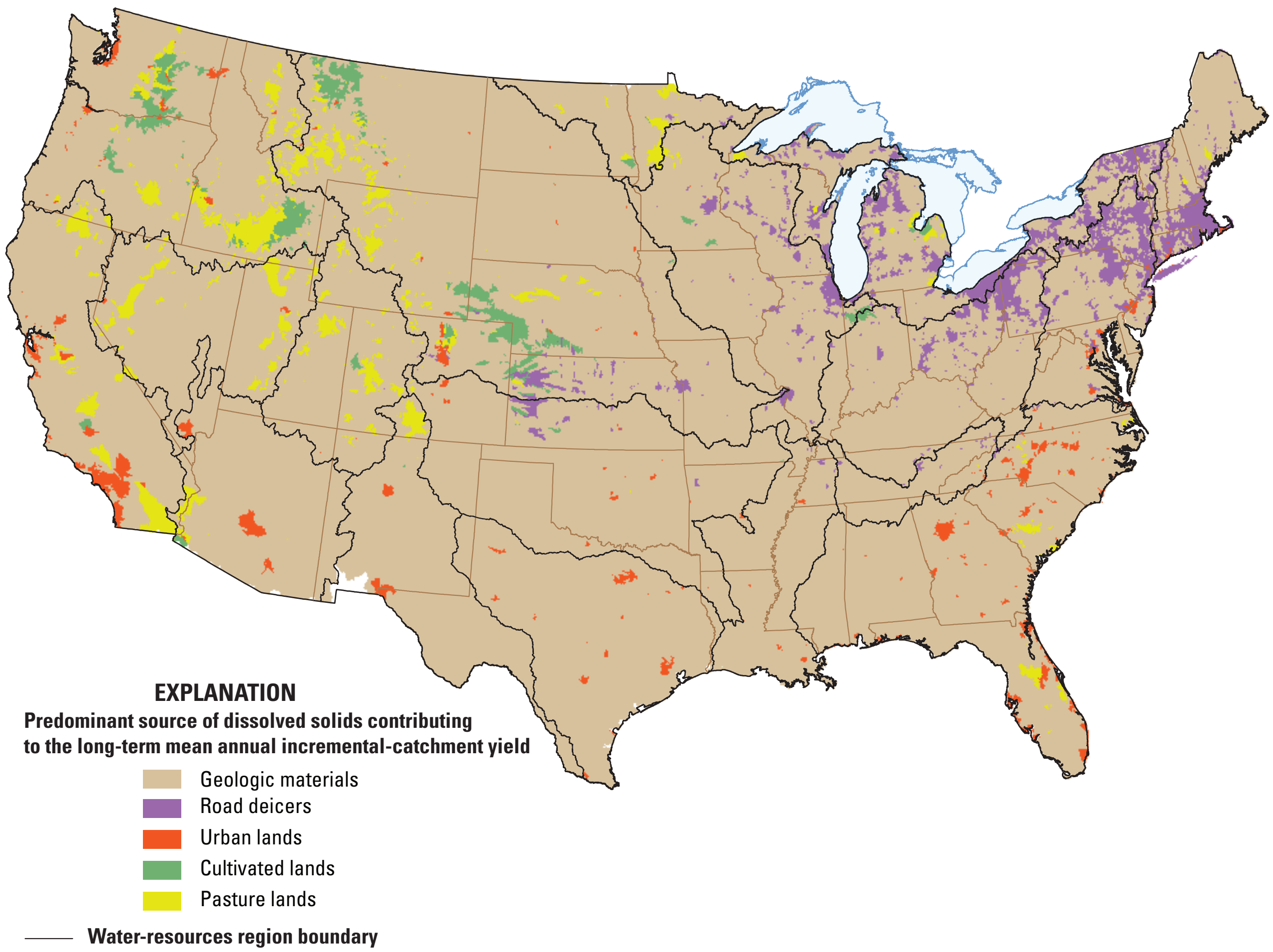


Figure 10. Map of conterminous U.S. showing predominant source of dissolved solids contributing to the long-term mean annual incremental-catchment yield, predicted from the national SPARROW model of dissolved-solids transport.

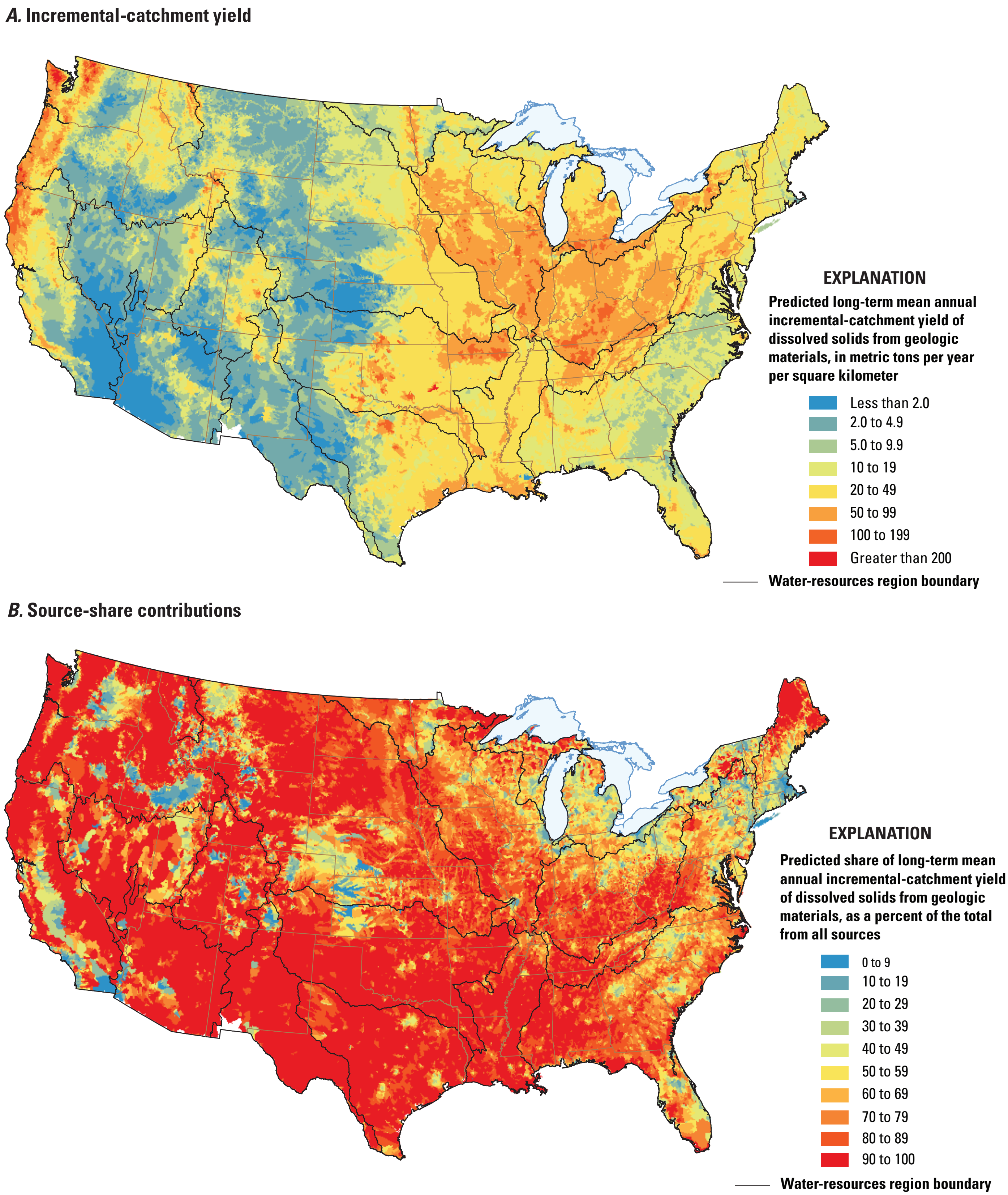


Figure 11. Maps of conterminous U.S. showing long-term mean annual incremental-catchment yield (*A*) and source-share contributions (*B*) of dissolved solids from geologic materials, predicted by the national SPARROW model of dissolved-solids transport.

Table 10. Percentage of long-term mean annual dissolved-solids load delivered to all stream reaches in each water-resources region that was contributed from each major source, as determined using predictions from the national SPARROW model of dissolved-solids transport.

Water resources region		Percentage of long-term mean annual dissolved-solids load delivered to all stream reaches in water-resources region				
Code	Name	Geologic materials	Road deicers	Urban lands	Cultivated lands	Pasture lands
1	New England	49.1	38.3	10.2	0.1	2.2
2	Mid-Atlantic	50.1	36.8	8.8	0.4	3.9
3	South Atlantic-Gulf	73.9	0.7	14.7	1.9	8.8
4	Great Lakes	44.4	34.5	4.2	6.1	10.9
5	Ohio	70.8	22.4	3.9	1.4	1.5
6	Tennessee	81.8	10.5	4.8	0.1	2.9
7	Upper Mississippi	70.2	18.6	3.6	4.0	3.6
8	Lower Mississippi	90.2	1.7	5.2	1.5	1.4
9	Souris-Red-Rainy	75.0	4.2	2.7	9.1	9.1
10	Missouri	78.0	6.3	3.5	4.4	7.8
11	Arkansas-White-Red	92.4	2.4	3.1	0.4	1.7
12	Texas-Gulf	90.1	0.0	8.0	0.2	1.6
13	Rio Grande	82.0	0.2	3.2	0.3	14.3
14	Upper Colorado	70.4	1.0	0.7	2.7	25.3
15	Lower Colorado	85.9	0.3	6.5	1.3	5.9
16	Great Basin	68.4	2.5	2.8	2.1	24.2
17	Pacific Northwest	84.1	0.1	3.0	4.6	8.2
18	California	64.2	0.0	7.2	5.0	23.7
Conterminous United States		71.4	13.9	5.1	2.9	6.7

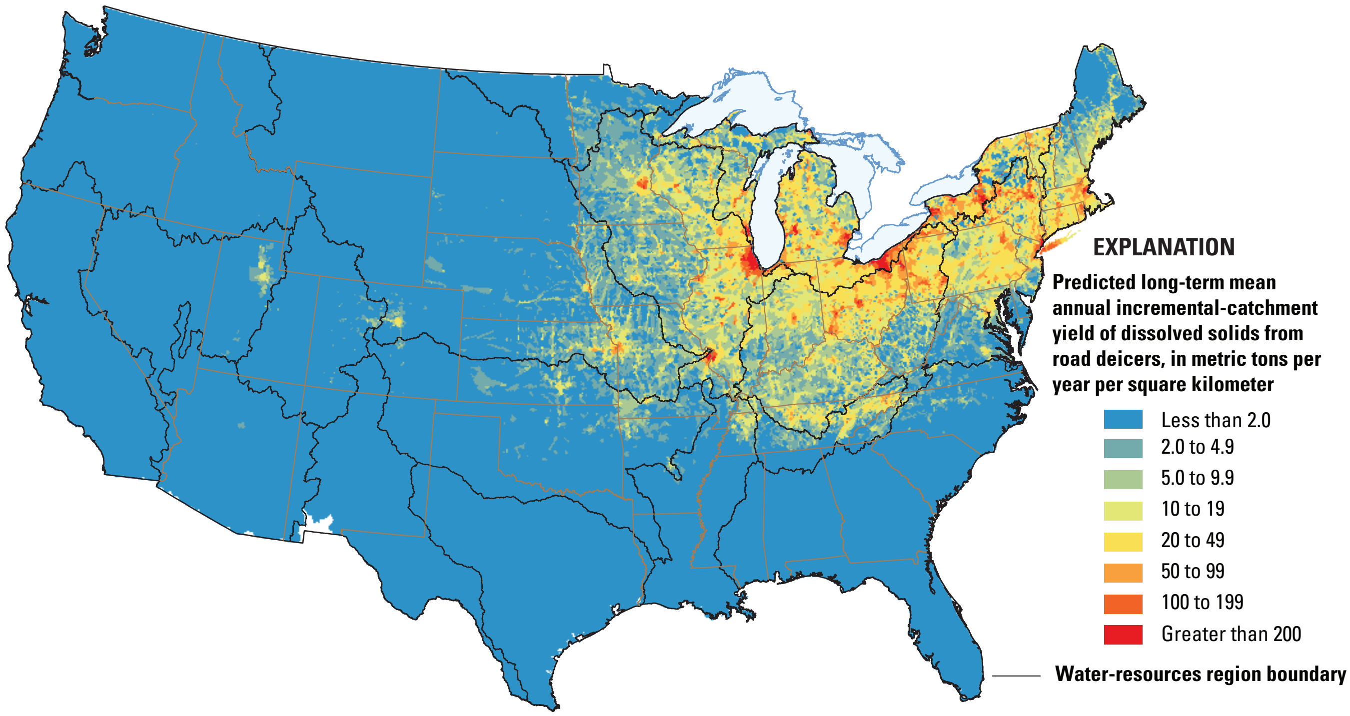
The median yield is 108 (Mt/yr)/km^2 for all incremental catchments in the Nation where road deicers are the predominant source (5 percent of the total; table 9). This is 4.5 times the median incremental-catchment yield where geologic materials are the predominant source. Most of the incremental catchments where yields from road deicers are greater than 2 (Mt/yr)/km^2 and contribute to more than 10 percent of the incremental-catchment yield are in the northeastern part of the country (figs. 12*A* and *B*). Incremental-catchment yields of dissolved solids are predicted to exceed 200 (Mt/yr)/km^2 in several clusters of incremental catchments near the Great Lakes around population centers such as Chicago, Cleveland, Detroit, and Buffalo (fig. 12*A*). Incremental-catchment yields of dissolved solids contributed from road deicers in the West, however, are generally less than 50 (Mt/yr)/km^2.

Road deicers provide 13.9 percent of the nationwide total amount of dissolved solids delivered to streams (table 10). Incremental-catchment yields of dissolved solids from road deicers represent just over one-third of the total amount of dissolved solids delivered to streams in the New England, Mid-Atlantic, and Great Lakes water-resources regions. In the remaining water-resources regions, except for the Ohio, Tennessee, and Upper Mississippi, road deicers provide less than 10 percent of the total amount of dissolved solids delivered to streams (table 10).

Urban lands.—The predominant source of dissolved solids is urban lands in 6 percent of the incremental catchments in the South Atlantic-Gulf water-resources region, and 7 percent of the incremental catchments in the California region (table 9). In other regions, urban lands are the predominant source of dissolved solids in 3 percent or less of the incremental catchments (fig. 10).

The median yield is 41 (Mt/yr)/km^2 for all incremental catchments in the Nation where urban lands are the predominant source (2 percent of the total; table 9). This is 1.7 times the median incremental-catchment yield where geologic materials are the predominant source. Not surprisingly, the spatial distribution of yields from urban lands generally follows the same pattern as for the land use itself (fig. 13; "Land use and land cover" in appendix 5, Watershed-Attribute Portfolio).

A. **Incremental-catchment yield**



B. **Source-share contributions**

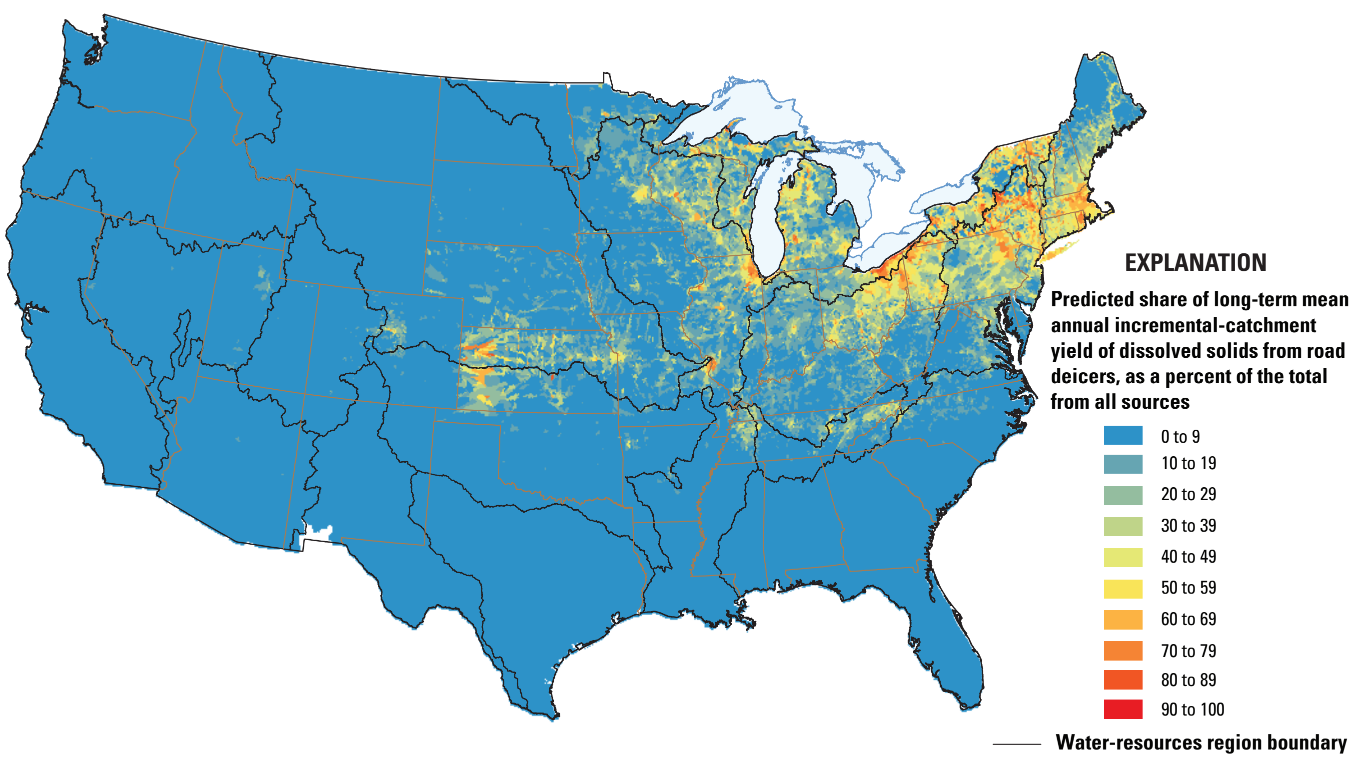
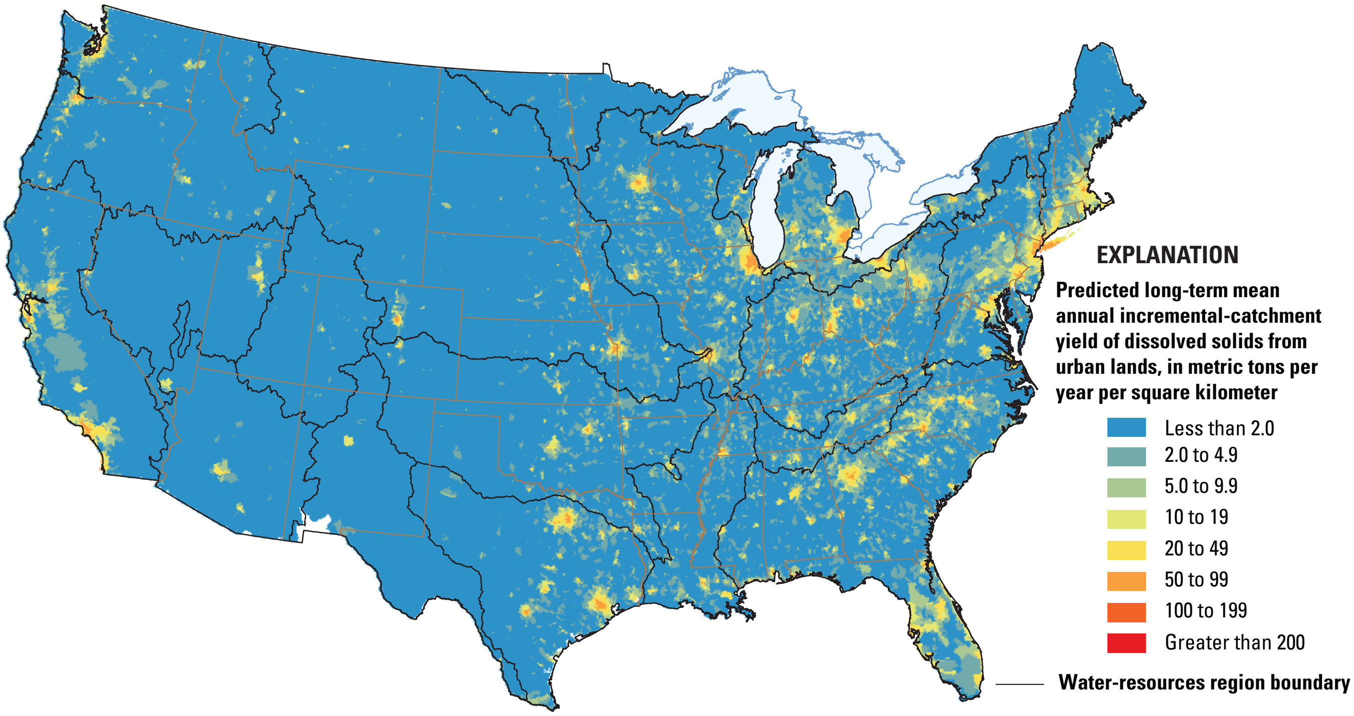


Figure 12. Maps of conterminous U.S. showing long-term mean annual incremental-catchment yield (*A*) and source-share contributions (*B*) of dissolved solids from road deicers, predicted by the national SPARROW model of dissolved-solids transport.

A. **Incremental-catchment yield**



B. **Source-share contributions**

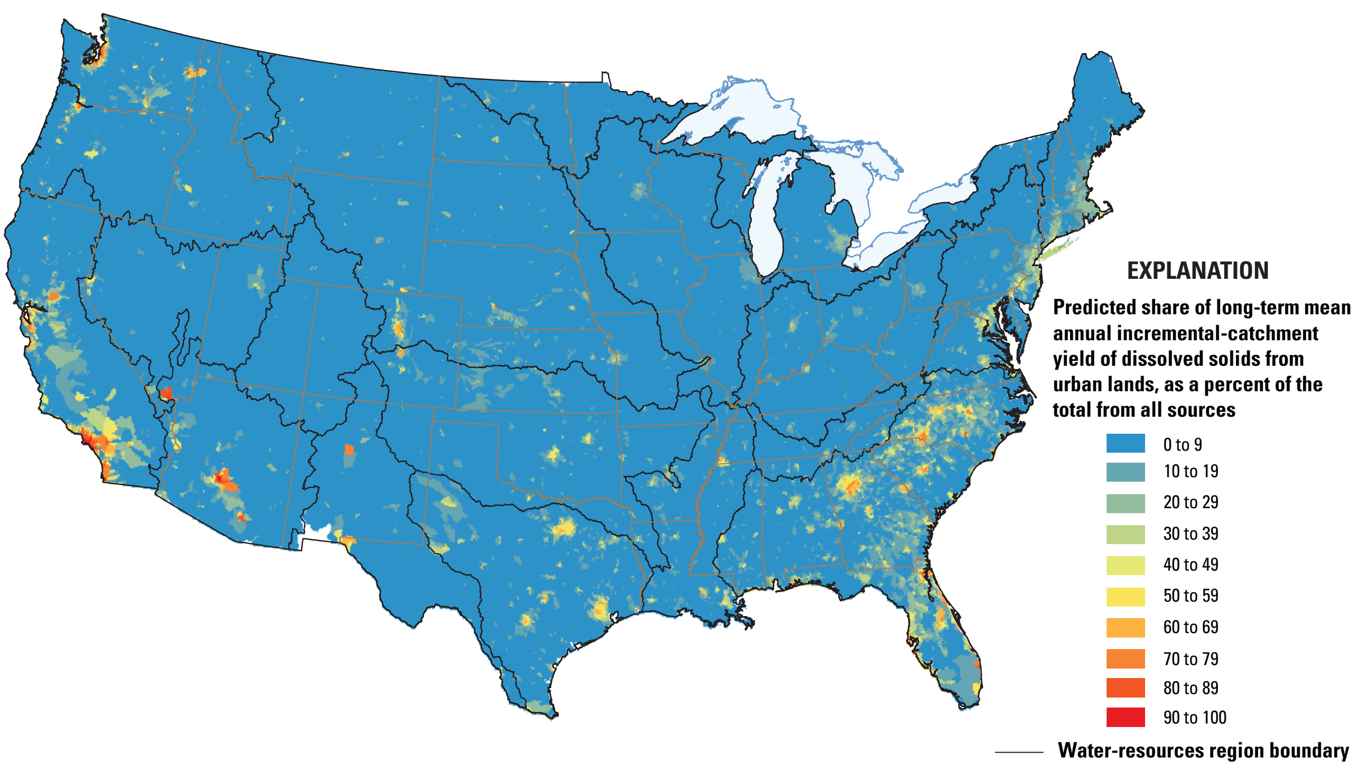


Figure 13. Maps of conterminous U.S. showing long-term mean annual incremental-catchment yield (*A*) and source-share contributions (*B*) of dissolved solids from urban lands, predicted by the national SPARROW model of dissolved-solids transport.

Overall, dissolved-solids deliveries from urban lands represent about 5.1 percent of the nationwide total amount of dissolved solids delivered to streams (table 10). Incremental-catchment yields of dissolved solids from urban lands represent 14.7 percent and 10.2 percent of the of the total amount of dissolved solids delivered to streams in the New Englands and South Atlantic-Gulf water-resources regions, respectively. In the remaining water-resources regions, urban lands provide less than 10 percent of the total amount of dissolved solids delivered to streams in the water-resources region (table 10).

Cultivated lands.—The predominant source of dissolved solids is cultivated lands in 3 percent of the incremental catchments in the Missouri water-resources region, and 2 percent of the incremental catchments in the Pacific Northwest region (table 9). In the Great Lakes and Upper Mississippi regions, cultivated lands are the predominant source in only 1 percent of the incremental catchments. In other regions, cultivated lands are the predominant source of dissolved solids in less than 0.5 percent the incremental catchments (fig. 10).

The median yield is 12 (Mt/yr)/km^2 for all incremental catchments in the Nation where cultivated lands are the predominant source (1 percent of the total; table 9). This is about half of the median incremental-catchment yield where geologic materials are the predominant source, which indicates that deliveries from cultivated lands generally are most significant in areas where deliveries from geologic sources are already low. This concept is illustrated in greater detail through maps of incremental-catchment yields of dissolved solids from cultivated lands (fig. 14). For example, in southeastern Washington and southeastern Idaho, there are several incremental catchments for which yields from cultivated lands are 2.0 (Mt/yr)/km^2 or greater. For many of these incremental catchments, yields from cultivated lands are 50 percent or more of the total incremental-catchment yield from all sources. In contrast, there are several incremental catchments in the southern part of Michigan and northern parts of Indiana and Ohio where yields are even greater than those in the Washington-Idaho example—greater than 10 (Mt/yr)/km^2. In most cases, however, yields from cultivated lands in these incremental catchments are less than 50 percent of the total yield from all sources.

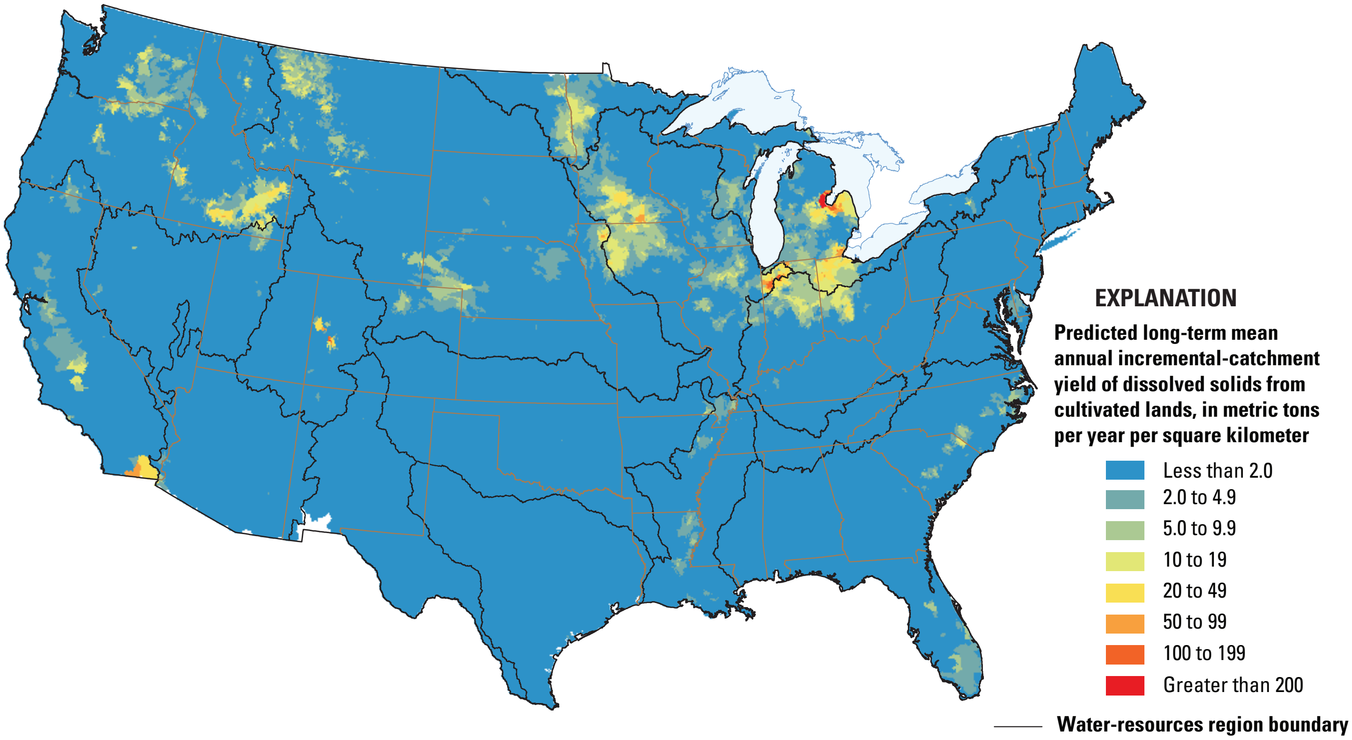
Dissolved-solids deliveries from cultivated lands provide about 2.9 percent of the nationwide total amount of dissolved solids delivered to streams (table 10). Incremental-catchment yields of dissolved solids from cultivated lands represent 9.1 percent and 6.1 percent of the total amount of dissolved solids delivered to streams in the Souris-Red-Rainy and Great Lakes water-resources regions, respectively. In the remaining water-resources regions, cultivated lands provide 5.0 percent or less of the total amount of dissolved solids delivered to streams in the water-resources region (table 10).

Pasture lands.—The predominant source of dissolved solids is pasture lands in 14 percent of the incremental catchments in the Great Basin water-resources region, and 14 percent of the incremental catchments in the Upper Colorado region (table 9). In the Souris-Red-Rainy, Missouri, and Pacific Northwest regions, pasture lands are the predominant source in 6 percent of the incremental catchments. In other regions, pasture lands are the predominant source of dissolved solids in 3 percent or less of the incremental catchments (fig. 10).

Nationwide, pasture lands are more frequently the predominant source of dissolved solids in an incremental catchment compared to cultivated lands or urban lands; however, it is less frequently the predominant source than road deicers or geologic materials. The median yield is 31 (Mt/yr)/km^2 for all incremental catchments in the Nation where pasture lands are the predominant source (3 percent of the total; table 9). This is 1.3 times the median incremental-catchment yield where geologic materials are the predominant source. Many of the catchments where yields from pasture lands are high, greater than 50 (Mt/yr)/km^2, and contribute more than half of the total dissolved solids deliveries are in western States and in Michigan (figs. 15*A* and *B*).

Nationwide, dissolved-solids deliveries from pasture lands provide about 6.7 percent of the total amount of dissolved solids delivered to streams (table 10). Incremental-catchment yields of dissolved solids from pasture lands represent one quarter of the total amount of dissolved solids delivered to streams in the Upper Colorado, Great Basin, and California water-resources regions. In the Rio Grande and Great Lakes regions, incremental-catchment yields of dissolved solids from pasture lands represent 14.3 percent and 10.9 percent, respectively, of the total amount of dissolved solids delivered to streams in those regions. In the remaining water-resources regions, pasture lands provide less than 10 percent of the total amount of dissolved solids delivered to streams in the water-resources region.

A. **Incremental-catchment yield**



B. **Source-share contributions**

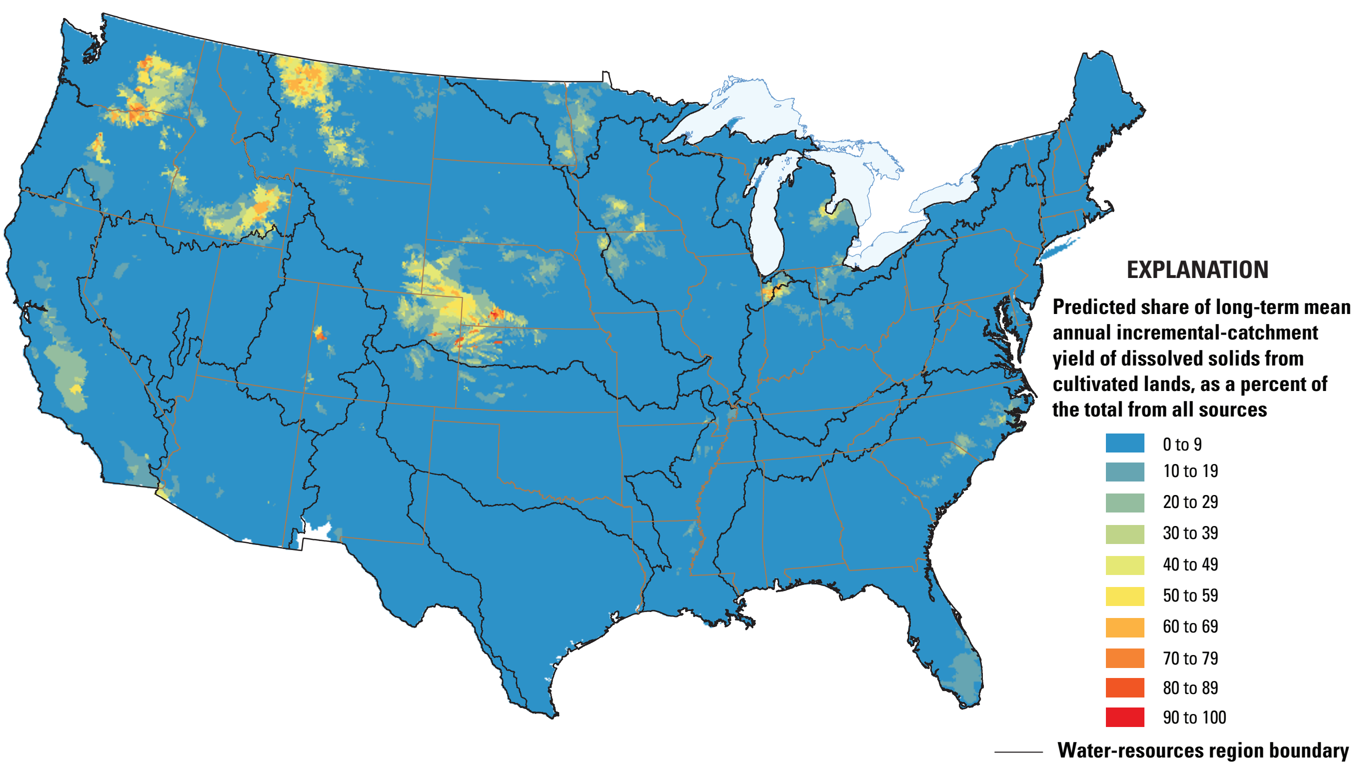
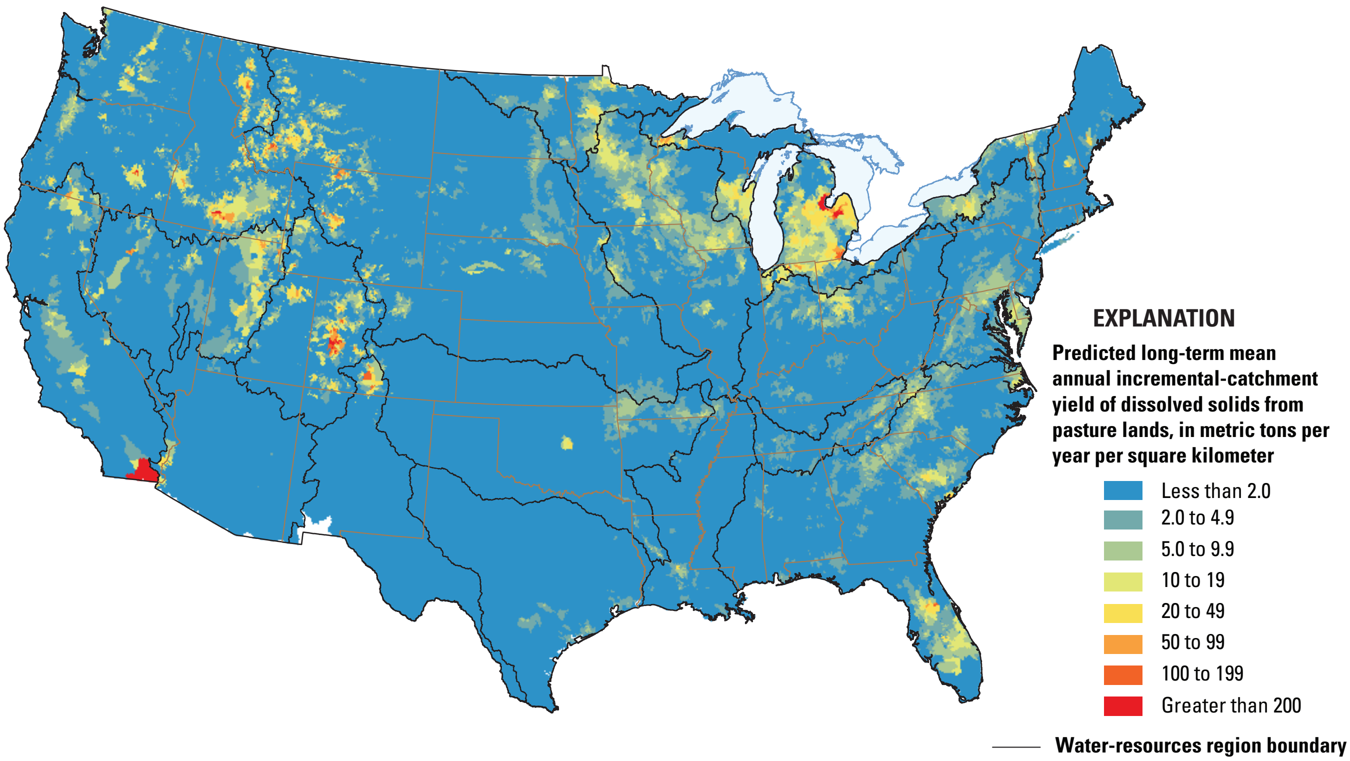


Figure 14. Maps of the conterminous U.S. showing long-term mean annual incremental-catchment yield (*A*) and source-share contributions (*B*) of dissolved solids from cultivated lands, predicted by the national SPARROW model of dissolved-solids transport.

A. Incremental-catchment yield



B. Source-share contributions

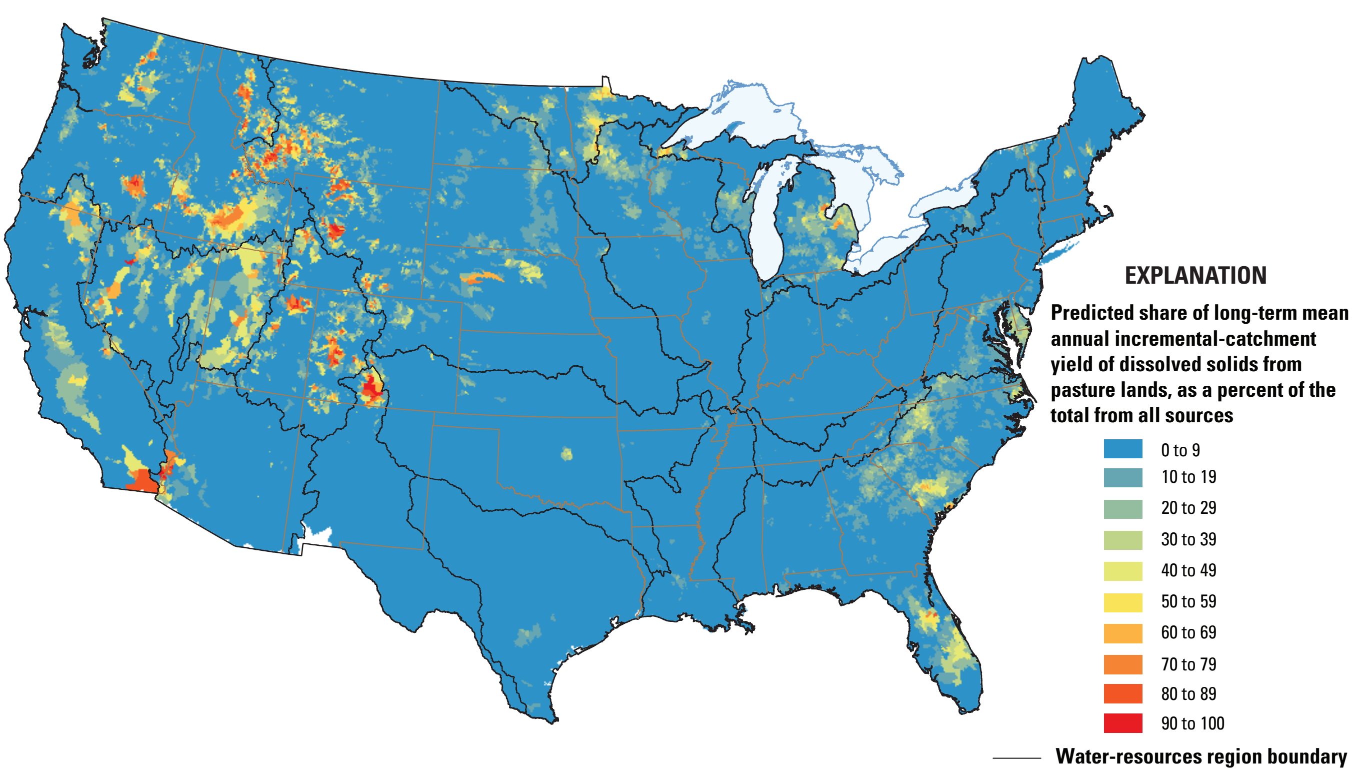


Figure 15. Maps of the conterminous U.S. showing long-term mean annual incremental-catchment yield (*A*) and source-share contributions (*B*) of dissolved solids from pasture lands, predicted by the national SPARROW model of dissolved-solids transport.

Human sources.—The share of the incremental-catchment yield of dissolved solids contributed from road deicers, urban lands, cultivated lands, and pasture lands provides an estimate of the dissolved solids from human sources (fig. 16). Each water-resources region within the Nation has multiple clusters of incremental catchments where human sources provide 50 percent or more of the dissolved-solids deliveries to streams. Tabulation of loads from all incremental catchments indicates that 271.9 million Mt of dissolved solids are delivered to the Nation's streams annually, and that 28.6 percent of this is contributed from human sources (table 10). Contributions to the total annual load of dissolved solids delivered to streams from each source, in million Mt (and as a percent), are as follows:

Geologic Materials:	194.2 (71.4%)
Road deicers:	37.7 (13.9%)
Urban lands:	13.9 (5.1%)
Cultivated lands:	7.9 (2.9%)
Pasture lands:	18.2 (6.7%)

Although there are more than twice as many cultivated lands (1.25 million km^2) as pasture lands (0.56 million km^2) in the Nation (Wieczorek and LaMotte, 2010g), the predictions in the above table show that the total annual load of dissolved solids delivered to streams from cultivated lands is less than half of that for pasture lands. In some regions, however, predicted yields of cultivated lands are similar or greater than those of pasture lands (table 9). For example, where cultivated lands or pasture lands were predominant sources, the median predicted yield of dissolved solids was 19 (Mt/yr)/km^2 for cultivated lands and 25 (Mt/yr)/km^2 for pasture lands in the Souris-Red-Rainy region. In the Great Lakes region, the median predicted yields were 210 (Mt/yr)/km^2 for cultivated lands and 158 (Mt/yr)/km^2 for pasture lands. Differences in the spatial distributions of lands-to-water variables affecting cultivated lands and pasture lands cause their yields to vary. For the Great Lakes region, as an example, yields from cultivated lands and pasture lands are generally higher than other parts of the country because of the relatively small low-streamflow index and relatively large vegetation index, baseflow index, and percentage of catchment area that is tiled and drained by ditches.

The 37.7 million Mt of total dissolved-solids deliveries from road deicers to streams is about twice as large as the estimate for road deicer usage shown in figure 3*B*, which was 19.7 million Mt for year 2000 (Kostick, 1993–2009). This

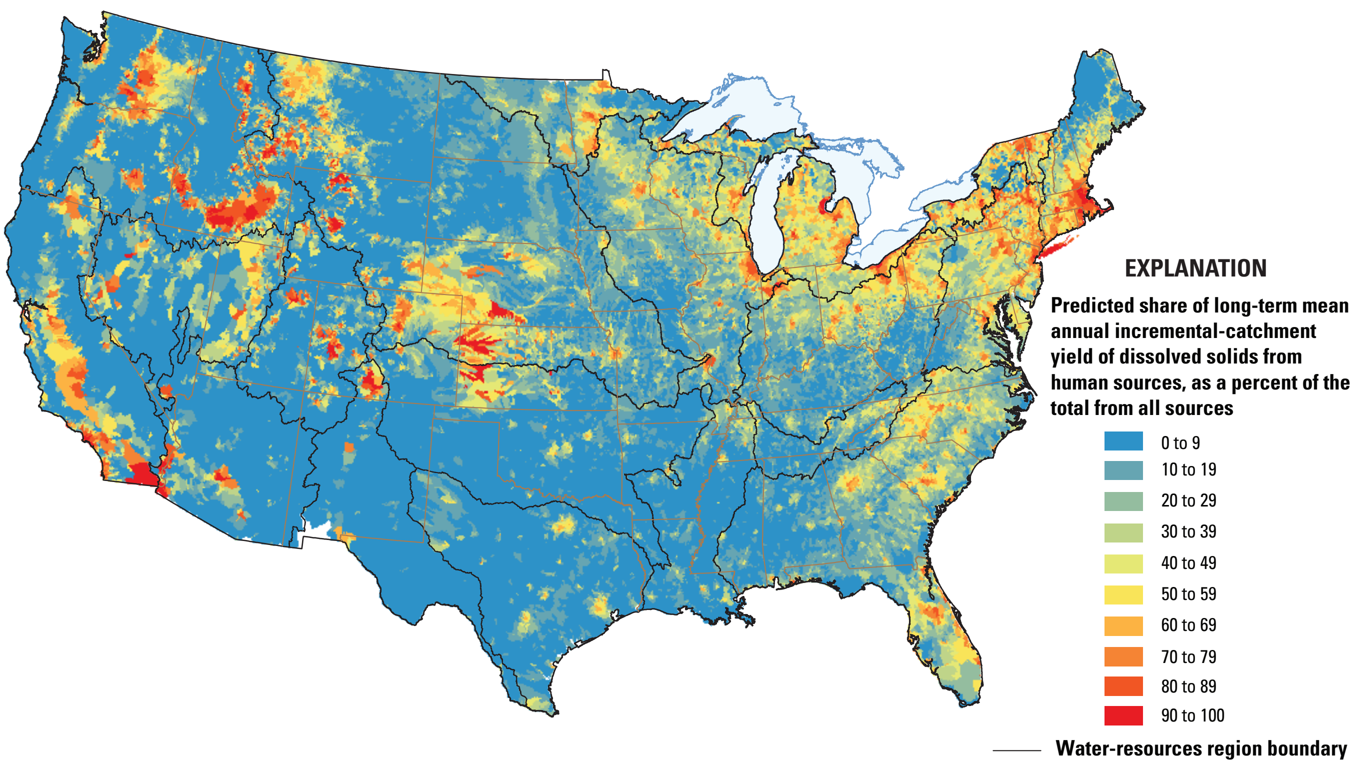


Figure 16. Map of the conterminous U.S. showing share of long-term mean annual incremental-catchment yield contributed from human sources, predicted by the national SPARROW model of dissolved-solids transport.

discrepancy could have arisen from one of or a combination of several reasons: road deicer usage is under reported, road deicer deliveries are overestimated by the model, road deicer usage is responsible for various processes that promote additional dissolved-solids delivery from sources besides road deicers, or road deicer usage is spatially correlated to other sources of dissolved-solids that are not accounted for in the model.

Accumulated Loads and Yields

Dissolved-solids loads in each reach are cascaded through the hydrologic network, accumulating mass with downstream transport. In a small percentage of the reaches, losses were encountered with downstream transport and the dissolved-solids loads decreased. Maps showing the spatial distribution of predicted accumulated yields of dissolved solids compare well with those for observed yields from monitoring stations (figs. 5 and 17), and additionally, they fill in spatial gaps with great detail. The regional-scale patterns previously described for the observed yields also hold for the predicted accumulated yields.

Overall, the predicted accumulated yields and the predicted incremental-catchment yields show the same regional patterns; however, in some cases there are differences on larger streams. For example, near the Arizona-Nevada border, yields for incremental-catchments of the Colorado River are less than 2.0 (Mt/yr)/km^2, similar to the surrounding incremental catchments for tributaries to the Colorado River (fig. 9). Accumulated yields for the Colorado River in that area, however, are much greater (between 10 and 20 (Mt/yr)/km^2) owing to loads accumulated in the upper part of the basin (fig. 17). This illustrates the difference between incremental-catchment and accumulated yields that can occur in larger rivers where the local source and land-to-water delivery conditions are considerably different that those upstream. Several of the larger streams crossing the Missouri, Arkansas-White-Red, and the Texas-Gulf water-resources regions from west to east show the opposite pattern—including the Colorado (of Texas), Canadian, the Arkansas, the Platte, and the Missouri. As these streams flow into the eastern part of those water-resources regions, they have low accumulated yields, typically between 10 and 20 (Mt/yr)/km^2. These yields are in contrast to the surrounding and locally originating streams that have higher incremental-catchment and accumulated yields, typically between 20 and 50 (Mt/yr)/km^2, but up to 100 (Mt/yr)/km^2.

Results from the national SPARROW model of dissolved-solids transport include information on the percent of each catchment's yield that is delivered to a user-defined receiving water body—in this study these were chosen to be either an ocean or an international-boundary water, such as the Rainy River, the Great Lakes and St. Lawrence River, and the lower Rio Grande downstream from El Paso, Texas. Compared to nutrient loads, which can attenuate through biologic consumption, chemical reaction, or settling in reservoirs, dissolved-solids loads are chemically conservative. In most streams, the entire dissolved-solids load delivered from each incremental catchment was transported to the receiving water body, with no losses along the way (fig. 18). The exceptions are streams in the southwestern part of the country where load losses occurred owing to streamflow diversion for off-stream use, or by streambed infiltration. For example, streams within the Great Basin water-resources region drain internally rather than to the ocean, and they terminate in the topographically lowest point within their watershed to form either a playa or a terminal lake such as the Great Salt Lake. Consequently, their load does not reach one of the predefined receiving water bodies. There are several other streams outside the Great Basin region that also drain internally; most are in southeastern California, southeastern Oregon, and south-central New Mexico, but others are scattered about in other states mostly in the west.

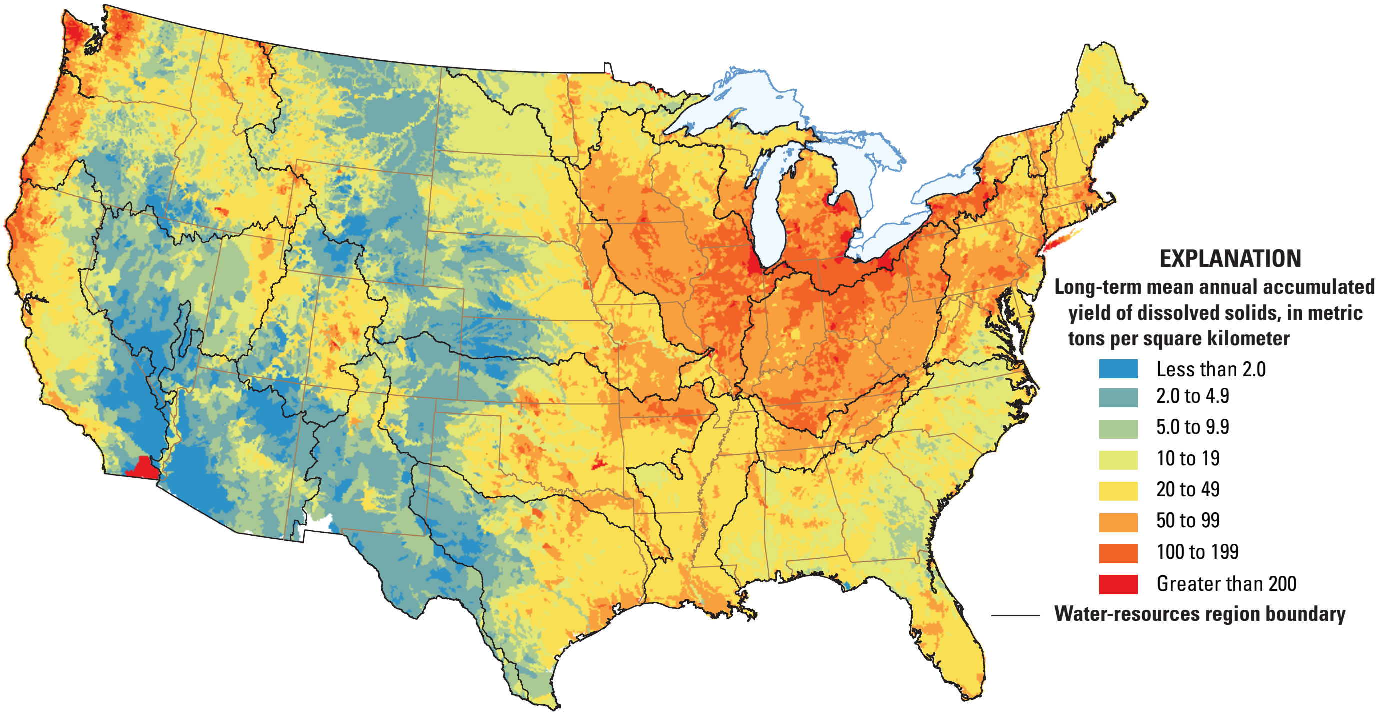


Figure 17. Map of the conterminous U.S. showing long-term mean annual accumulated yield of dissolved solids from all sources, predicted from the national SPARROW model of dissolved-solids transport.

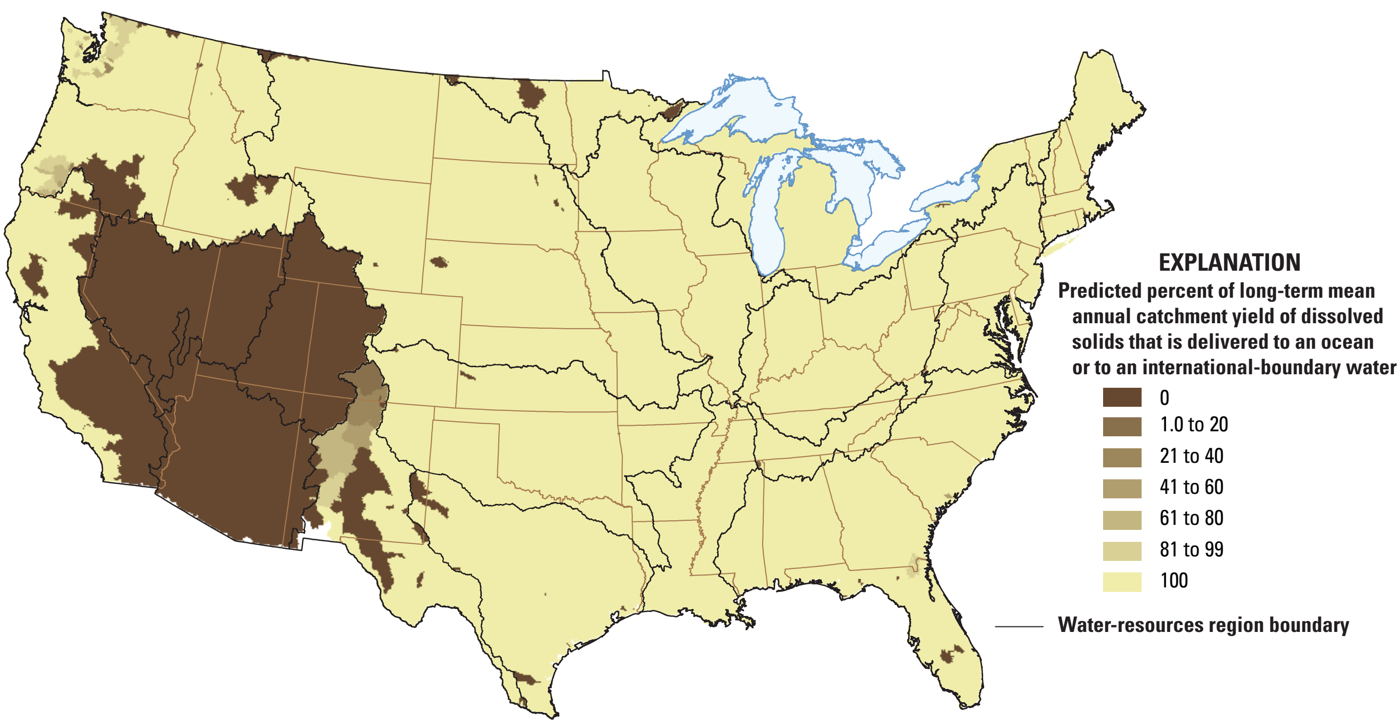


Figure 18. Map of the conterminous U.S. showing percent of long-term mean annual catchment yields of dissolved solids that is delivered to an ocean or to a water body along an international boundary, predicted from the national SPARROW model of dissolved-solids transport.

In contrast to the catchments in internally drained basins, most catchments in the Upper and Lower Colorado regions drain to the Pacific Ocean through the Sea of Cortez. Streamflow for several reaches in these regions, however, is diverted for off-stream use along its path to the ocean, especially in the lower reaches. In cases like the diversions to the Colorado River Aqueduct or the aqueducts of the Central Arizona Project, the water is conveyed hundreds of miles to the location of use. Much of the water is used for irrigation in an arid climate, and consequently the dissolved solids carried in the diverted water are not likely to be transported back to the Colorado River, but rather they are likely to accumulate in the soils or in the groundwater near the place of use (Anning, 2007).

Predictions from the SPARROW model of dissolved-solids transport were graphed to show how accumulated loads in selected large streams (fig. 1) change from their headwaters to their outlets, and to show the major sources of the load (fig. 19). Each water-resources region is represented in these graphs by one of the largest streams in the region with significant water-quality monitoring. In these graphs, accumulated loads of dissolved solids are shown as a function of drainage area for each source, and the data for each source are stacked on top of each other so that the top of the stack indicates the total accumulated load from all sources. The relative portion from each source can be coarsely determined looking at the distribution of the wedges forming the total. The slope of the top-most line in the accumulated load-drainage area relation represents the accumulated yield of dissolved solids from all sources. Changes in the slope in the upstream or downstream direction occur as a result of heterogeneous rates of dissolved solids yielded from the catchments. Data from the water-quality monitoring stations are also graphed to show the model's fit in selected parts of the river's drainage. It should be noted that the model estimation is based on data for catchments between monitoring stations, including those not shown on the graph that are on tributaries to the river being illustrated. Also, note that while the accumulated load of each major river is graphed against drainage area as a continuous variable for the purpose of illustration, physically, the drainage area of each river actually increases in unequal increments of area as tributaries of different sizes are incorporated into the river basin in the downstream direction.

For most of the major streams shown in these graphs, accumulated loads only increased in each reach from the stream headwaters to stream outlets, except for the Rio Grande and the Colorado River (figs. 19*L* and *M*). Also, geologic materials provided the major source of the accumulated load of dissolved solids for most streams shown. Other sources also provided a substantial portion of the accumulated load, however, and the sets of significant sources varied by water-resources region.

In the Connecticut and Susquehanna Rivers, road deicers contribute nearly as much to the accumulated load as geologic materials do (fig. 19*A* and *B*). Both urban lands and pasture lands contribute a lesser amount to the accumulated load, and contributions from the remaining sources are negligible.

In the Chattahoochee and Trinity Rivers, urban lands and to a lesser extent, pasture lands, are the primary human sources contributing to the accumulated load of dissolved solids (fig. 19*C* and *K*). In the Chattahoochee River, much of the accumulated load from urban lands occurs where the drainage area grows from 3,000 km^2 to 5,000 km^2, which contains the Atlanta metropolitan area. Accumulated loads in the Chattahoochee River from that urban area remain in the river without appreciable gain from other urban sources throughout the remainder of its drainage to the Gulf of Mexico. In the Trinity River, accumulated loads from urban lands increase dramatically where the drainage grows from about 5,000 km^2 to 20,000 km^2 in the area that contains the Dallas-Fort Worth metropolitan area.

Like was the case for the Connecticut and Susquehanna Rivers, accumulated loads of dissolved solids contributed from road deicers are also significant, but to a lesser extent, in the Fox, Ohio, and Tennessee Rivers (fig. 19*D*, *E*, and *F*). Pasture lands, cultivated lands, and urban lands are also important contributors to the accumulated load, but to a larger extent for the Fox River than for the Ohio or Tennessee Rivers. Accumulated loads from each source in the Fox River increase steadily in about the same proportions with increased drainage area, which illustrates the rather homogeneous spatial distribution of dissolved-solids sources in that river basin. Contributions in the headwaters part of the Ohio and Tennessee River basins are not shown because there are multiple tributaries forming those parts of the drainage basins.

In the Missouri and Arkansas Rivers, geologic materials are the primary source of dissolved solids. Yields from this source increase towards their outlets, as indicated by the increase in the slopes of their accumulated load/drainage area relation (fig. 19*I* and *J*). Human sources are more significant contributors to the accumulated load of the Missouri River than of the Arkansas River, and both pasture lands and cultivated lands are the primary human sources of dissolved solids for the Missouri River. Dissolved solids from urban lands and from road deicers, however, contribute more substantially toward the outlet of the Missouri River.

Accumulated loads from the Missouri River flow into the Mississippi River, and this relation appears in the graph where the drainage area of the Mississippi River increases from about 450,000 km^2 to 1,800,000 km^2 (fig. 19*G*). The shallower slope in the accumulated load-drainage area relation for this part of the graph indicate that yields from the Missouri River basin are lower than those from the other drainages of the Mississippi River Basin. Although difficult to see clearly in the graph, the accumulated load in the Mississippi River decreases substantially from 127 million Mt/yr to 100 million Mt/yr just before its outlet as a result of diverting flow into the Atchafalaya River.

Pasture lands are the primary human source of dissolved solids in the Upper Rio Grande, the Colorado, the Bear, the Snake, and the Sacramento Rivers (fig. 19*L, M, N, O*, and *P*). Cultivated lands are significant for the Snake River as well (fig. 19*O*). Mountainous headwater areas have larger yields from geologic sources than do lowland, downstream areas in the Upper Rio Grande, Colorado, and Snake River Basins. Losses in the accumulated loads of dissolved solids occur in the lower part of the Colorado River, where accumulated loads decrease from almost 6 million Mt/yr to less than 1 million Mt/yr (fig. 19*M*). Losses of accumulated loads also occur in the Upper Rio Grande River (fig. 19*L*). Note that for these two rivers, the losses are due to diversions and the relative proportion of dissolved solids from each source remains the same above and below where the loss takes place. In the Upper Rio Grande, contributions of dissolved solids from urban lands around Albuquerque create the increase in load from that source where the drainage area is about 450,000 km^2.

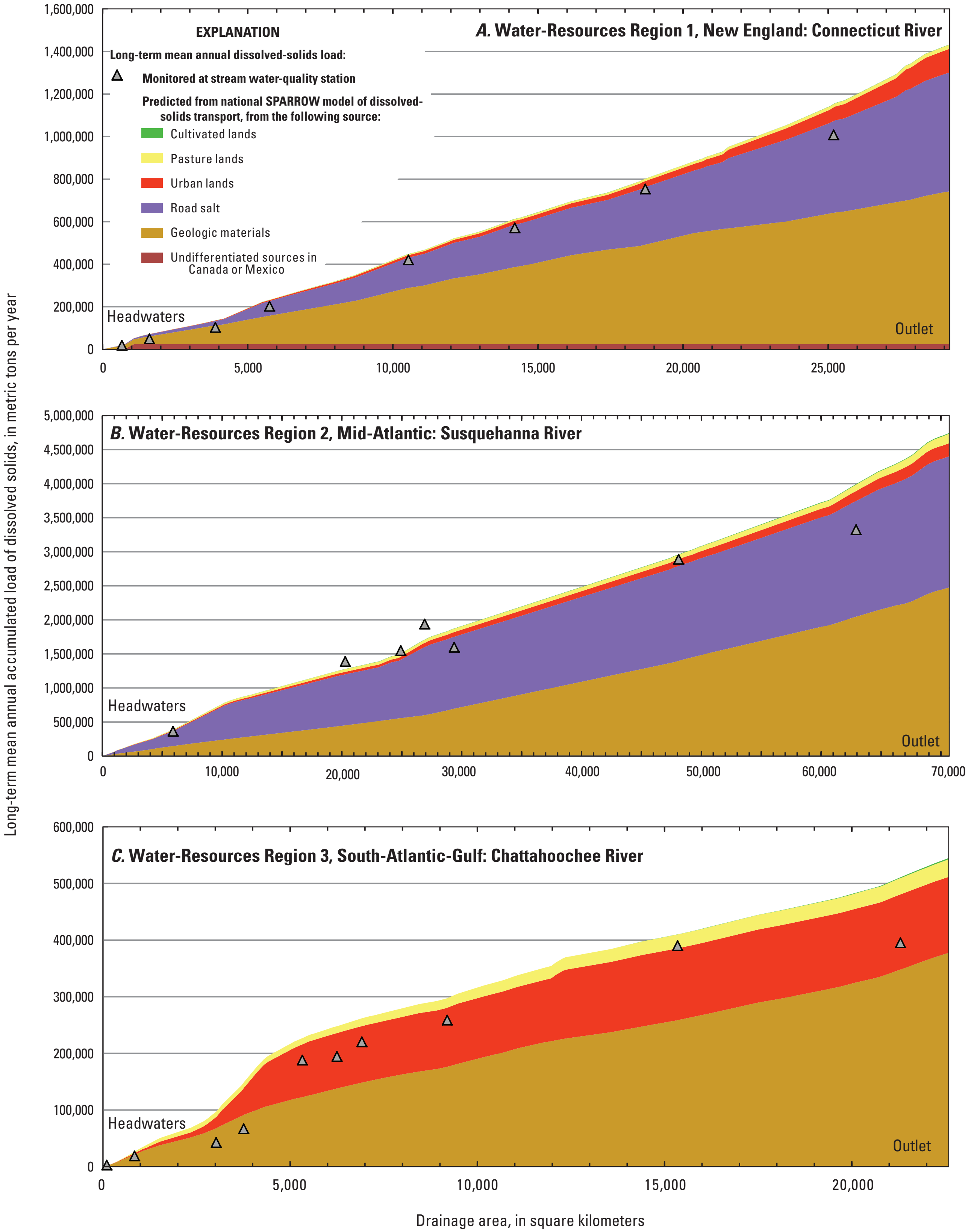
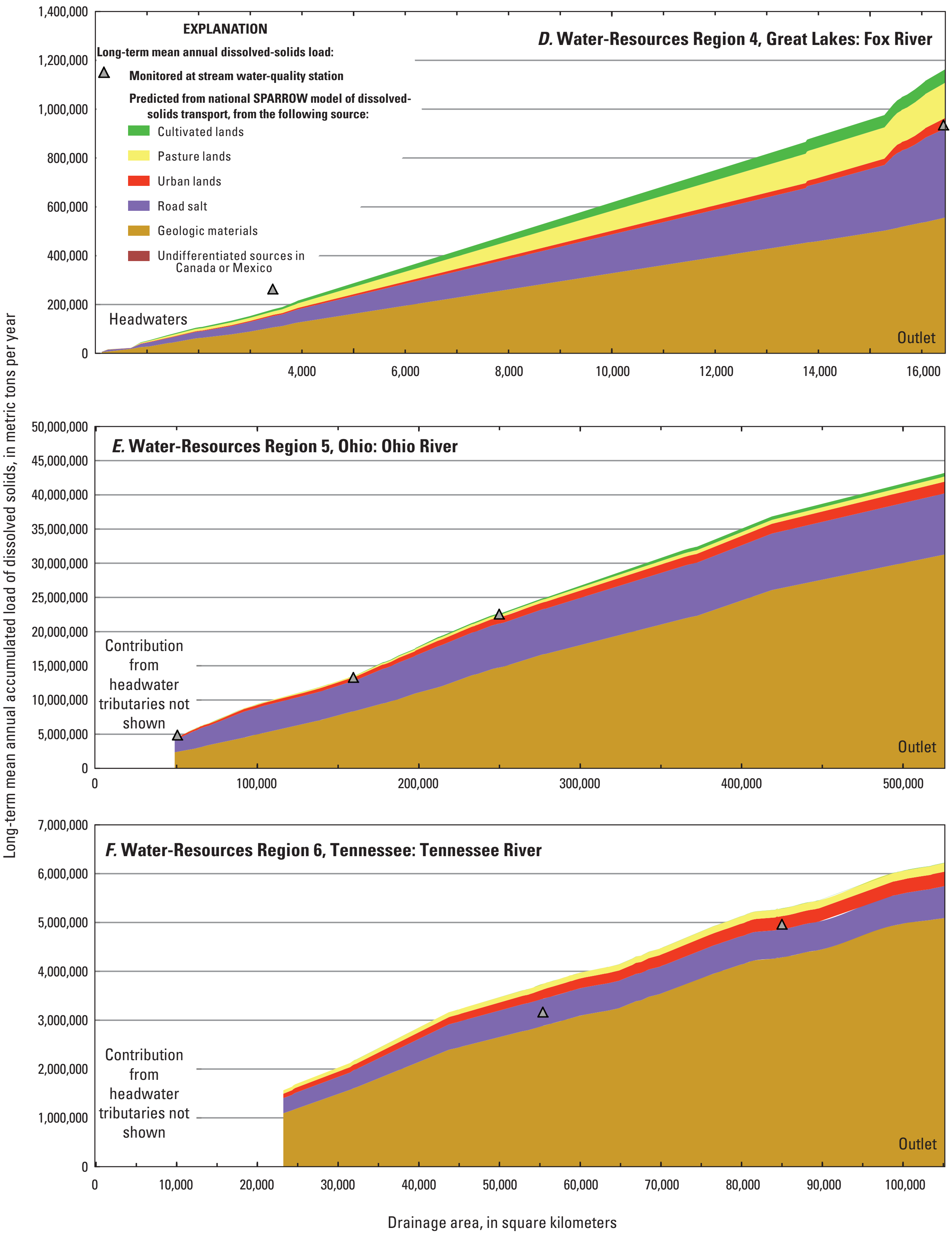


Figure 19. Plots showing long-term mean annual accumulated load of dissolved solids from different sources along selected major streams of the water-resource regions in the conterminous United Sates, predicted from the national SPARROW model of dissolved-solids transport. *A*, Connecticut River. *B*, Susquehanna River. *C*, Chattahoochee River. *D*, Fox River. *E*, Ohio River. *F*, Tennessee River. *G*, Mississippi River. *H*, Red River. *I*, Missouri River. *J*, Arkansas River. *K*, Trinity River. *L*, Upper Rio Grande. *M*, Colorado River. *N*, Bear River. *O*, Snake River. *P*, Sacramento River. See figure 1 for river locations.



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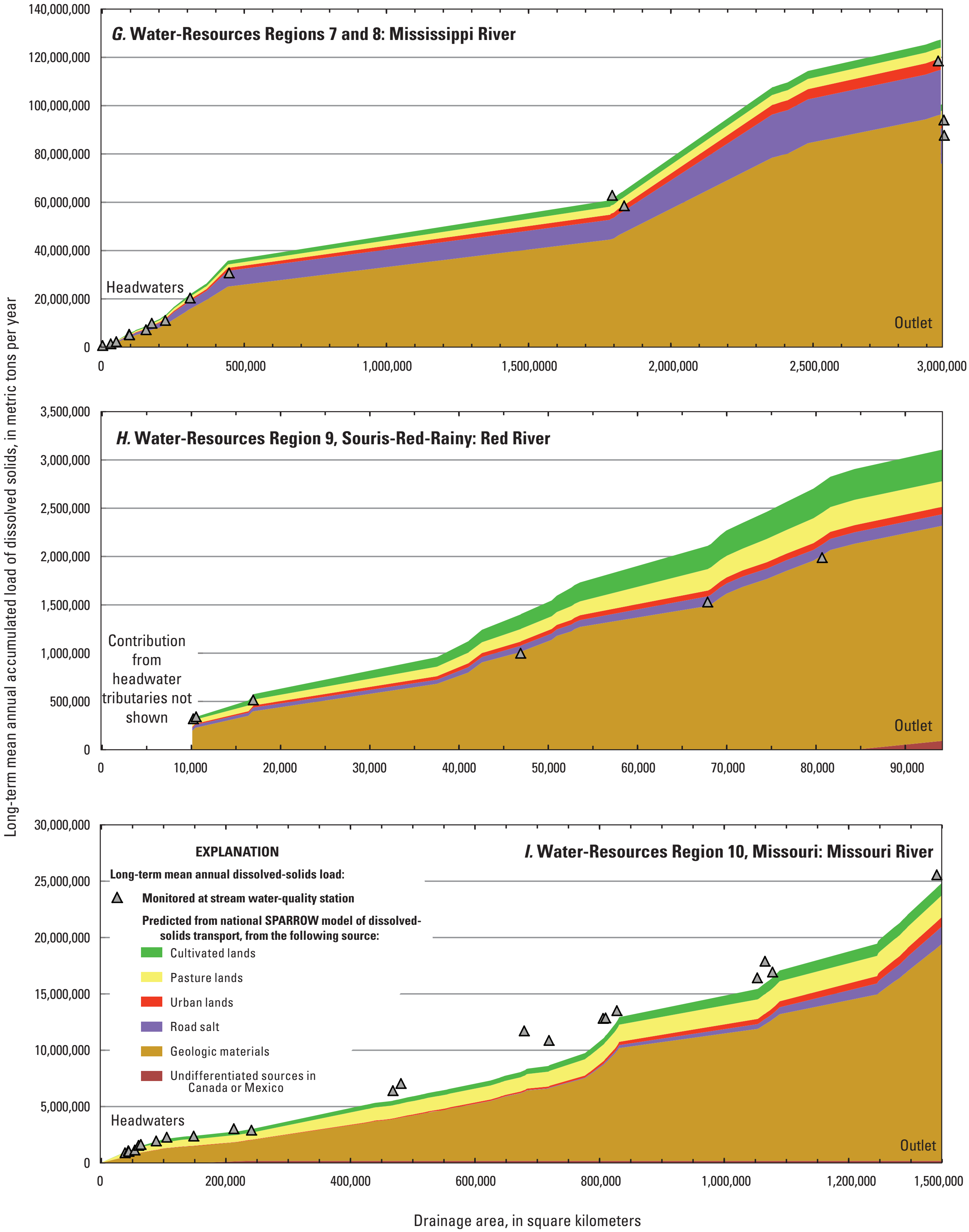

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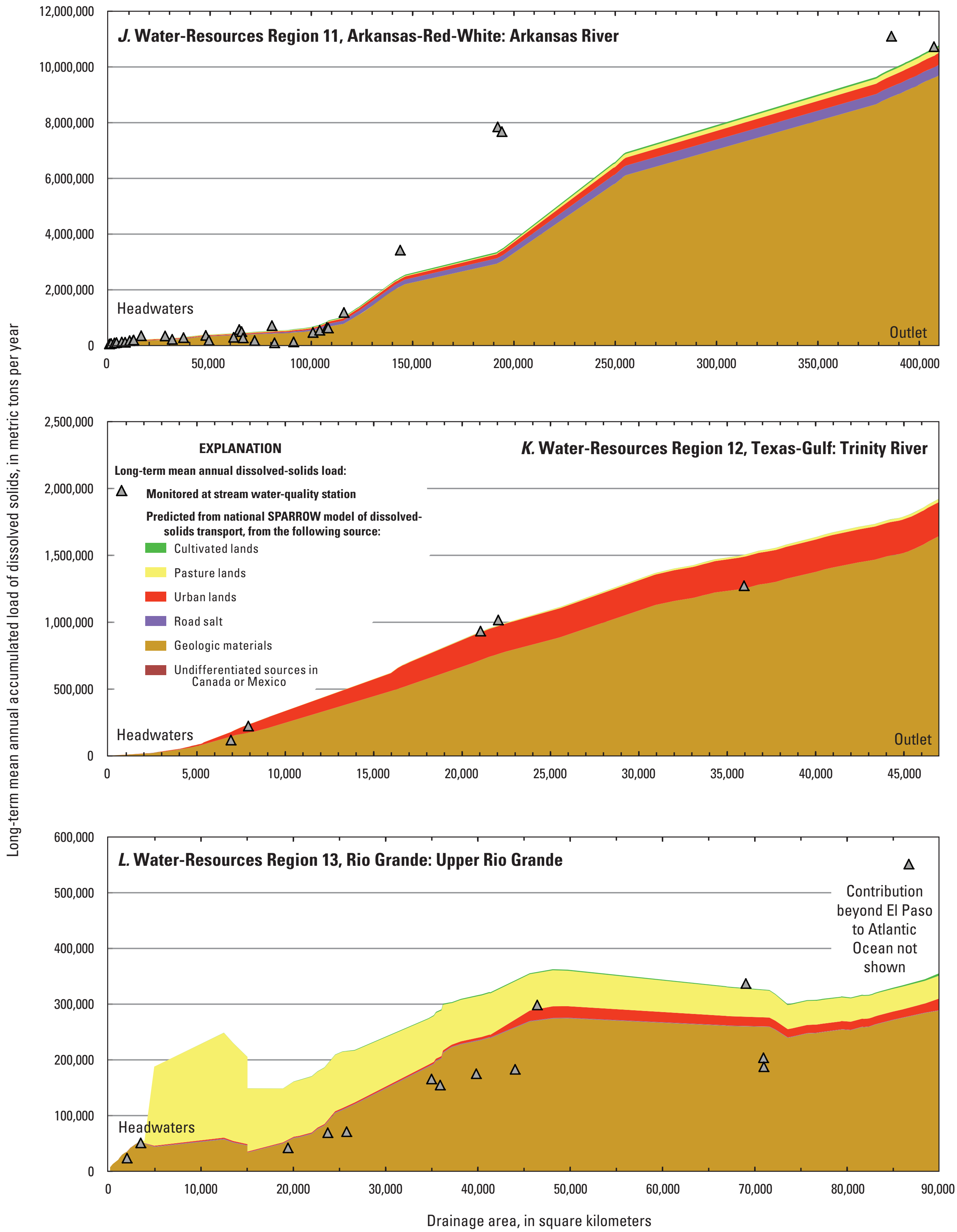

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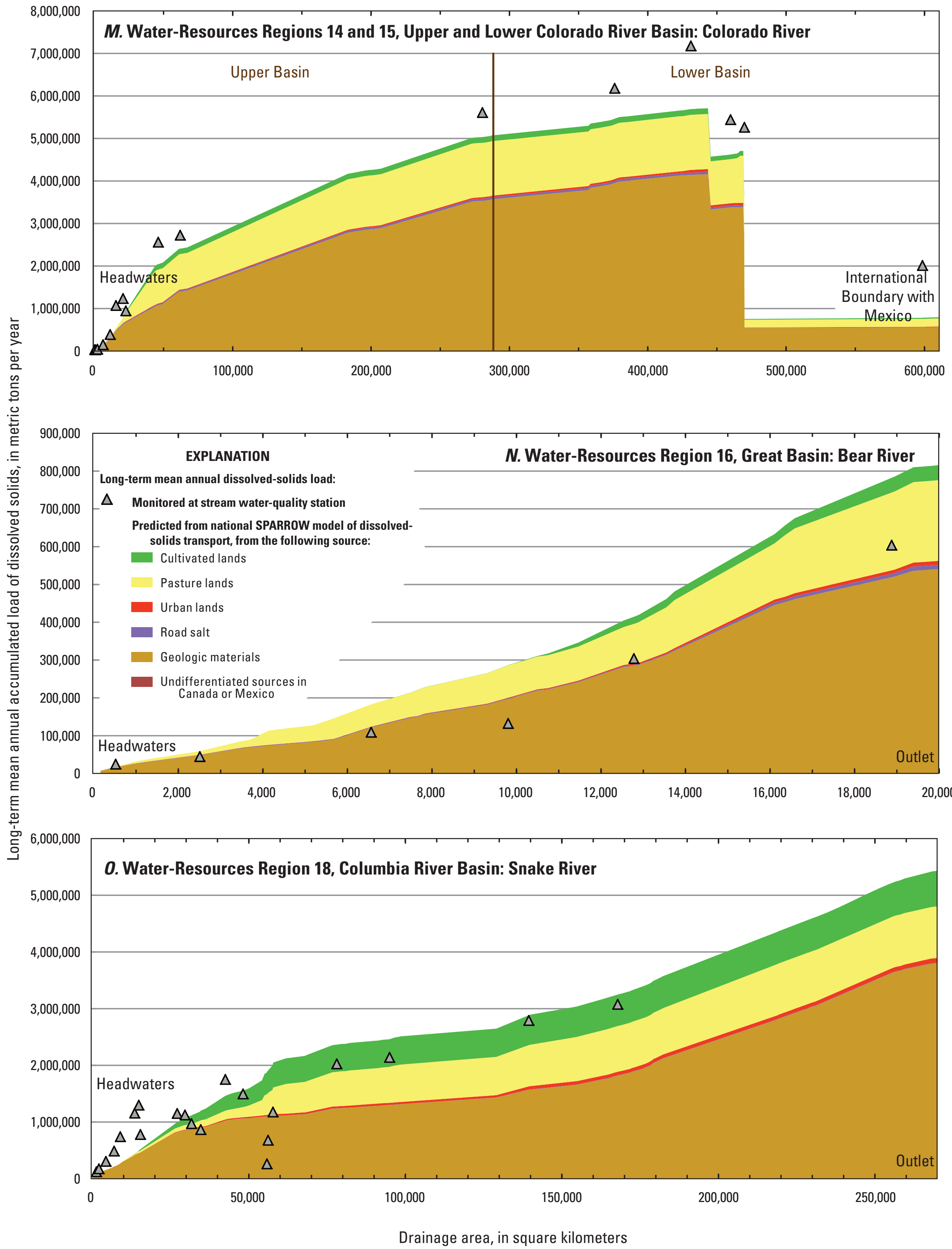

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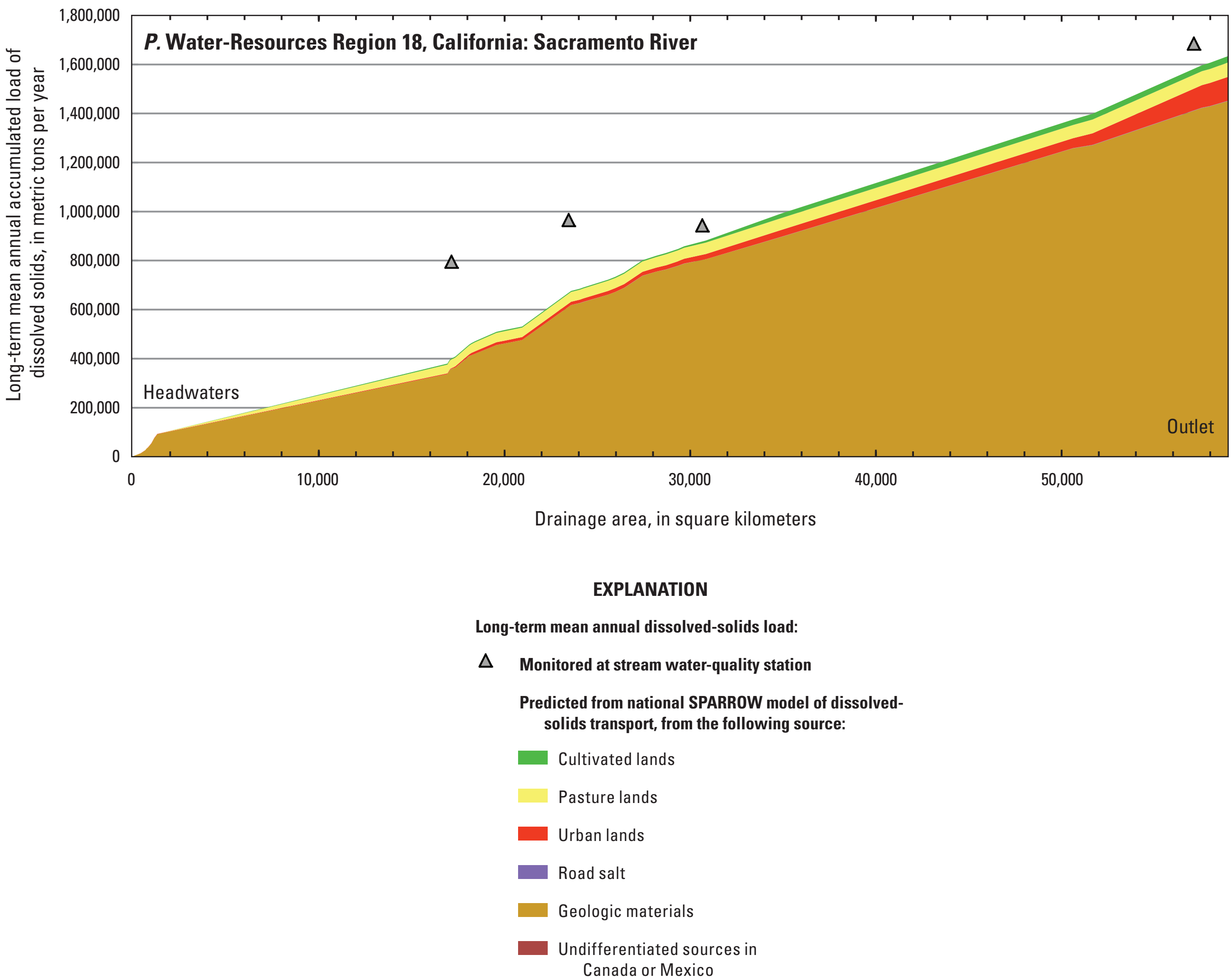

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Concentrations

Long-term mean annual concentrations of dissolved solids were derived by dividing the accumulated load predictions by the annual discharge data that is contained in the reach network. Random and bias errors associated with the predicted concentrations were characterized and the data were used to provide a detailed picture of the spatial patterns in long-term mean annual dissolved-solids concentrations for the Nation. Analysis of the predicted concentrations showed that, nationwide, 12.6 percent of the reaches exceeded the U.S. Environmental Protection Agency's 500 mg/L secondary drinking water standard. Concentrations were further explored by examining spatial patterns of long-term temporal trends in dissolved solids that were observed in the monitoring station data. An improved understanding of relations between sources and long-term temporal trends in concentrations was gained through an analysis that combined information on sources of accumulated dissolved-solids loads in stream reaches with information on temporal trends in concentrations at monitoring stations on those reaches.

Concentrations predicted from the national SPARROW model of dissolved-solids transport are in reasonable agreement with concentrations observed at monitoring stations (fig. 20); however, random error and bias error are present. When log-base-10-transformed predicted concentrations are linearly regressed against log-base-10-transformed observed concentrations, the intercept of the line is 0.548 and the slope is 0.795. The intercept is significantly different than zero, and the slope is also significantly different than one ($p<0.05$). The residual error from the regression is 0.259 and the adjusted R-squared value is 0.667. The regression equation and a 1-to-1 line intersect at concentrations of about 470 mg/L; concentrations are overpredicted where less than about 470 mg/L, and concentrations are underpredicted where greater than 470 mg/L (fig. 20). Note that the bias error is approximately zero at 470 mg/L and increases with concentrations greater or less than that value. Bias error in the predicted concentrations could have resulted from bias propagated from either the load data or the discharge data. Given the study objective of understanding spatial trends in dissolved-solids concentrations across the Nation, which cover over 3 orders of magnitude, the predicted concentrations were not compensated for the detected bias.

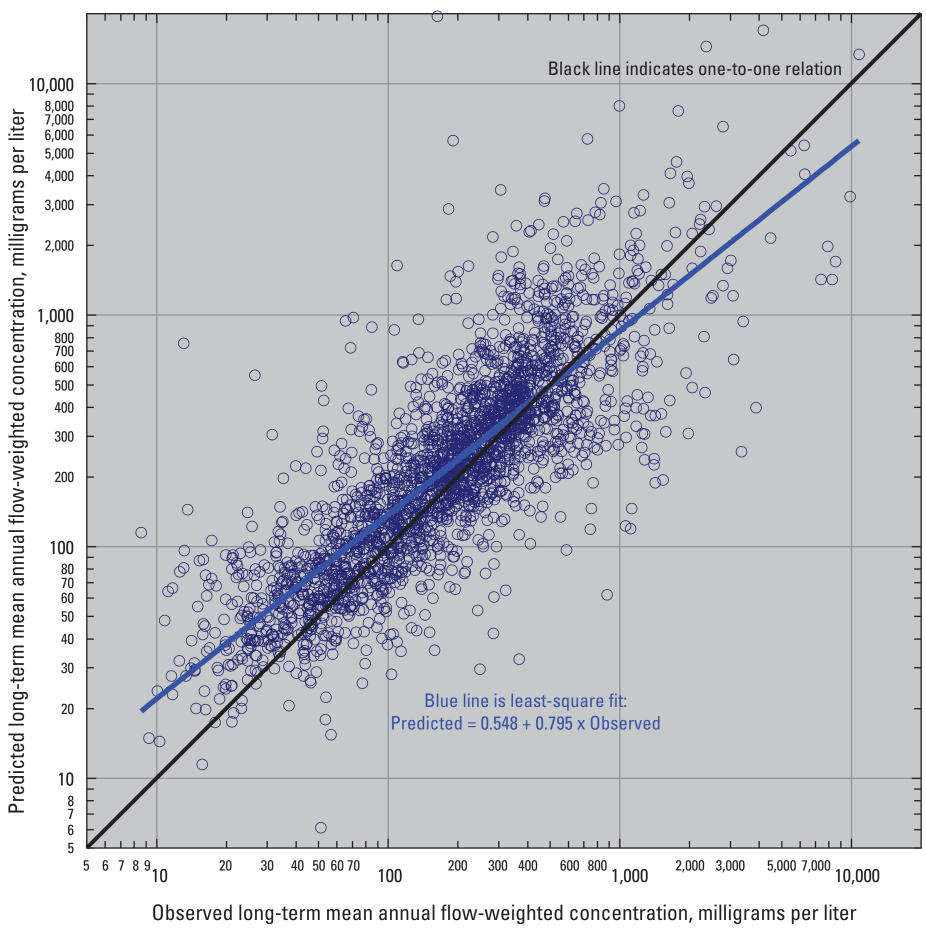

Figure 20. Plot showing relation between predicted and observed long-term mean annual flow-weighted concentrations for 2,560 water-quality monitoring stations used in the national SPARROW model of dissolved-solids transport.

Spatial Patterns

As a result of the reasonable agreement between predicted and observed concentrations, maps of both predicted and observed concentration data show similar regional patterns (figs. 6 and 21), and summary statistics for concentrations in each water-resources region depict similar trends (tables 3 and 11). Whereas the nationwide median predicted concentration is 131 mg/L, median concentrations for water-resources regions varied and were highest in the Souris-Red-Rainy region (491 mg/L) and lowest in the New England (42 mg/L) and South Atlantic-Gulf regions (49 mg/L; table 11). Some of the regional patterns in predicted dissolved-solids concentrations include

- Widespread low concentrations, generally less than 100 mg/L, in much of the New England, South-Atlantic Gulf, and Pacific Northwest water-resources regions (fig. 21). Moderate dissolved-solids yields and higher runoff rates promote lower concentrations in these regions.
- Widespread moderate concentrations, generally between 100 and 500 mg/L, in much of the Great Lakes, Ohio, and Upper Mississippi River water-resources regions (fig. 21). Whereas dissolved-solids yields are generally high in these regions, runoff rates are also high, which helps moderate concentrations in these regions.
- Widespread higher concentrations, generally greater than 500 mg/L, in a belt of catchments that extends almost continuously from Canada to Mexico in the center of the country, cutting through the Souris-Red Rainy, Missouri, Arkansas-Red-White, Texas-Gulf, and Rio Grande water-resources regions (fig. 21). Although dissolved-solids yields are moderate to low in these areas, low runoff rates result in the high concentrations for these areas.

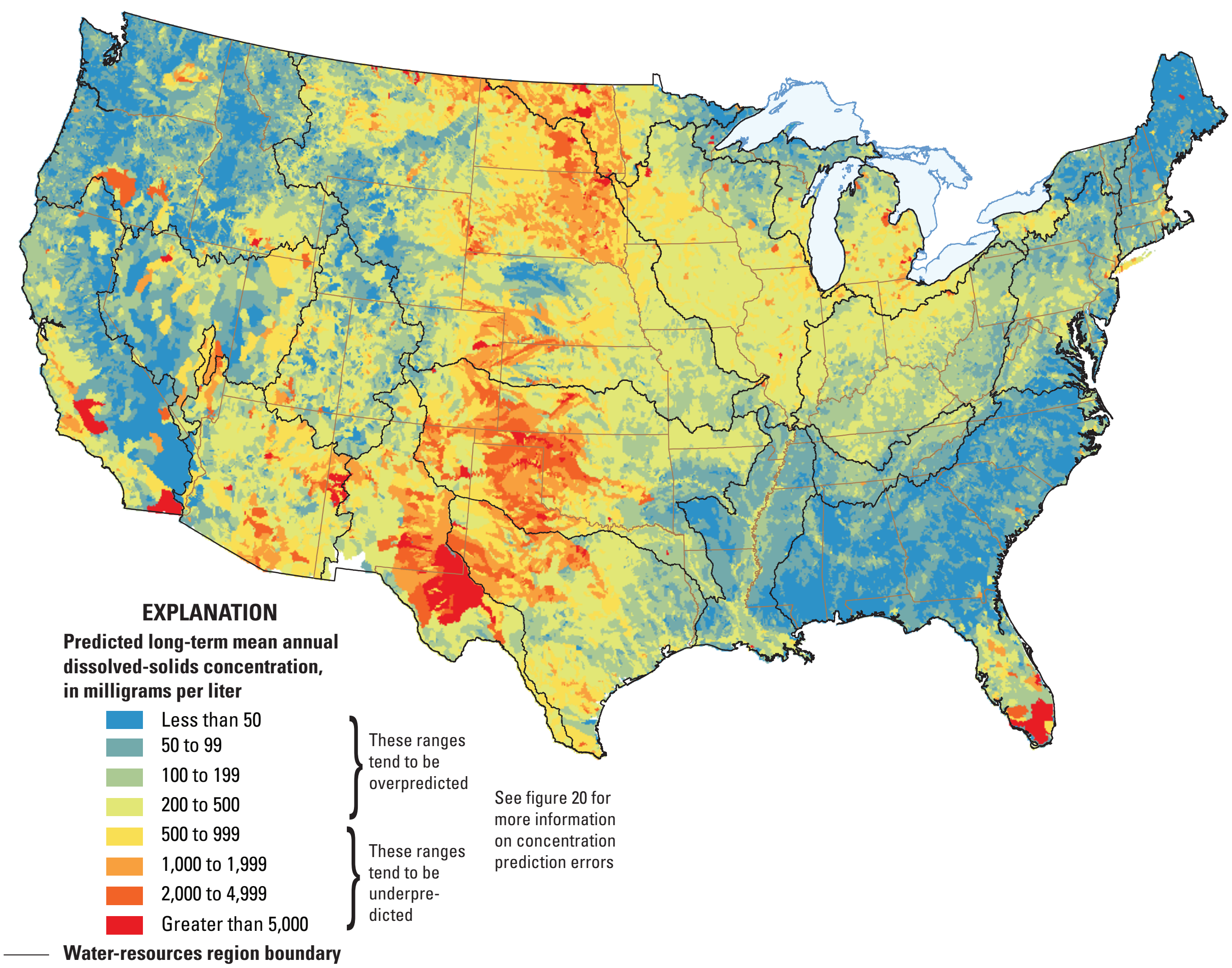

Figure 21. Map of the conterminous U.S. showing long-term mean annual flow-weighted dissolved-solids concentrations, predicted from the national SPARROW model of dissolved-solids transport.

Table 11. Percentile statistics of long-term mean annual flow-weighted concentrations predicted by the national SPARROW model of dissolved-solids transport, tabulated for reaches in water-resources regions of the conterminous United States.

[mg/L, milligrams per liter]

Water-resources region		Percentile statistic for predicted long-term mean annual flow-weighted concentration, mg/L[1]							Percent of reaches predicted to exceed 500 mg/L[2]
Code	Name	Minimum	10th	25th	Median	75th	90th	Maximum	
1	New England	<10	23	31	42	65	98	7,258	0.8
2	Mid-Atlantic	<10	36	59	98	137	205	4,343	1.1
3	South Atlantic-Gulf	<10	27	36	49	68	107	12,372	0.8
4	Great Lakes	<10	54	101	216	377	547	12,690	12.1
5	Ohio	11	97	131	176	243	334	10,021	1.9
6	Tennessee	<10	51	68	96	127	177	4,945	0.5
7	Upper Mississippi	<10	126	224	336	432	572	>15,000	14.8
8	Lower Mississippi	<10	42	56	74	108	185	>15,000	0.7
9	Souris-Red-Rainy	<10	33	143	491	871	1,296	>15,000	49.8
10	Missouri	<10	71	144	261	548	1,018	>15,000	27.6
11	Arkansas-White-Red	<10	98	171	273	910	2,161	>15,000	34.0
12	Texas-Gulf	<10	102	157	270	508	1,252	6,169	25.2
13	Rio Grande	<10	118	200	330	949	2,465	>15,000	36.5
14	Upper Colorado	<10	57	104	195	339	540	3,596	11.2
15	Lower Colorado	<10	80	159	298	529	1,058	>15,000	27.2
16	Great Basin	<10	37	74	152	313	576	6,670	13.8
17	Pacific Northwest	<10	27	43	68	108	188	>15,000	1.4
18	California	<10	27	51	97	184	354	>15,000	6.6
Conterminous United States		<10	35	61	131	289	597	>15,000	12.6

[1]Censored values of <10 and >15,000 are applied to predictions to constrain them within values near the minimum and maximum values of long-term mean annual flow-weighted concentration observed for the monitoring stations.

[2] U.S. Environmental Protection Agency secondary drinking water standard, nonenforcable.

The U.S. Environmental Protection Agency has established a secondary, nonenforceable standard of 500 mg/L for dissolved solids in drinking water, which provides a metric for evaluating predicted concentrations in the context of drinking water supplies. In such an evaluation, however, a few nuances should be kept in mind. In practice, the standard only applies to drinking water actually served to customers by water utilities, and does not apply to all stream reaches in the Nation nor to individual reaches when water is not withdrawn for use. The model predictions represent a flow-weighted mean annual concentration, and so if the predicted concentration for a reach is 500 mg/L, concentrations in the reach likely exceed this concentration for part of the year and are below it during other parts of the year. Likewise, concentrations in a reach with a predicted concentration of 600 mg/L may be less than the standard for part of the year, and concentrations in a reach with a predicted concentration of 400 mg/L may be greater than the standard for part of the year.

Predicted concentrations exceed the drinking-water standard of 500 mg/L in 12.6 percent of the Nation's stream reaches. Exceeding this standard, however, is more pronounced in certain water-resources regions. For example, about half of the reaches in the Souris-Red-Rainy region have concentrations predicted to exceed the standard, and between 25 and 37 percent of the reaches in the Missouri, Arkansas-White-Red, Texas-Gulf, Rio Grande, and Lower Colorado regions are predicted to exceed the standard. Seven of the water-resources regions are predicted to have less than 2 percent of their reaches exceed the standard. Note that the bias in predicted concentrations discussed above is minimal at the value for the standard (fig. 20).

Temporal Trends

Concentrations of dissolved solids can change over time and show long-term temporal trends as a result in temporal trends in stream discharge, source-loading rates, or both. Concentration-trend analyses examine changes in flow-adjusted concentrations because such adjustment removes the effects of trends in stream discharge and provides information on temporal trends in the source-loading rates. This study examined the spatial distribution of flow-adjusted concentrations observed at water-quality monitoring stations across the Nation, as well as the relations of those trends to source-contributions of dissolved solids predicted from the national SPARROW model of dissolved-solids transport.

In developing the long-term mean annual dissolved-solids load for each monitoring station in this study, the concentration model contained a long-term linear-trend component. The sign and significance of that trend term in the concentration model are indicative of the presence of long-term trends in flow-adjusted concentrations, and were therefore used in this analysis. Monitoring stations were categorized as having an increasing trend over time in concentrations if the model coefficient for the long-term trend component was both positive and significantly different than zero ($p<0.05$). Similarly, monitoring stations were categorized as having a decreasing trend over time in concentrations if the model coefficient for the long-term trend component was both negative and significantly different than zero ($p<0.05$). If the model coefficient for the long-term trend component was not significantly different than zero ($p>0.05$), then the monitoring station was categorized as not having a trend in concentrations over time.

For the 2,560 monitoring stations analyzed nationwide, long-term trends in flow-adjusted dissolved-solids concentrations, and therefore source-loading rates in the contributing drainage, were increasing over time at 23 percent of the stations, were decreasing over time at 18 percent of the stations, and were stable (not changing) over time at 59 percent of the stations (table 12). The time period for each station varies, but it is constrained between 1980 and 2009. Spatially, long-term trends show a strong regional pattern where from the western parts of the Great Plains to the West Coast, concentrations mostly are not changing or are decreasing, and from the eastern parts of the Great Plains to the East Coast, concentrations mostly are not changing or are increasing (fig. 22). For water-resources regions in the West (Rio Grande, Upper Colorado, Lower Colorado, Great Basin, Pacific Northwest, and California), between 23 and 42 percent of the monitoring stations showed decreasing trends whereas between 5 and 17 percent showed increasing trends (table 12). For water-resources regions in the East (New England, Mid-Atlantic, Great Lakes, Ohio, Tennessee, Upper Mississippi and Souris-Red-Rainy), between 24 and 62 percent of the monitoring stations showed increasing trends, whereas between 0 and 12 percent showed decreasing trends. For water-resources regions in the central part of the country (Missouri, Arkansas-Red-White, Texas-Gulf, and Lower Mississippi), the percentages of monitoring stations with increasing and decreasing trends were more similar to each other, compared to the percentages for water-resources regions in the East or West.

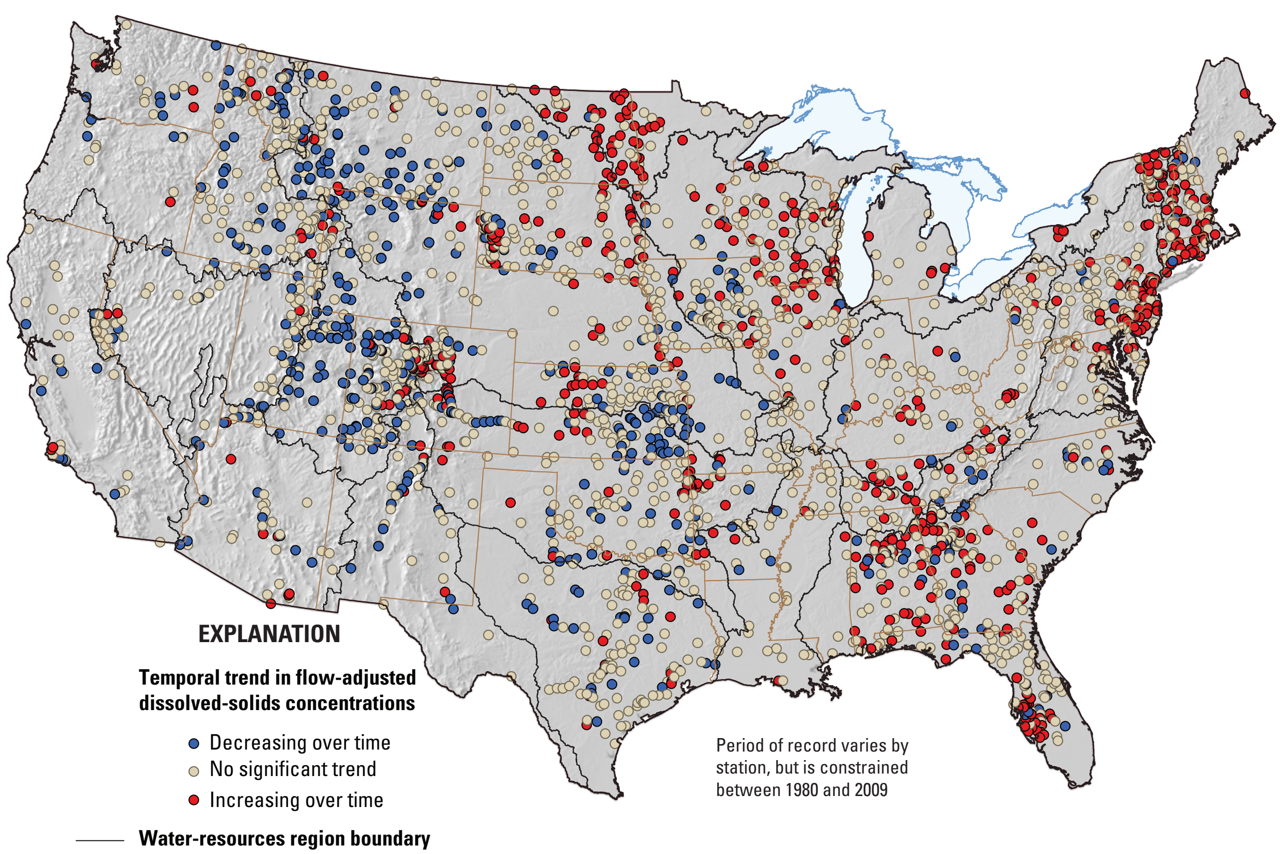

Figure 22. Map of the conterminous U.S. showing temporal trend in flow-adjusted dissolved-solids concentrations observed at 2,560 water-quality monitoring stations used to estimate the national SPARROW model of dissolved-solids transport.

Table 12. Percent of water-quality monitoring stations in water-resources regions in the conterminous United States that show an increasing trend, no trend, or decreasing temporal trend in flow-adjusted dissolved-solids concentrations.

[Note: Period of record varies by monitoring station, but is constrained between 1980 and 2009]

Water resources region		Number of water-quality monitoring stations	Percent of monitoring stations with indicated type of long-term trend in flow-adjusted concentrations		
Code	Name		Increasing	No trend	Decreasing
1	New England	88	55	40	6
2	Mid-Atlantic	175	39	59	2
3	South Atlantic-Gulf	314	35	54	12
4	Great Lakes	62	26	74	0
5	Ohio	104	24	69	7
6	Tennessee	44	25	66	9
7	Upper Mississippi	200	25	66	9
8	Lower Mississippi	46	13	78	9
9	Souris-Red-Rainy	61	62	36	2
10	Missouri	502	18	59	23
11	Arkansas-White-Red	257	18	58	25
12	Texas-Gulf	125	12	68	20
13	Rio Grande	40	10	55	35
14	Upper Colorado	186	12	45	42
15	Lower Colorado	47	17	55	28
16	Great Basin	82	5	72	23
17	Pacific Northwest	193	8	64	28
18	California	34	6	68	26
Conterminous United States		2,560	23	59	18

Long-term trends in flow-adjusted concentrations were further evaluated to determine if the three trend categories (increasing trends, no trends, decreasing trends) had any associations with dissolved-solids sources. This analysis merged the concentration-trend data for each monitoring station with predicted source-contribution data for the accumulated load in the stream reach associated with the monitoring station. To simplify the analysis, sources were grouped as follows: (1) geologic materials, (2) urban lands and road deicers, and (3) cultivated lands and pasture lands. The distribution of the source contribution of the accumulated dissolved-solids load in the reaches for stations within each trend group were compared to identify associations between trends and sources. Specifically, the source-contribution data from a given source group (regardless of trend type) were ranked. Then an analysis of variance test (ANOVA) followed by a Tukey multiple comparison analysis was performed on the ranks to identify whether the central tendency (median) of the source-contribution percentage was significantly different for the groups of monitoring stations with increasing trends, no trends, and decreasing trends.

This analysis should be considered a reconnaissance for two reasons. First, although data from the monitoring stations was constrained to the period 1980–2009, the actual period of record for each station varied. Second, some of the monitoring stations have drainages nested within those of other monitoring stations, and consequently the observations in this analysis are not entirely independent. For these reasons, results from this analysis should be considered to provide reconnaissance information on associations between trends and sources, but not definitive cause and effect relations.

Results from this analysis indicate that compared to monitoring stations with no trends or decreasing trends, stations with increasing trends are associated with a smaller percentage of the accumulated dissolved-solids load originating from geologic sources and a greater percentage originating from urban lands and road deicers (fig. 23). Conversely, when compared to stations with increasing trends or no trends, stations with decreasing trends have a larger percentage of the accumulated dissolved-solids load originating from geologic sources and a smaller percentage originating from urban lands and road deicers (fig. 23). Stations with decreasing trends also have larger percentages of accumulated dissolved-solids load from cultivated lands and pasture lands, as compared to stations with increasing trends or no trends.

Although this analysis is a reconnaissance, results from it are consistent with those from other studies. For example, the association of increasing temporal trends to larger percentages of the accumulated load originating from urban lands and road deicers is consistent with increases in road deicer usage from 1940–2009 that are shown in figure 3*B* (Kostick 1992, Kostick 1993–2009), and is also consistent with the 5-fold increase that has been observed for urban lands in the Nation between 1950 and 2000 (Brown and others, 2005). The association of increasing temporal trends to larger percentages of the load originating from urban lands and road deicers is also consistent with results from several recent studies that have similarly found increasing temporal trends in specific conductance or chloride concentrations in streams, lakes, or groundwater. For example, Mullaney and others (2009) found increasing temporal trends in chloride loads for 1991–2004 in several urban streams in northern parts of the Nation. They attributed the trends to a variety of factors, including changes in the application of deicing salt, the expansion of road networks and impervious areas that require deicing, increases in the number of septic systems, increases in the volume of wastewater discharge, and the arrival of saline groundwater plumes from landsfills and salt-storage areas over time. Kaushal and others (2005) observed strong increases in the baseline concentration of chloride in six rural watersheds with low density of roadways in Marylands, New York, and New Hampshire over the past 30 years, and attributed those increases to road deicers. Godwin and others (2002) found that chloride concentrations in the Mohawk River, New York, increased 243 percent from 1952 to 1998, and similarly sodium concentrations increased 130 percent. They attributed the increase largely to the application of road deicers on roads in the watershed. Novotny and others (2008) investigated 13 lakes in the Twin Cities Metropolitan Area of Minnesota (TCMA), and found sodium and chloride concentrations in the lakes were 10 and 25 times higher, respectively, than in other nonurban lakes in the region. Their regional analysis of historical water quality records of 38 lakes in the TCMA showed increases in lake salinity from 1984 to 2005 that were highly correlated with the amount of rock salt purchased by the State of Minnesota.

The association between negative trends and larger percentages of the accumulated load originating from geologic materials may simply be a reflection of the lack of urban lands and road deicers where the percentage of the load from geologic materials is large. The association between negative trends to larger percentages of the accumulated load originating from cultivated lands or pasture lands may result if (1) the areas of those lands have diminished over time, (2) if dissolved-solids sources in the soils of those lands have been depleted over time by agricultural activities such as irrigation, or (3) if salinity-control programs have mitigated effects on dissolved-solids loads from agricultural activities. This explanation is supported by the spatial predominance of decreasing trends in concentrations for the West, where irrigation is a common practice and where catchments with predominant sources of cultivated lands and pasture lands tend to occur (fig. 10). In addition, Anning (2007) found that dissolved-solids concentrations were decreasing over time in many streams of the Upper Colorado River water-resources region; however, the rate of decrease was greater downstream from salinity-control projects than upstream of the projects, implying their effectiveness in dissolved-solids control. Leib and Bauch (2008) also found downward trends in dissolved-solids concentrations in the Upper Colorado River water-resources region. They found dissolved solids may have been affected by several factors, including (1) an increase in channel stability that reduced loading by dissolution of bank and bottom materials, (2) a decrease in groundwater discharge to streams that reduced loads originating from geologic sources and from irrigation seepage, and (3) conversion of irrigated lands to urban lands that reduced loads originating from irrigation seepage.

Summary of Findings and Potential for Model Improvement

This study improved the understanding of dissolved-solids conditions in streams of the conterminous United States, including a characterization of the spatial patterns of dissolved-solids sources, loads, yields, and concentrations, and an understanding of the natural and human factors affecting these conditions. Information on nationwide dissolved-solids conditions was gained by developing a SPARROW model for dissolved-solids transport, a GIS-based contaminant-transport model that integrates water-quality monitoring data with watershed attributes.

Model predictions show that weathering products from geologic materials provided 71.4 percent of the dissolved solids delivered to the Nation's streams. Human sources of dissolved solids provided the remaining 28.6 percent delivered to the Nation's streams—13.9 percent from road deicers, 9.6 percent from cultivated lands and pasture lands, and 5.1 percent from urban lands. Road deicers were more frequently a

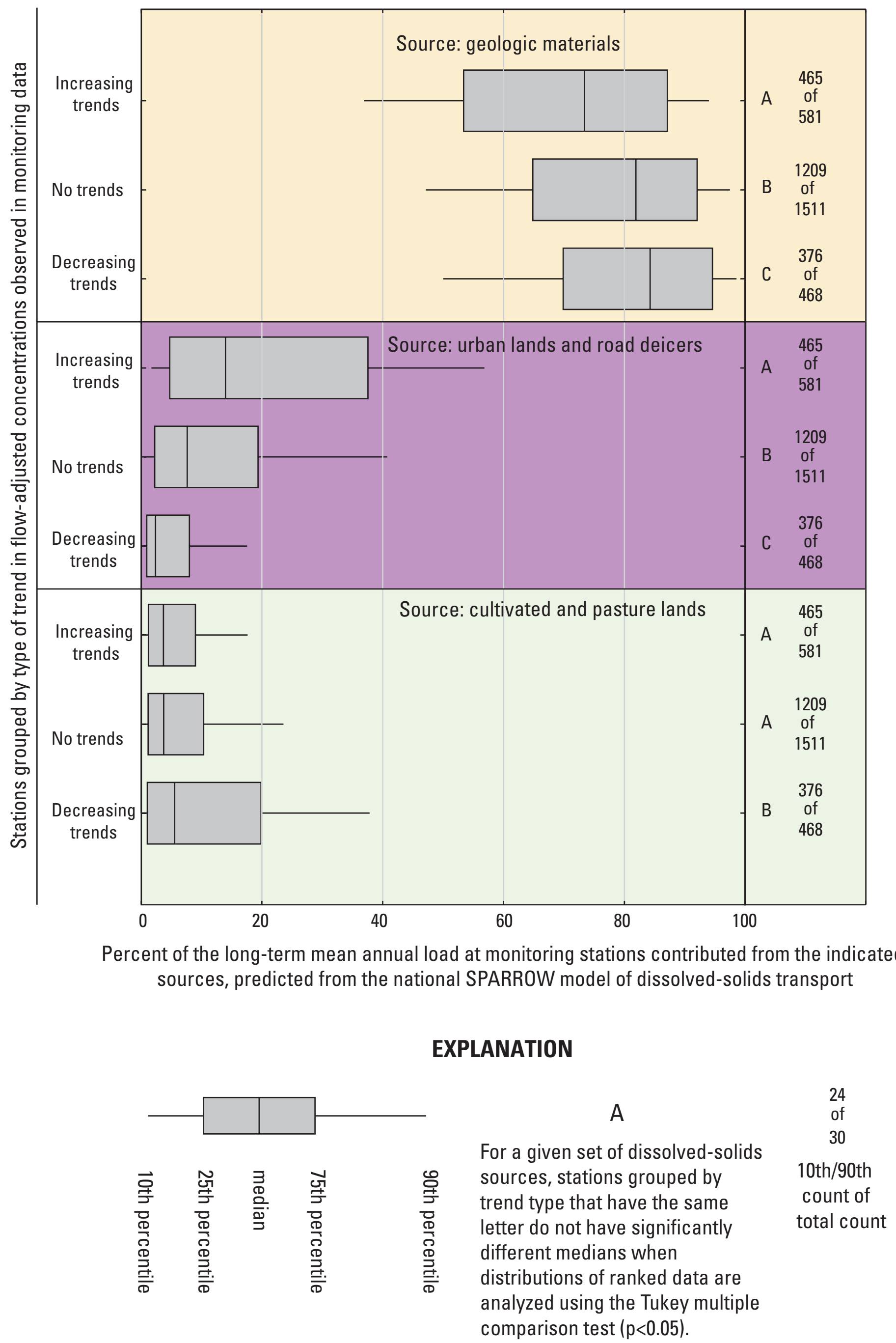

Figure 23. Box plots showing percent of the predicted total long-term mean annual dissolved-solids load from geologic materials, urban land and road deicers, or cultivated and pasture lands, for monitoring stations with increasing, decreasing, or no temporal trend observed in flow-adjusted concentrations.

significant contributor of dissolved solids in northeastern streams than elsewhere in the country; whereas, cultivated lands and pasture lands were a more significant contributor in western streams.

Incremental-catchment yields showed significant variability across the Nation's water-resources regions, and were generally largest in the Great Lakes (median of 81 (Mt/yr)/km^2), Ohio (median of 78 (Mt/yr)/km^2) and Upper Mississippi regions (median of 74 (Mt/yr)/km^2), and lowest in the Lower Colorado (median of 3 (Mt/yr)/km^2), Rio Grande (median of 5 (Mt/yr)/km^2), and Great Basin regions (median of 8 (Mt/yr)/km^2). Dissolved-solids loads yielded from most incremental basins to the stream-reach network were transported, without losses, to either the ocean or to one of the large streams flowing along the U.S. international boundary. Exceptions to this include streams in the southwestern part of the Nation where loads were diminished as a result of streamflow diversion or possibly streambed infiltration.

The nationwide median predicted concentrations for reaches is 131 mg/L; however, median concentrations for water-resources regions varied and were highest in the Souris-Red-Rainy region (491 mg/L), and they were lowest in the New Englands (42 mg/L) and South Atlantic-Gulf regions (49 mg/L). For the 2,560 monitoring stations used in this study, observed long-term temporal trends in concentrations increased over time at 23 percent of the stations, decreased at 18 percent of the stations, and did not change over time at 59 percent of the stations. Whereas increasing trends in concentrations at monitoring stations were largely associated with increased source loading from urban lands and road deicers, decreasing trends in concentrations were largely associated with decreased source-loading from both cultivated lands and pasture lands.

Several enhancements to the national SPARROW model of dissolved-solids transport potentially would allow for an even better understanding of the sources and transport of dissolved solids than the current model. The scope of work associated for such enhancements, however, was beyond the resources and timelines of this study. Future studies should consider improvements in the following areas:

- **Monitoring data density.—**The densities of monitoring stations used for estimating the national SPARROW model of dissolved-solids transport are variable across the Nation; however, the densities in several western and midwestern drainages are much lower than for other parts of the Nation. Increased monitoring in those areas would improve the representation of the major sources and lands-to-water transport factors occurring in those areas.

- **Geologic sources.—**Dissolved solids originating from subsurface sources that are delivered to streams in groundwater discharge are not well represented in the current model. Without representation, this source was effectively lumped with the surficial lithology. Exploratory models showed that the variable representing saline groundwater presence at depths less than 500 feet was significant. Analysis of residuals and a cursory review of information on saline springs, however, suggest this source variable could be improved if it reflected information about whether the groundwater actually discharges to streams, at what volumetric rate, and at what concentration.

- **Fossil fuel extraction.—**Dissolved solids originating from sources related to fossil fuel extraction are not contained in the current model. Exploratory models indicated that the top 100 coalbed-methane mines were locally significant sources. In terms of the percent delivered to the Nation's streams, however, they were negligible. For further analysis of this source, a regional model would be more appropriate. The oil and gas source variable coefficients were not significant in exploratory models. Similar to the suggestion for saline groundwater, representation of oil and gas wells as a source could be improved by using estimates of the dissolved solids yielded from individual wells rather than representation of their occurrence. Concern about the effects of hydraulic fracturing of unconventional oil and gas deposits has recently grown as this extraction technique is used more frequently. As documentation of hydraulic fracturing improves, a variable could be developed to help characterize its effect on dissolved solids in streams.

- **Road deicers.—**Results from the current model show the significance of road deicers as a source of dissolved solids, especially for streams in the northeastern part of the Nation. Knowledge of the effects of this source on streams could be refined through a more focused, regional SPARROW model of chloride in northeastern streams, and through improvement in the spatial resolution for deicer application-rate estimates.

- **Stream representation.—**Transport of dissolved solids in streams is affected by streamflow diversion and streamflow regime, especially those in the southwestern part of the Nation. Improving representation of stream diversions and return flows in the hydrologic network would improve SPARROW models for dissolved solids and other constituents. In addition, including reach-level information regarding the perennial or ephemeral status of streamflow would also improve the model.

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Appendixes

Appendix 1. Station Information

A Microsoft Excel spreadsheet containing water-quality monitoring station information used in the national SPARROW model of dissolved-solids transport and related analyses is available for download from the Web page for this report, http://pubs.usgs.gov/sir/2014/5012/. (547 KB)

Appendix 2. Watershed Attributes

A Microsoft Excel spreadsheet containing watershed-attribute data used in the national SPARROW model of dissolved-solids transport is available for download from the Web page for this report, http://pubs.usgs.gov/sir/2014/5012/. (61 MB)

Appendix 3. Predictions

A Microsoft Excel spreadsheet containing the prediction file output from the national SPARROW model of dissolved-solids transport is available for download from the Web page for this report, http://pubs.usgs.gov/sir/2014/5012/. (62 MB)

Appendix 4. Network Modifications

A list of coding modifications the the the digital hydrologic network attributes is given in a Microsoft Word document that is available for download from the Web page for this report, http://pubs.usgs.gov/sir/2014/5012/. (16 KB)

Appendix 5. Watershed-Attribute Portfolio (shown on following pages)

Descriptions and maps showing occurrences of the most important watershed attributes investigated in development of the national SPARROW model of dissolved-solids transport.

Appendix 5. Watershed-Attribute Portfolio

Attribute name: Surficial lithology

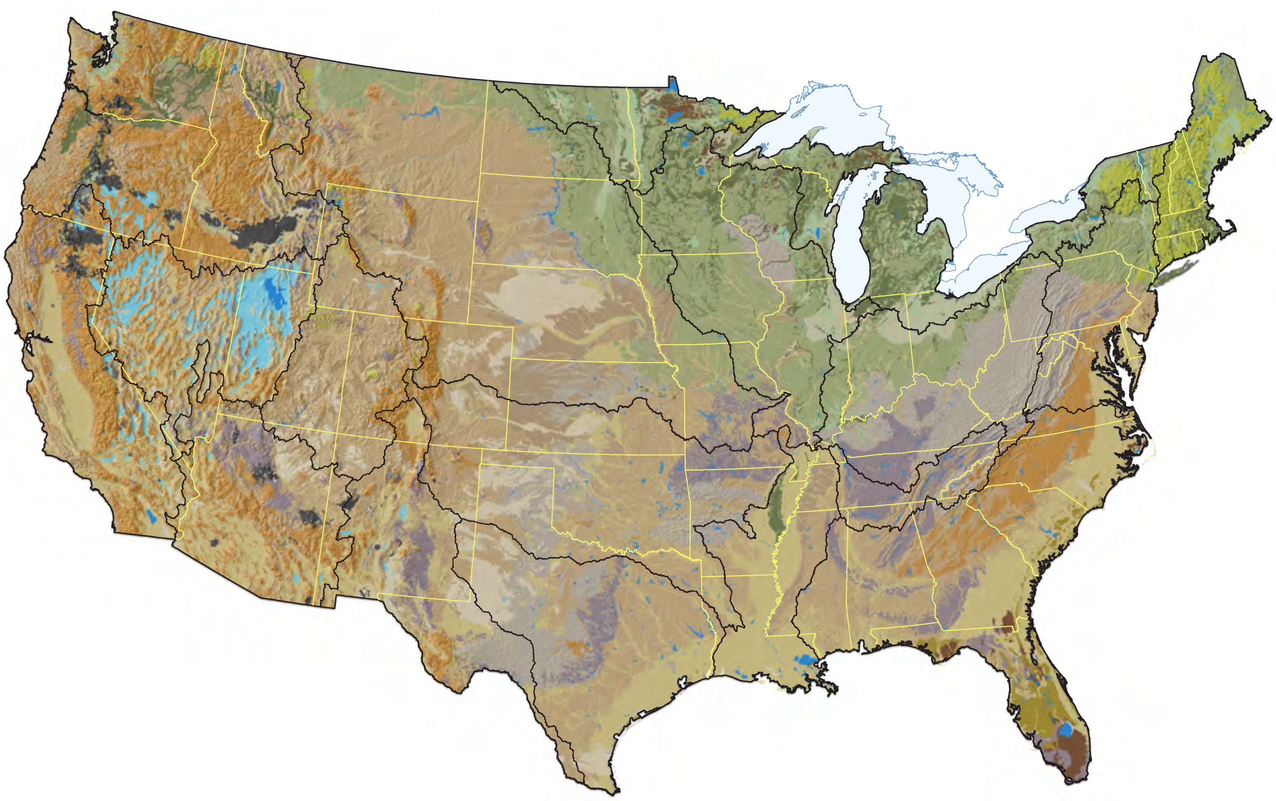
Description: This attribute represents the surficial lithology of the conterminous United States..

Units: square kilometers

Data source: The attribute was derived from U.S Geological Survey Scientific Investigations Map 3126, “Terrestrial Ecosystems–Surficial Lithology of the Conterminous United States” (Cress and others, 2010). Digital data accessed from http://rmgsc.cr.usgs.gov/outgoing/ecosystems/USdata/ on March 2, 2011.

Processing synopsis: Source image data was converted to a grid. GIS tools were then used to calculate the area of individual lithologic units by catchment.

Map: Distribution of surficial lithologic units from original data.



EXPLANATION

Carbonate residual material
Non carbonate residual material
Alkaline instusive volcanic rock
Silicic residual material
Extrusive volcanic rock
Colluvial sediment
Glacial till, clayey
Glacial till, loamy
Glacial till, coarse-textured
Glacial outwash and glacial lake sediment, coarse-textured
Glacial lake sediment, fine-textured
Eolian sediment, coarse-textured, sand dunes
Eolian sediment, find-textured, glacial loess
Saline lake sediment
Alluvium and fine-textured coastal zone sediment
Coastal zone sediment, coarse-textured
Hydric, peat and muck
Water (undifferentiated submerged lithologies)

Water-resources region boundary

Attribute name: Subsurface evaporite deposits

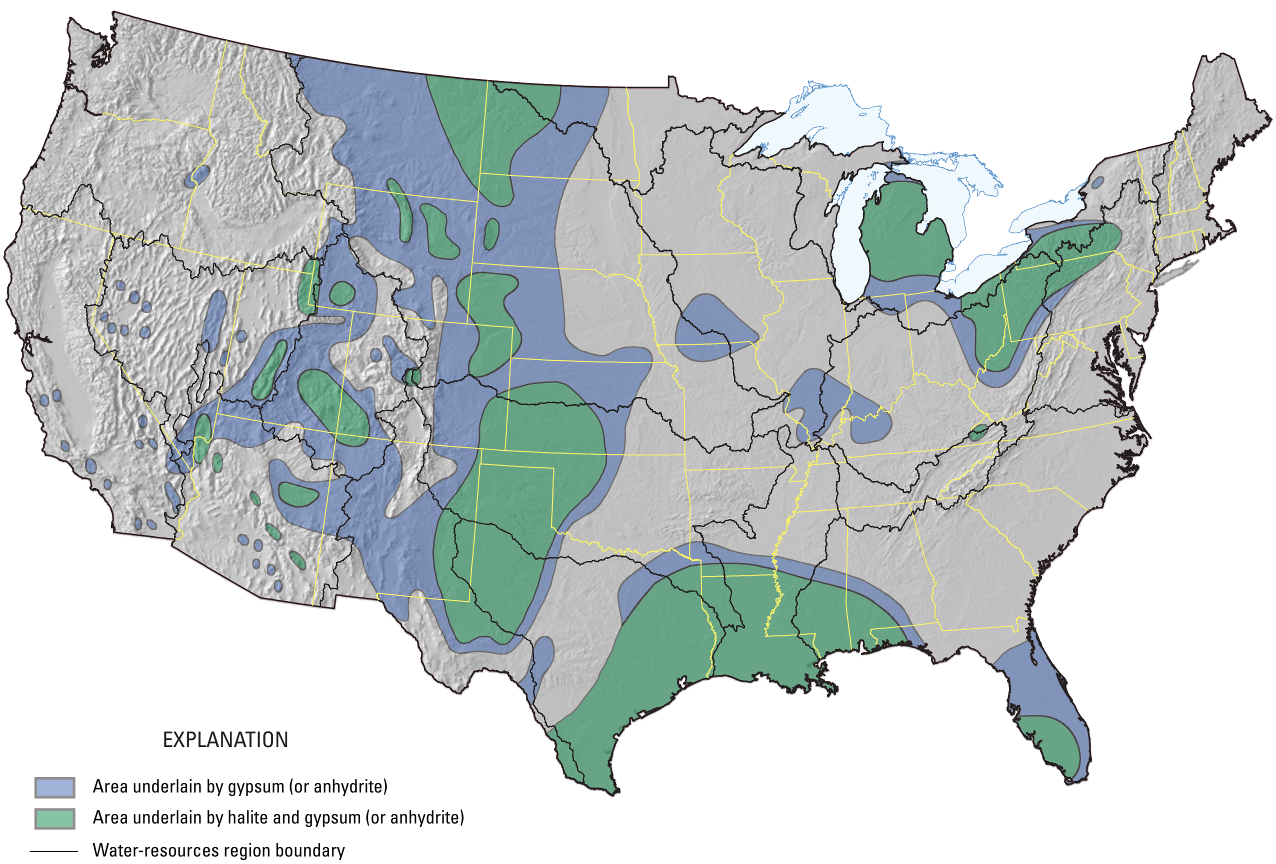
Description: This attribute represents subsurface evaporite deposits of the conterminous United States..

Units: square kilometers

Data source: The attribute was derived from "Evaporite-karst problems and studies in the USA" by Kenneth S. Johnson (Johnson, 2008). Report accessed from http://www.springerlink.com/content/754qn37m17084218/ on February 18, 2011.

Processing synopsis: Source map was rectified to state boundaries. Subsurface evaporite deposit polygons were digitized from the rectified map. GIS tools were then used to calculate the area of subsurface evaporite deposits by type and catchment.

Map: Distribution of subsurface evaporite deposits from original data.



Attribute name: Presence of saline groundwater

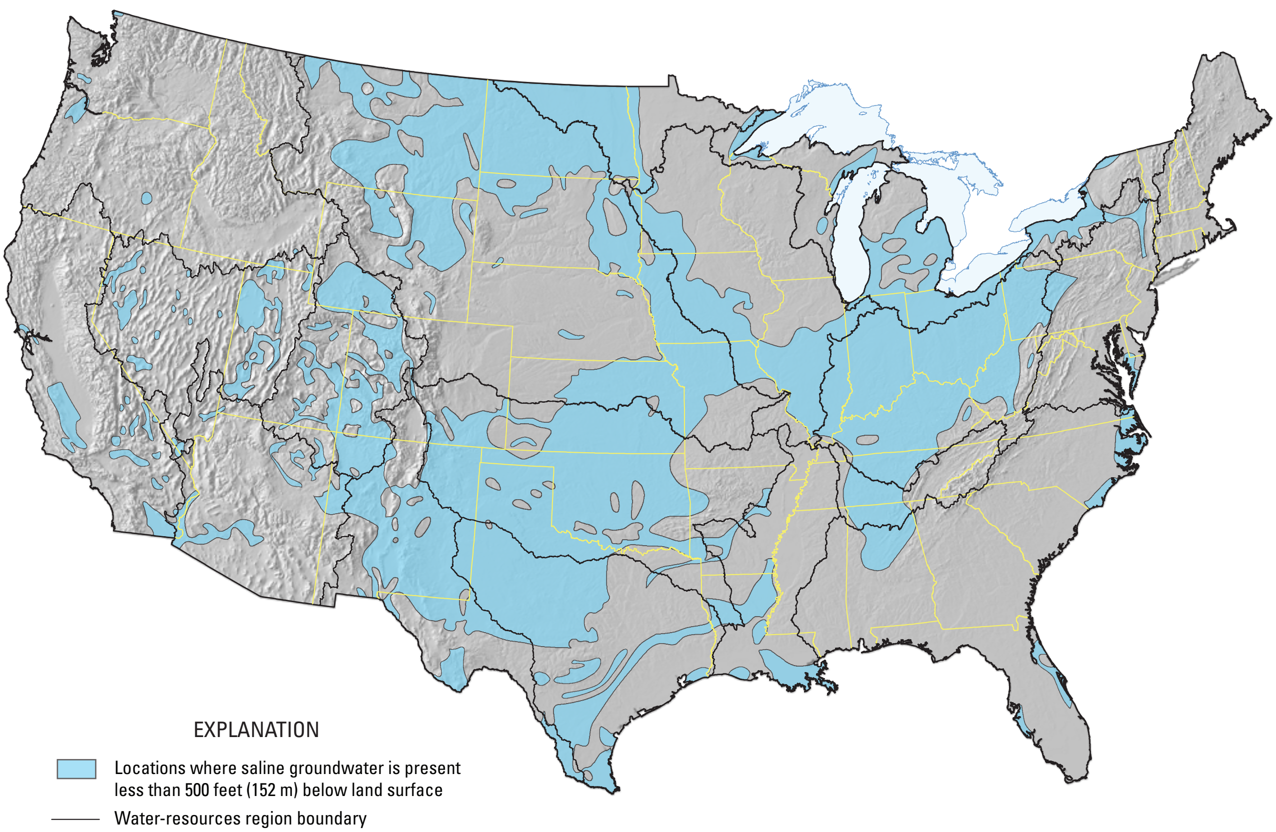
Description: This attribute represents the presence of saline groundwater less than 500 feet (152 m) below land surface in the conterminous United States. “Saline” for this attribute is defined as water with dissolved-solids concentrations greater than 1,000 mg/L.

Units: square kilometers

Data source: The attribute was derived from U.S Geological Survey Fact Sheet 075-03, “Desalination of Ground Water: Earth Science Perspectives ” (Alley, 2003). Fact sheet accessed from http://pubs.usgs.gov/fs/fs075-03/ on January 4, 2012.

Processing synopsis: Source vector data were georeferenced to United States boundary. Georeference linework was converted to polygons. GIS tools were then used to calculate the area of saline groundwater less than 500 feet (152 m) below land surface by catchment.

Map: Locations where saline groundwater is present at less than 500 feet (152 m) below land surface from original data.



Attribute name: Fossil fuel extraction (oil and gas wells)

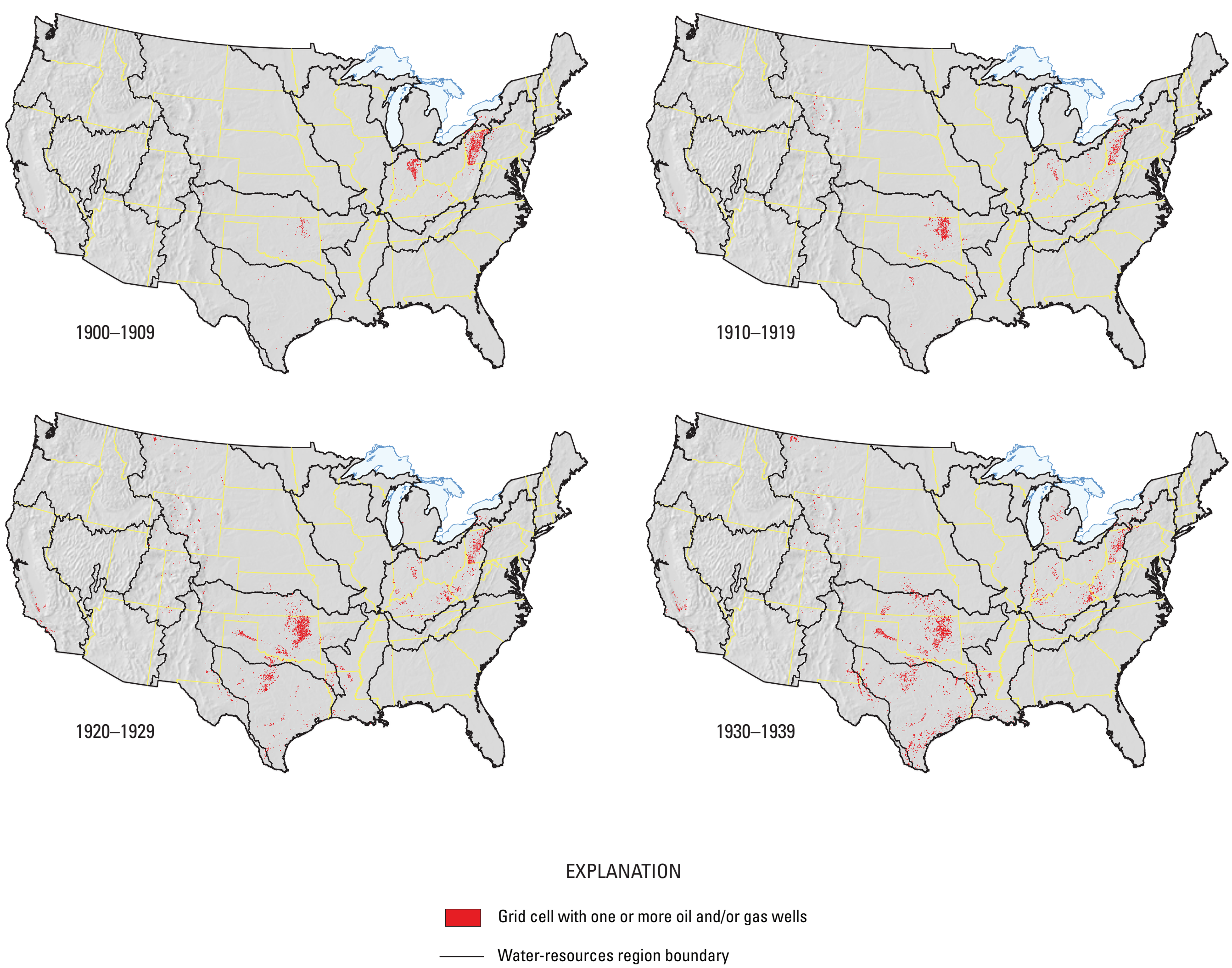
Description: This attribute represents historical oil and gas exploration and prodution (1900–2005) in the conterminous United States.

Units: square kilometers

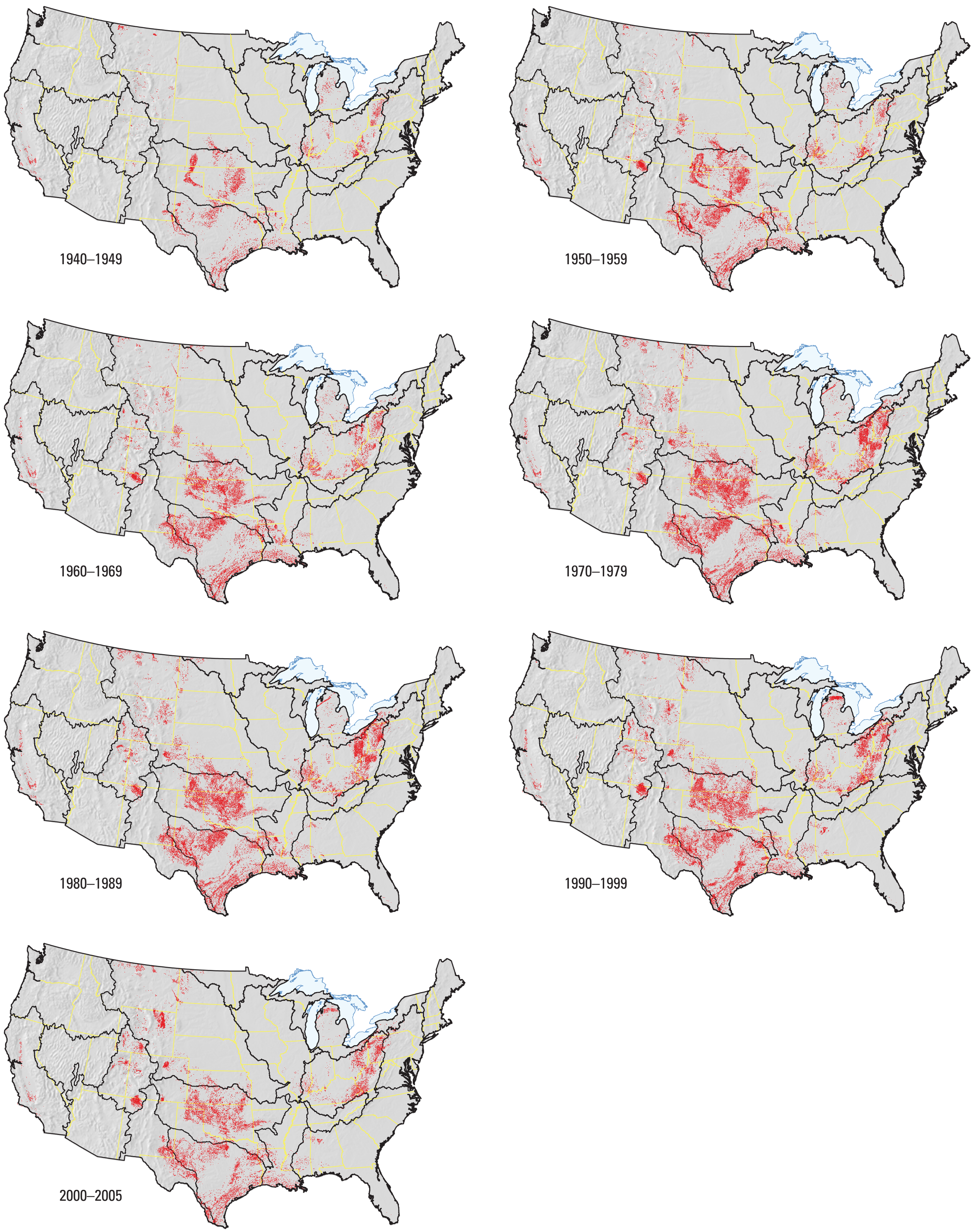
Data source: The attribute was derived from U.S Geological Survey Digital Data Series DDS-69-Q, “Areas of Historical Oil and Gas Exploration and Production in the United States” (Biewick, 2008). Digital data accessed from http://pubs.usgs.gov/dds/dds-069/dds-069-q/text/cover.htm on August 30, 2011.

Processing synopsis: Source data were obtained and GIS tools were then used to calculate the total area of 1 square-kilometer grid cells containing 1 or more oil and /or gas wells by decade and catchment.

Map: Distribution of 1 square-kilometer grid cells with one or more oil and/or gas wells from original data, 1900–2005.



Attribute name: Fossil fuel extraction (oil and gas wells)–Continued



Attribute name: Fossil fuel extraction (shale plays, coalbed-methane fields, coalbed-methane mines)

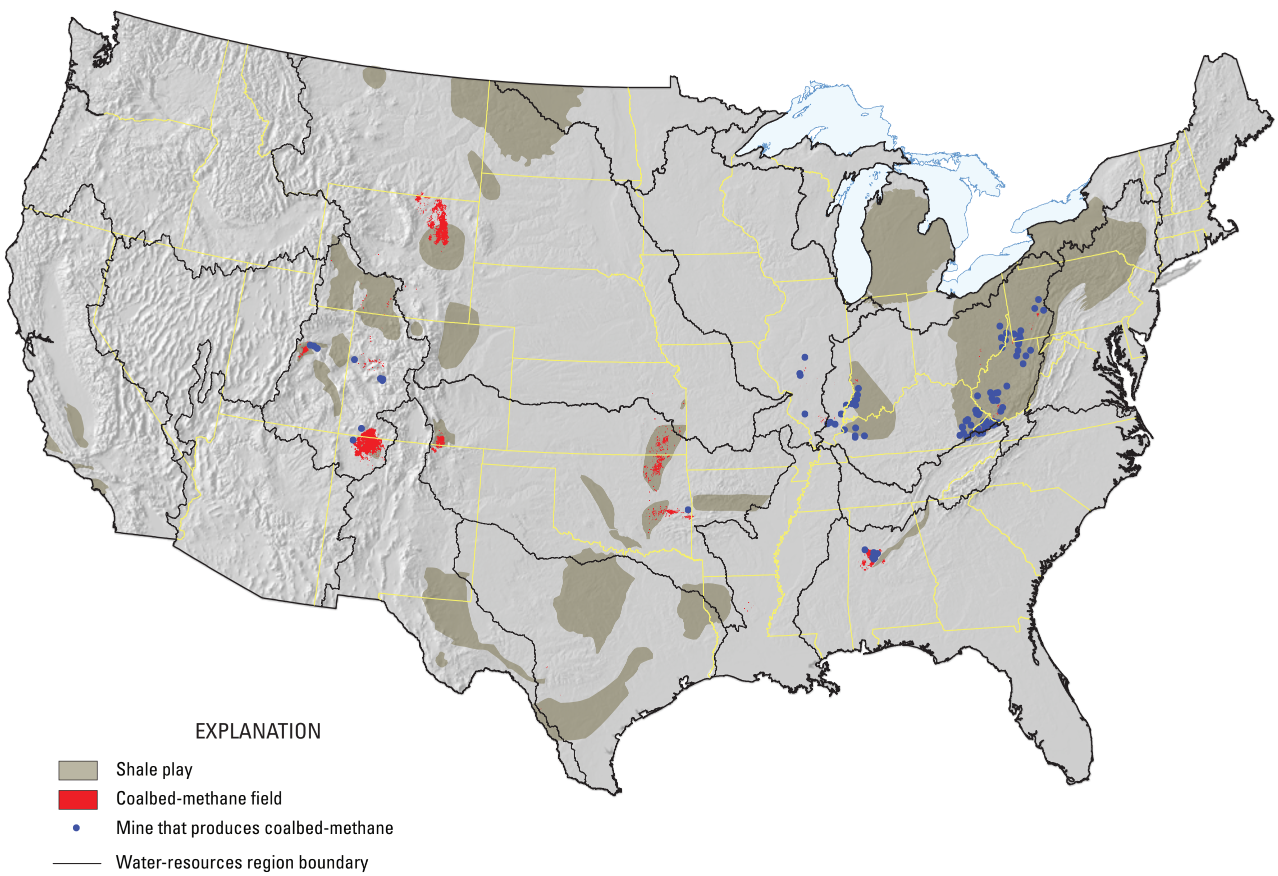
Description: These attributes represent the locations of shale plays, coalbed-methane fields, and the top 100 gassy coal mines (mines that produce coalbed-methane) in the conterminous United States.

Units: square kilometers (shale plays and coalbed-methane fields), count (gassy coal mines)

Data source: The shale plays, coalbed-methane fields, and gassy coal mines attributes were derived from data obtained from the U.S. Energy Information Administration (U.S. Energy Information Administration, 2011). Digital data accessed from http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm on May 7, 2011 (shale plays) and August 29, 2011 (coalbed-methane fields and gassy coal mines) .

Processing synopsis: GIS tools were used to calculate the area of shale plays, the area of coalbed-methane fields, and the number of gassy coal mines by catchment.

Map: Distribution of shale plays, coalbed-methane fields, and gassy coal mines from original data.



Attribute name: Land use and land cover

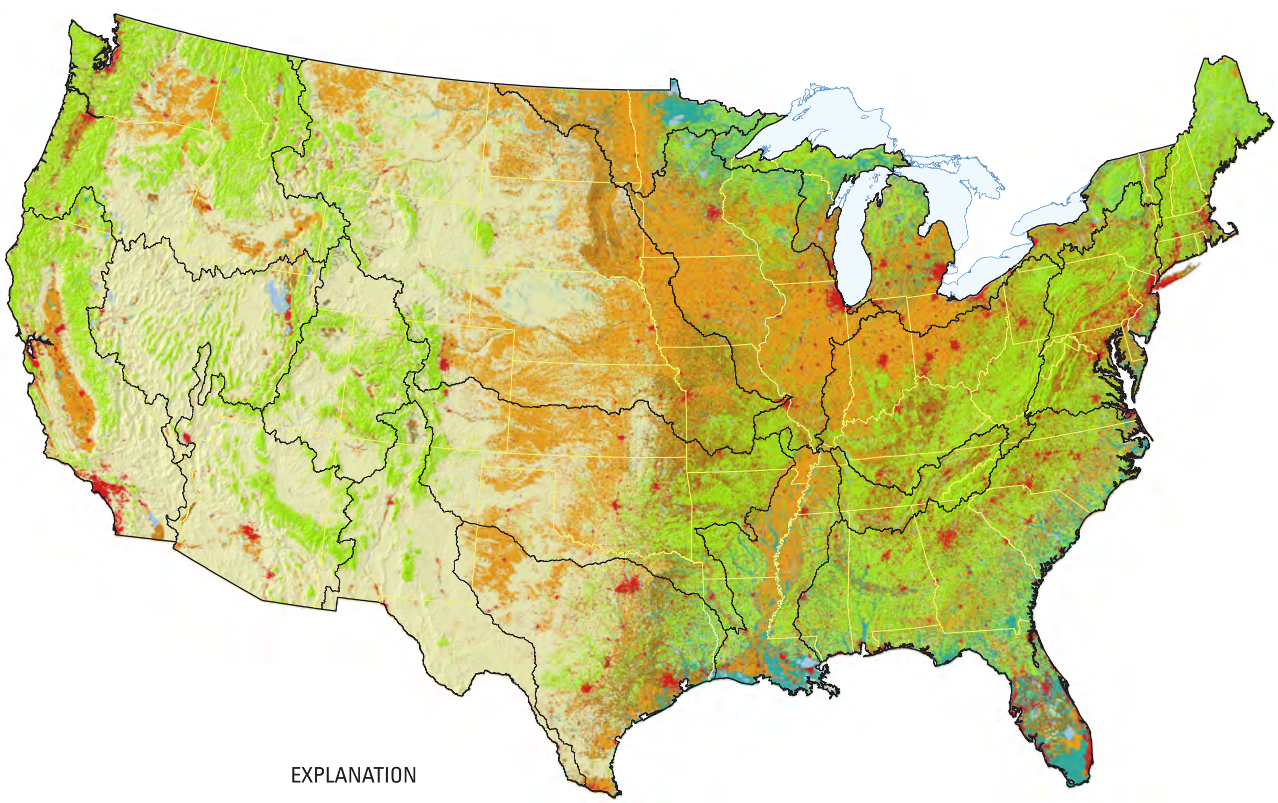
Description: This attribute represents the land use and land cover of the conterminous United States.

Units: square kilometers

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-15, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: NLCD 2001 Land Use and Land Cover” (Wieczorek, M.E., and LaMotte, A.E., 2010g). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_nlcd01.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Distribution of land use and land cover from original data.



EXPLANATION

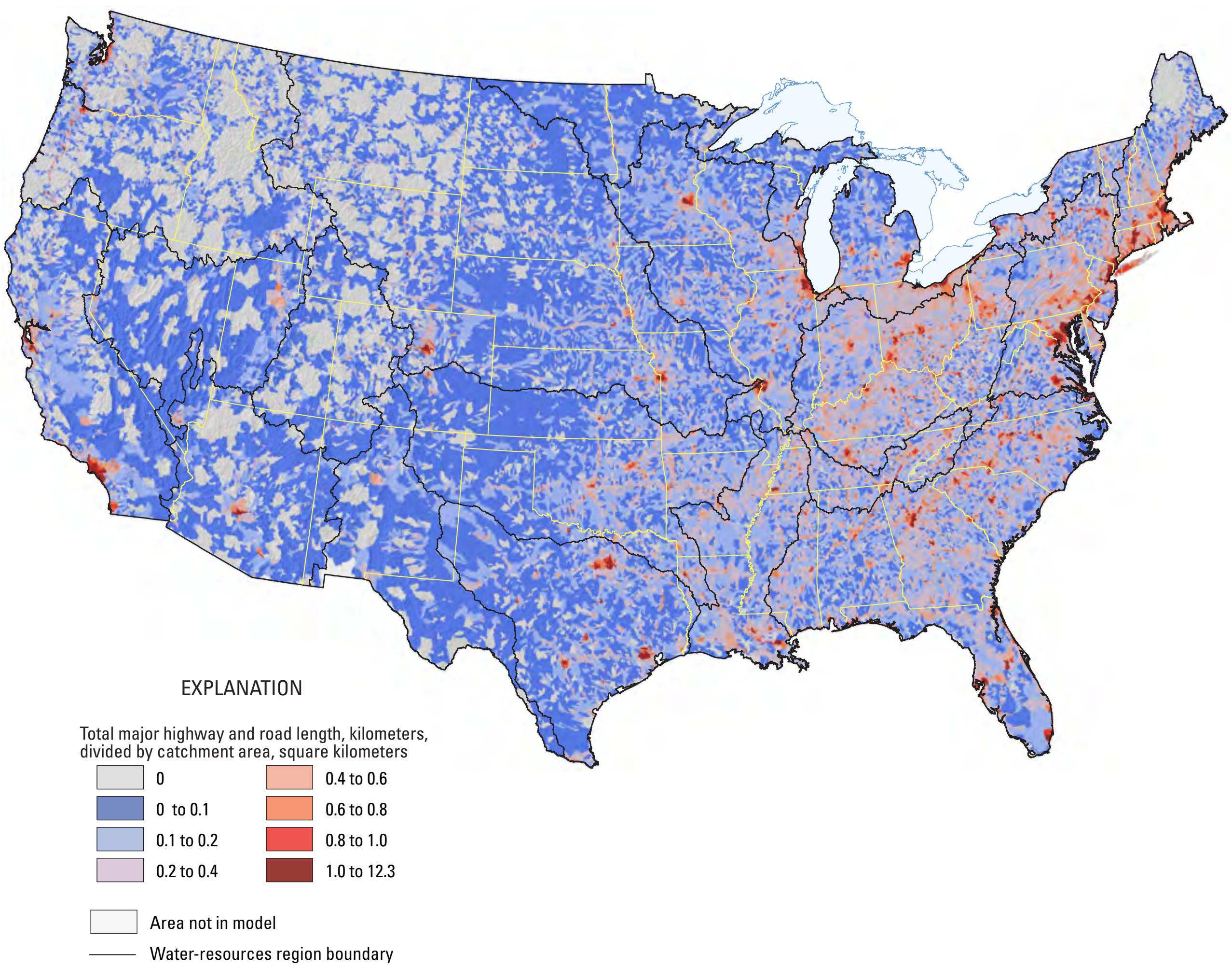
Land use and land cover class descriptions—number (21) is land use/land cover code

- Urban: open space (21), low intensity (22), medium intensity (23), high intensity (24)
- Cultivated crops (82)
- Pasture/hay (81)
- Deciduous forest (41), evergreen forest (42), mixed forest (43)
- Barren land (31), shrub/scrub (52), grassland/herbaceous (71)
- Woody wetlands (90), emergent herbaceous wetlands (95)
- Water

—— Water-resources region boundary

Attribute name: Road deicer (total length of major highways and roads)

Description:	This attribute represents the total length of major highways and roads for the conterminous United States.
Units:	kilometers
Data source:	The dataset was derived from ESRI Data & Maps: StreetMap, 2008 North America.
Processing synopsis:	GIS tools were used to calculate total length of major highways and roads by catchment.
Map:	Model catchments shaded by the total length of major highways and roads divided by catchment area.



Attribute name: Road deicers (snow days)

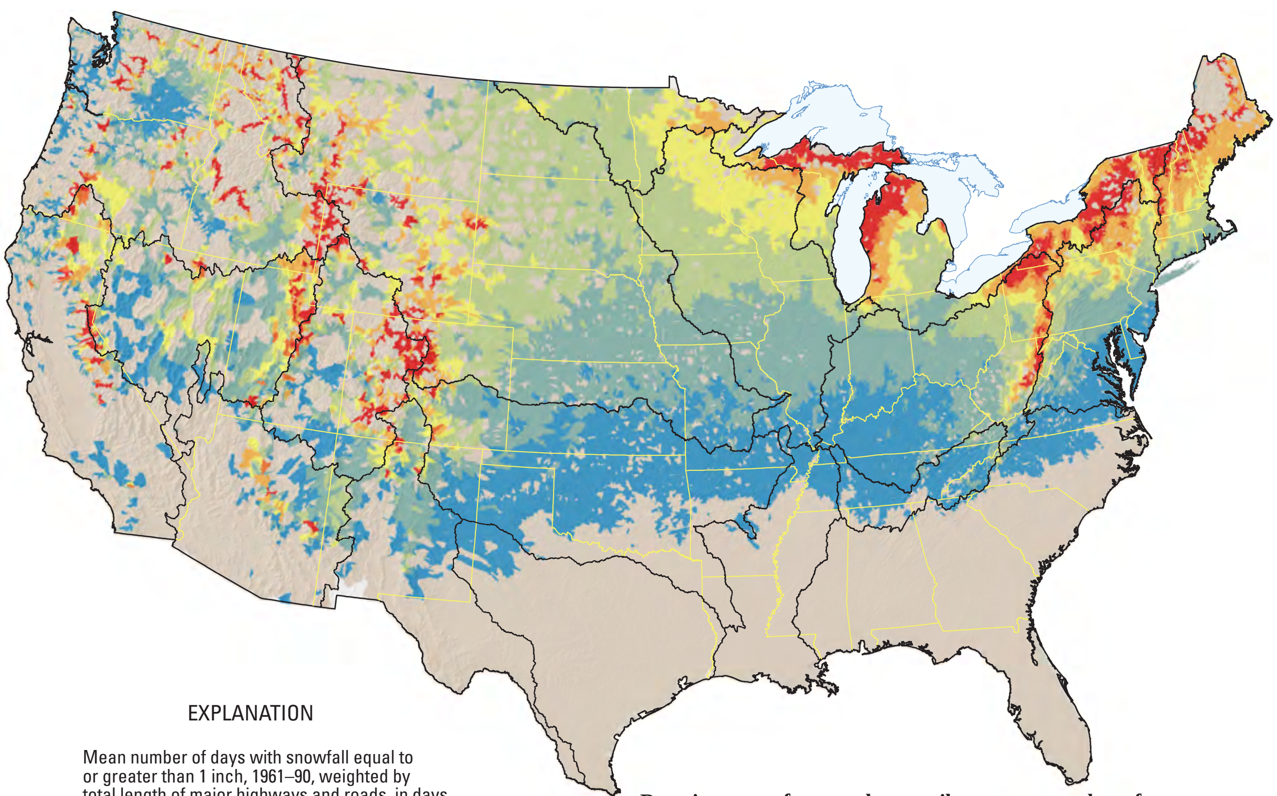
Description: This attribute represents the mean number of days per year with snowfall equal to or greater than 1 inch, 1961–90, weighted by total length of major highways and roads, in the conterminous United States.

Units: days

Data source: The dataset was derived from snowfall data obtained from the National Climatic Data Center (National Climatic Data Center, 2010) Digital data accessed from http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl?directive=order_details&subrnum=&region=Lower%2048%20States&filename=snow31b on December 6, 2010.

Processing synopsis: The attribute containing the mean number of days with snowfall equal to or greater than 1 inch, 1961–90, in the source dataset was defined as data ranges. To allow for computations, this attribute was assigned a discrete number of snowdays (see table below). GIS tools were used to assign a snowday value to the major highway and road data segments that had been split along catchment boundaries. To calculate the mean number of days with snowfall equal to or greater than 1 inch, weighted by the total length of major highways and roads, each highway/road segment length was multiplied by the corresponding value of snowdays. This product was summed for all segments within the catchment, and then divided by the total length of highways/roads in the catchment. Note that mean number of snowdays for each catchment were weighted because some catchments had no major highways or roads, while others had variable numbers of snow days for different parts of the catchment.

Map: Model catchments shaded by the average number of days with snowfall equal to or greater than 1 inch, 1961–90, weighted by total length of major highways and roads.



Reassignment of source data attribute mean number of days with snowfall equal to or greater than 1 inch, 1961–90

Original source data ranges (categorical)	Assigned number of snowdays (discrete)
< 0.5	0
0.5 to 2.4	1
2.4 to 5.4	4
5.5 to 10.4	8
10.5 to 15.4	13
15.5 to 20.4	18
20.5 to 30.4	25
30.5 to 60.4	45
> 60.4	65

Attribute name: Road deicers (State-specific deicer application weight)

Description: This attribute represents State-specific deicer application weight for the conterminous United States.

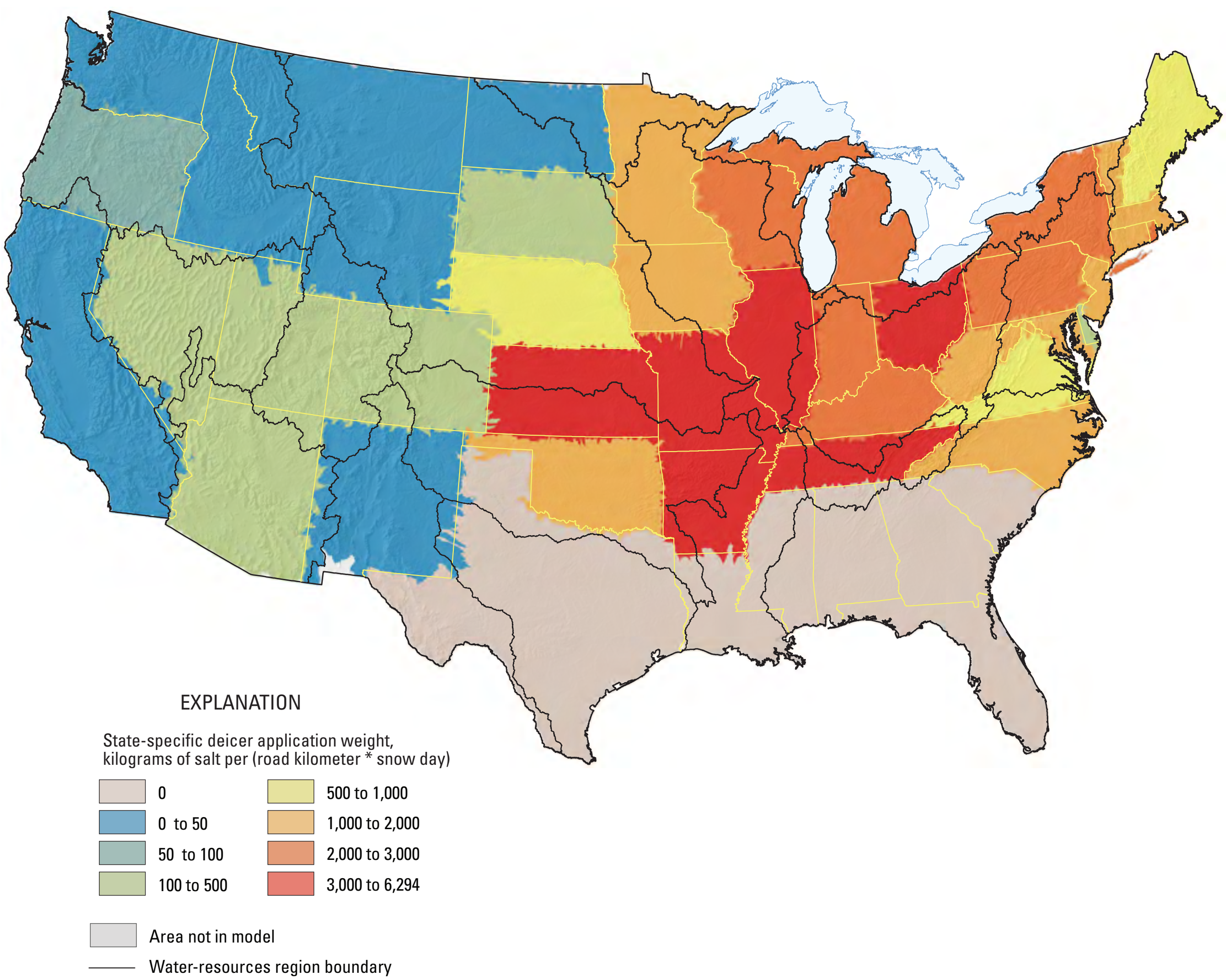
Units: kilograms of salt per (road kilometer * snow day)

Data source: The dataset was derived from data obtained from the U.S. Geological Survey Minerals Yearbook, Salt (Kostick, 1993–2009). Digital data accessed from http://minerals.usgs.gov/minerals/pubs/commodity/salt/index.html#myb on November 17, 2010.

Processing synopsis: Source yearly rock salt use data were used to calculate an average rock salt use rate for 1990–2009 for each state. The average state rock salt usage rates were then reduced by 25 percent because nationally for 1990-2009, 25 percent of rock salt was used for purposes other than de-icing (Kostick, 1993–2009). Next, for each catchment the total length of major highways and roads was multiplied by the number of snow days. This product for all catchments within each state was summed together for the 'state total road length * snow days'. In the final step, each state-specific deicer application weight was calculated as the reduced average annual state rock salt usage rate, divided by the 'state total road length * snow days'.

Note: In states where road deicers are applied to a substantial total length of minor roads, this rate will be higher than actual application rates. It is important to keep in mind that this rate is specifically developed for the national SPARROW model of dissolved-solids transport and allows for preserving the accuracy of the total mass of deicer used at the state level and distribution of that mass amongst the catchments of that state in a reasonably equitable manner based on the length of major roads and snow days.

Map: Model catchments shaded by the State-specific deicer application weight.



Attribute name: Atmospheric deposition of dissolved solids

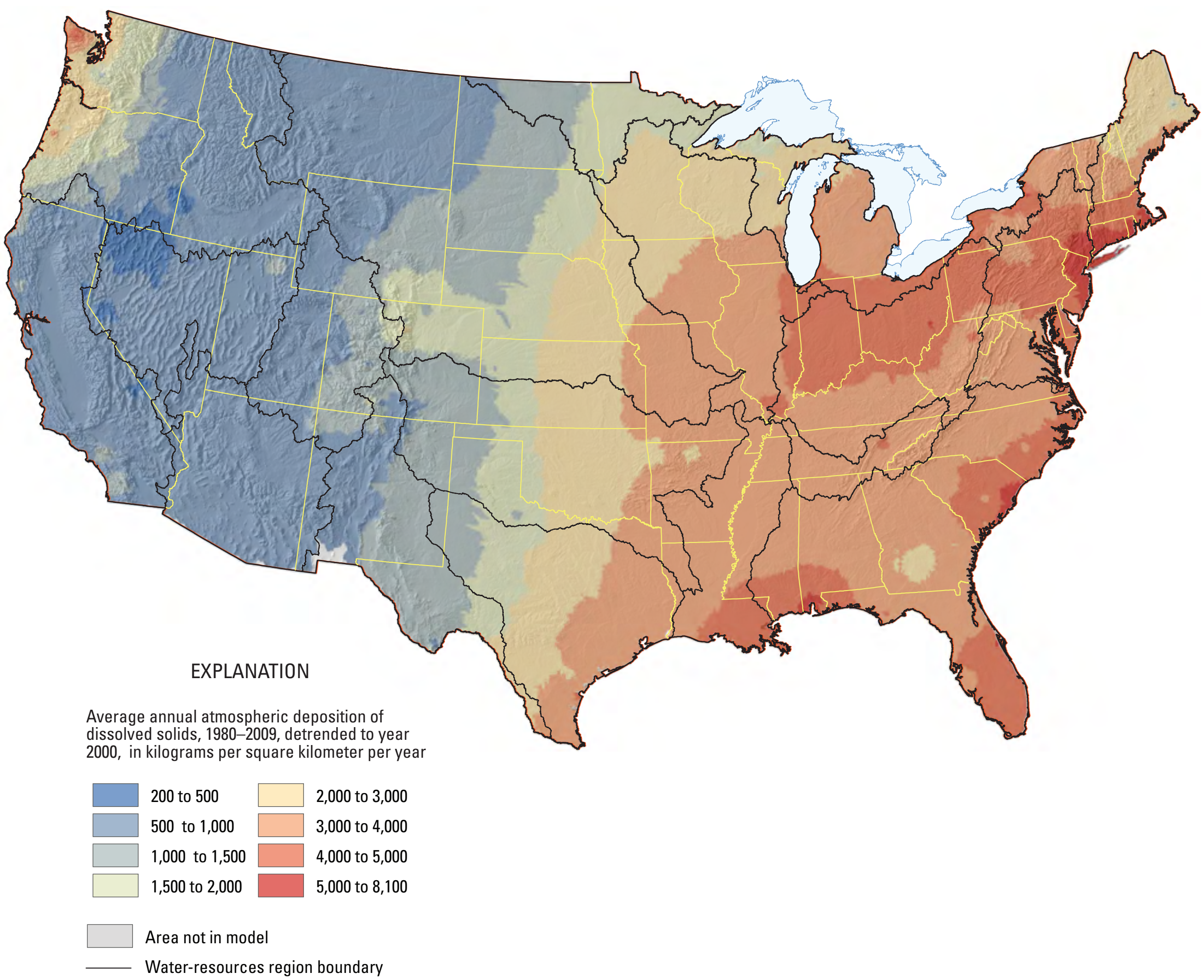
Description: This attribute represents 1980–2009 average annual (water year) atmospheric (wet) deposition of dissolved solids detrended to year 2000 for the conterminous United States.

Units: kilograms per square kilometer per year

Data source: The dataset was derived from total wet depositon data obtained from the National Atmospheric Deposition Program, National Trends Network (National Atmospheric Deposition Program, 2010). Digital data accessed from http://nadp.sws.uiuc.edu/data/ntndata.aspx on September 30, 2010.

Processing synopsis: Annual wet deposition rates for individual ions at a given monitoring station were added together to represent the total annual wet deposition rate for the station. For each of the 282 monitoring stations, these annual rates were used to compute an average annual rate, detrended to year 2000. A point layer was created from the station detrended data. A raster surface was then interpolated from the point data using an inverse distance weighted technique. GIS tools were then used to calculate the mean atmospheric deposition for each catchment.

Map: Model catchments shaded by the average annual atmospheric deposition of dissolved solids, 1980–2009, detrended to year 2000.



Attribute name: Climate conditions (precipitation)

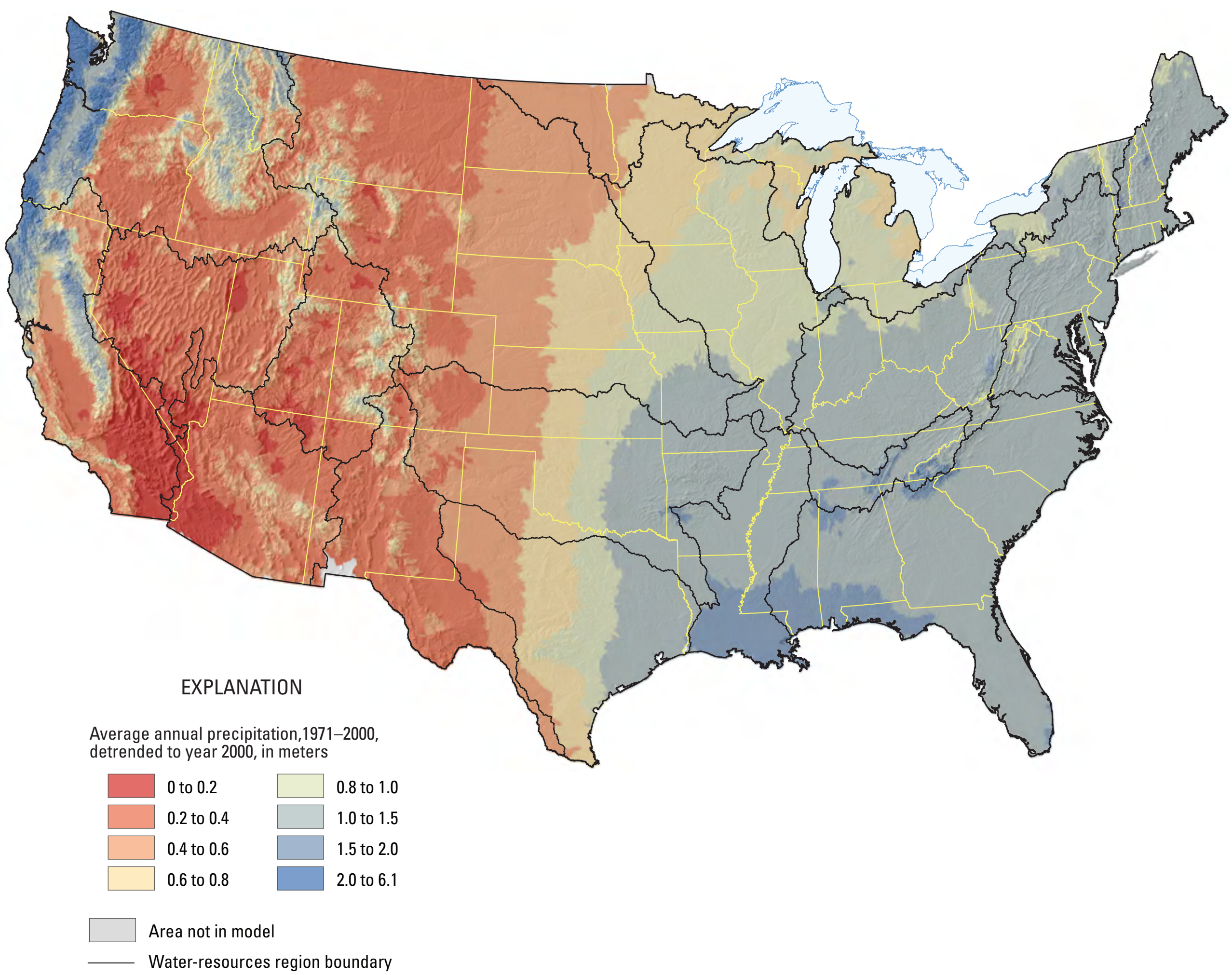
Description: This attribute represents average annual precipitation, 1971–2000, detrended to year 2000 in the conterminous United States.

Units: meters

Data source: Catchment average annual precipitation was obtained from U.S. Geological Survey Digital Data Series 491-21, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: 30-year average annual precipitation, 1971–2000” (Wieczorek, M.E., and LaMotte, A.E., 2010j). Digital data were accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_ppt30yr.xml on May 6, 2011. Detrending correction factor data were derived from data obtained from United States Historical Climatology Network (Menne and others, 2010). Digital data accessed from http://cdiac.ornl.gov/epubs/ndp/ushcn/access.html on March 26, 2010.

Processing synopsis: Source catchment average annual precipitation data were used as provided. Average annual precipitation data for each year from 1971–2009 were obtained for 1,219 climate monitoring stations from the detrending correction factor data source. An average value for 1971–2000 was computed for each station. The annual precipitation data were regressed against "year" for each station by using ordinary least squares regression on data for 1971–2009. The resulting equation was used to predict the annual precipitation for year 2000 at each station, and a precipitation detrending coefficient was computed as follows: (predicted annual precipitation for year 2000) / (average annual precipitation for years 1971–2000). A raster surface was then interpolated from the station data using an inverse distance weighted technique. GIS tools were used to calculate the mean precipitation detrending coefficient for each catchment. Average annual precipitaiton, 1971–2000, detrended to year 2000 was calculated by multiplying the catchment average annual precipitation by the mean detrending coefficient.

Map: Model catchments shaded by the average annual precipitation, 1971–2000, detrended to year 2000.



Attribute name: Climate conditions (air temperature)

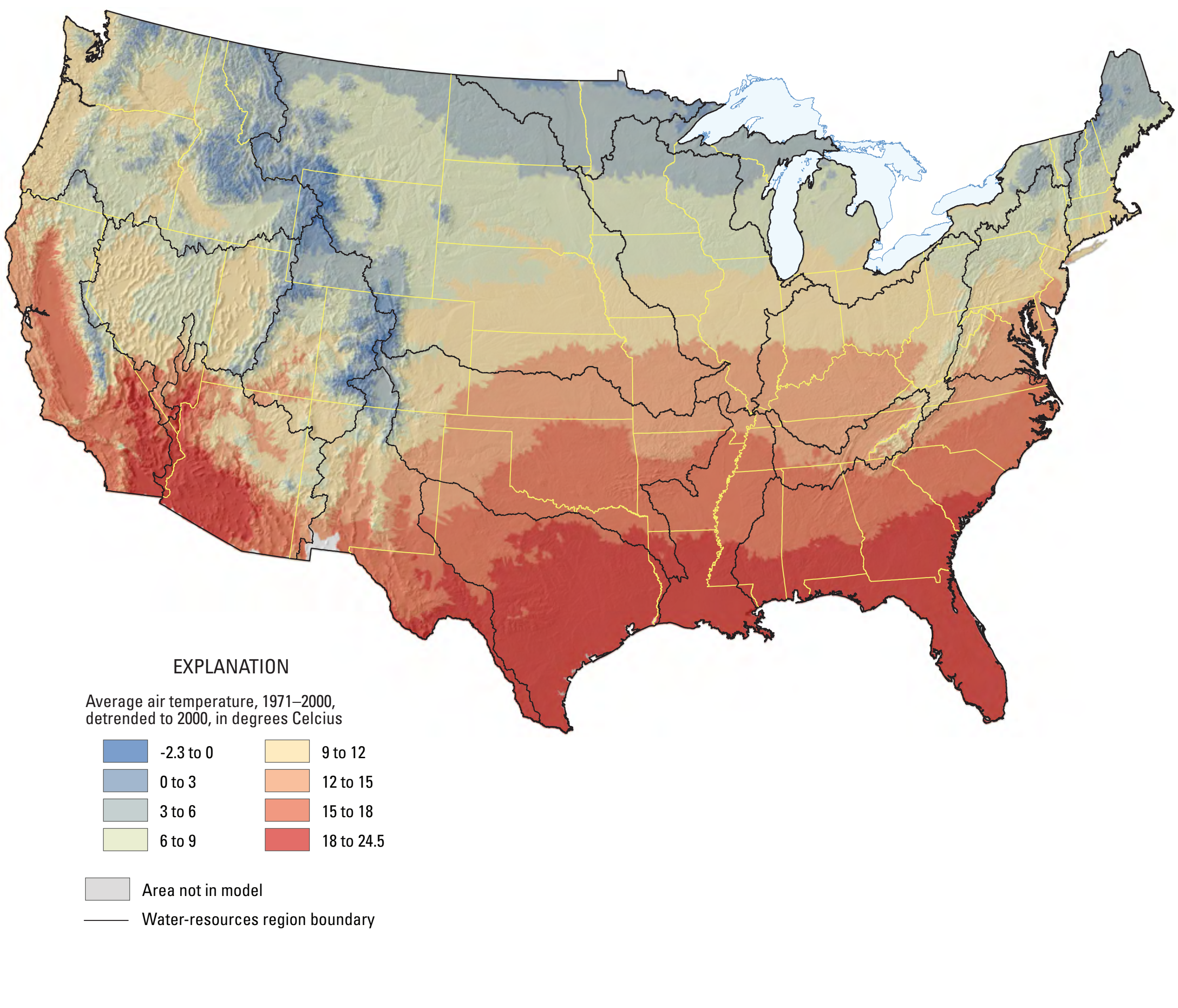
Description: This attribute represents the approximate average air temperature, 1971–2000, detrended to year 2000 in the conterminous United States.

Units: degrees Celcius

Data source: Catchment average air temperature was derived from U.S. Geological Survey Digital Data Series 491-29, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: 30-year average annual temperature, 1971–2000” (Wieczorek, M.E., and LaMotte, A.E., 2010m) and U.S. Geological Survey Digital Data Series 491-31, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: 30-year average daily minimum temperature, 1971–2000” (Wieczorek, M.E., and LaMotte, A.E., 2010n). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_tmax30yr.xml and http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_tmin30yr.xml on May 6, 2011. Detrending correction factor data derived from data obtained from United States Historical Climatology Network (Menne and others, 2010). Digital data accessed from http://cdiac.ornl.gov/epubs/ndp/ushcn/access.html on March 26, 2010.

Processing synopsis: Average air temperature, 1972-2000, for each catchment was calculated using the average minimum and average maximum air temperature data sources. Average annual air temperature data for each year from 1971–2009 were obtained for 1,219 climate monitoring stations from the detrending correction factor data source. An average value for 1971–2000 was computed for each station. The annual air temperature data were regressed against "year" for each station by using ordinary least squares regression on data for 1971–2009. The resulting equation was used to predict the annual air temperature for year 2000 at each station, and an air temperature detrending coefficient was computed as follows: (predicted annual air temperature for year 2000) / (average annual air temperature for years 1971–2000). A raster surface was then interpolated from the station data using an inverse distance weighted technique. GIS tools were used to calculate the mean air temperature detrending coefficient for each catchment. Average air temperature, 1971–2000, detrended to year 2000 was calculated by multiplying the catchment average air temperature by the mean detrending coefficient.

Map: Model catchments shaded by the average air temperature, 1971–2000, detrended to year 2000.



Attribute name: Basin characteristics (slope)

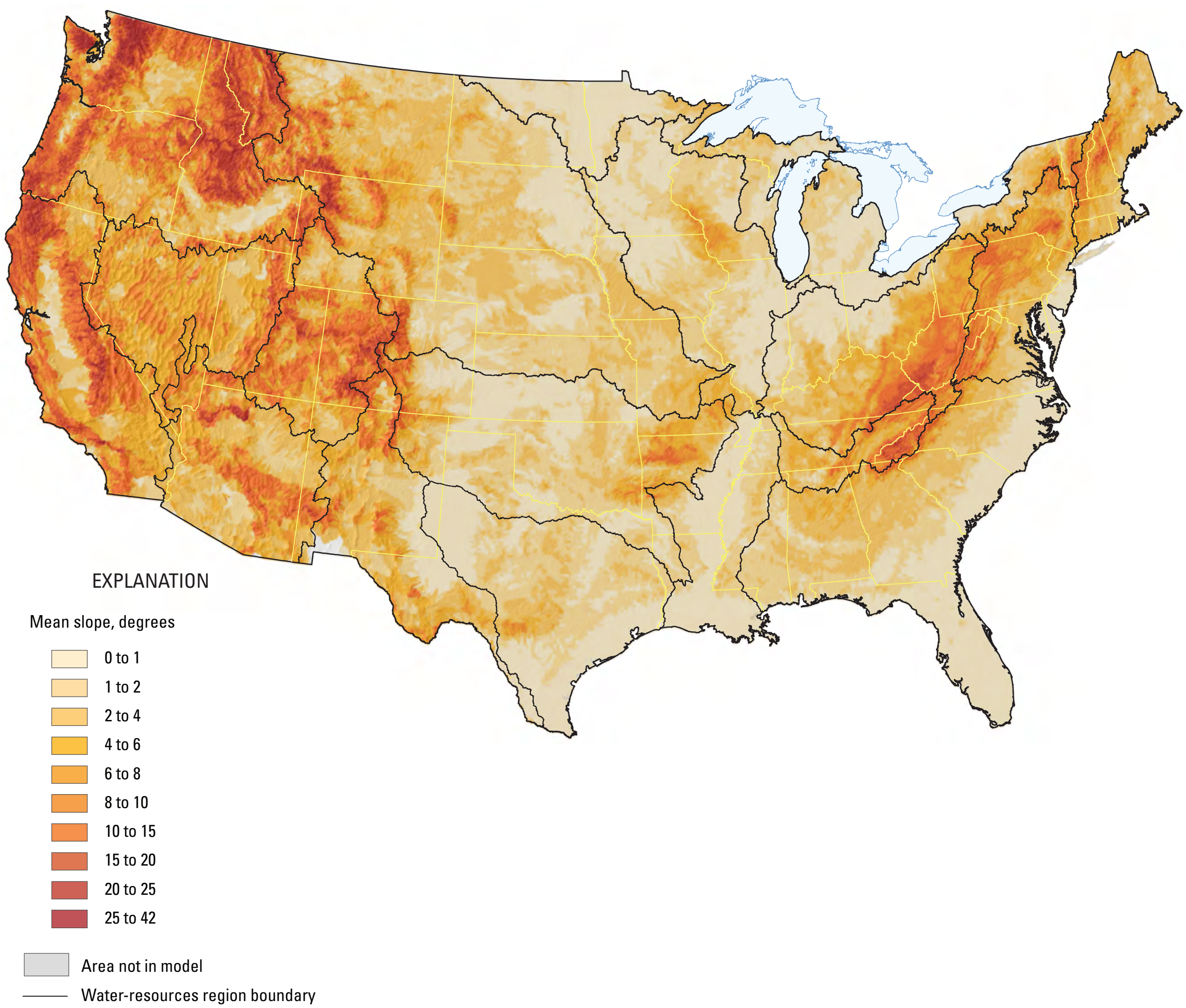
Description: This attribute represents mean slope of the conterminous United States..

Units: degrees

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-03, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: Basin Characteristics, 2002” (Wieczorek, M.E., and LaMotte, A.E., 2010b). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_bchar.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by mean slope.



Attribute name: Streamflow and runoff characteristics (average annual discharge)

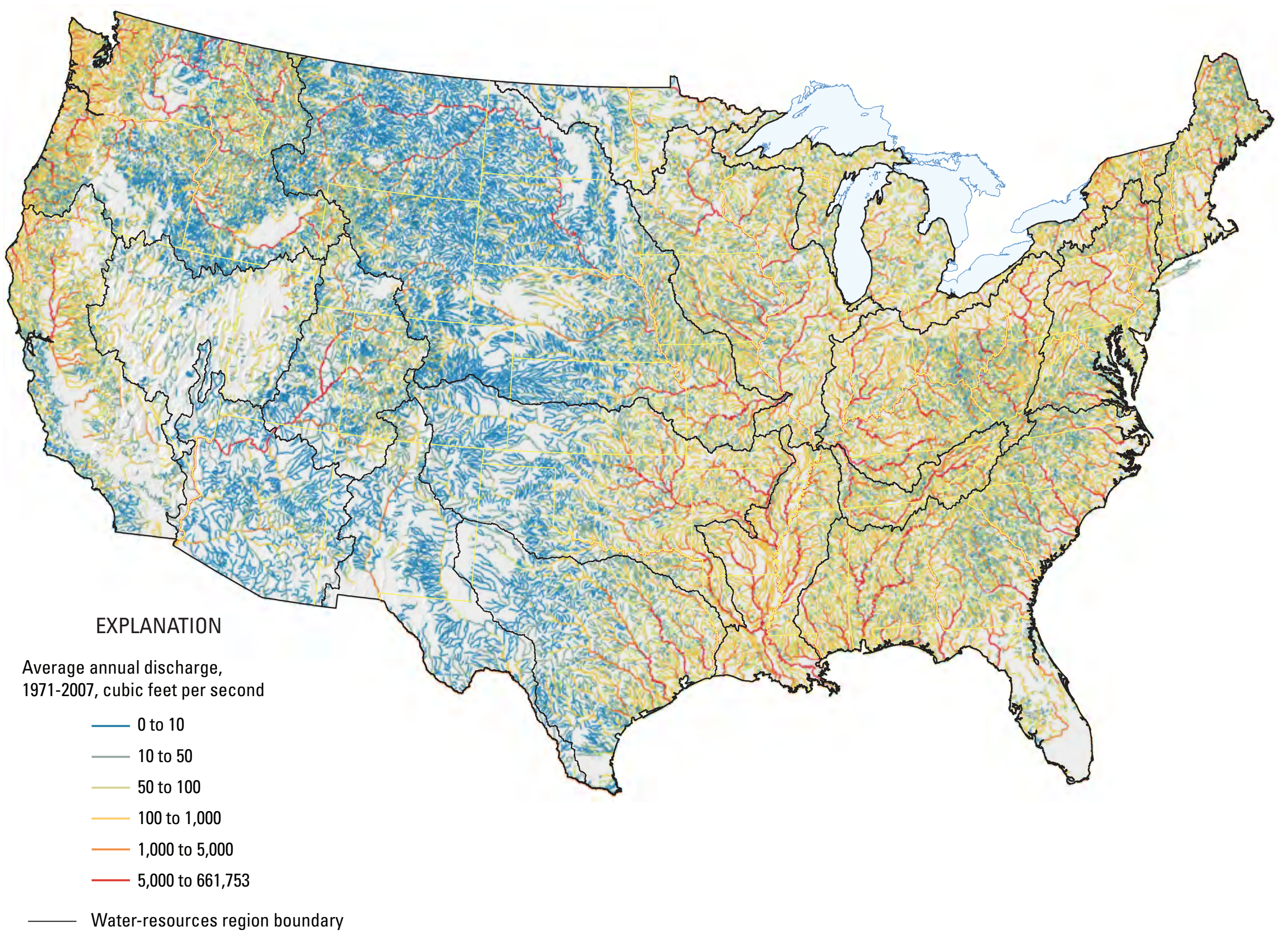
Description: This attribute represents average annual discharge for select streams, 1971–2007, in the conterminous United States.

Units: cubic feet per second

Data Source: This attribute was derived from U.S. Geological Survey Open-File Report 03-146, “Flow characteristics at U.S. Geological Survey streamgages in the conterminous United States” (Wolock, 2003b). Digital data access from http://water.usgs.gov/GIS/metadata/usgswrd/XML/qsitesdd.xml on February 25, 2011.

Processing synopsis: Source data were joined to the MRB_E2RF1 digital hydrologic network using the common River Reach File 1 segment identification number field.

Map: Model reaches shaded by average annual discharge, 1971–2007.



Attribute name: Streamflow and runoff characteristics (decrease in annual discharge)

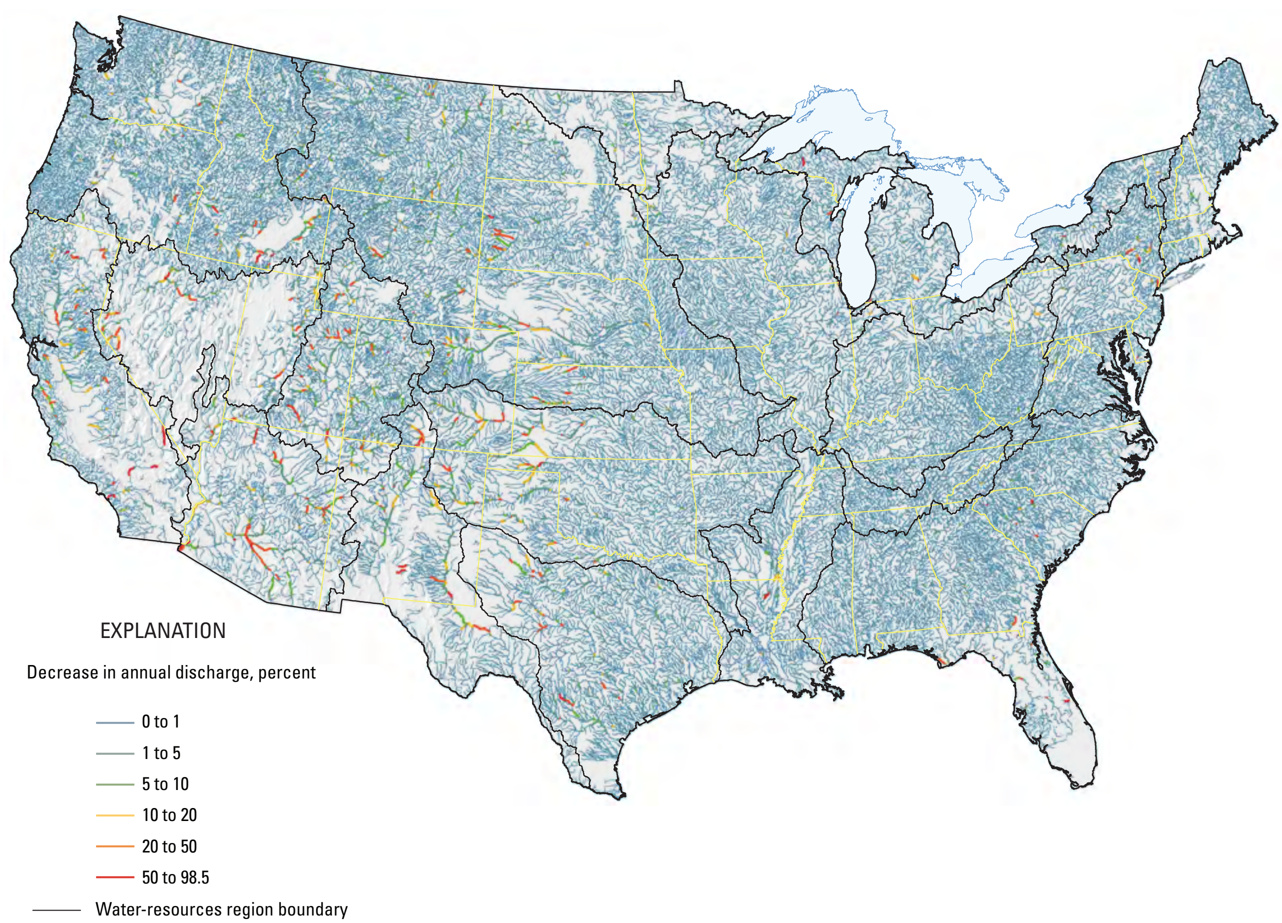
Description: This attribute represents the decrease in annual discharge for select streams in the conterminous United States.

Units: percent

Data source: This attribute was derived from U.S. Geological Survey Open-File Report 03-146, “Flow characteristics at U.S. Geological Survey streamgages in the conterminous United States” (Wolock, 2003b). Digital data access from http://water.usgs.gov/GIS/metadata/usgswrd/XML/qsitesdd.xml on February 25, 2011.

Processing synopsis: For reaches where average annual discharge entering was greater than average annual discharge leaving, decreases in discharge were computed as: (1 - average annual discharge leaving reach/average annual dishcarge entering reach) * 100. Otherwise the value was assigned as zero.

Map: Model reaches shaded by percent decrease in annual discharge.



Attribute name: Streamflow and runoff characteristics (base-flow index)

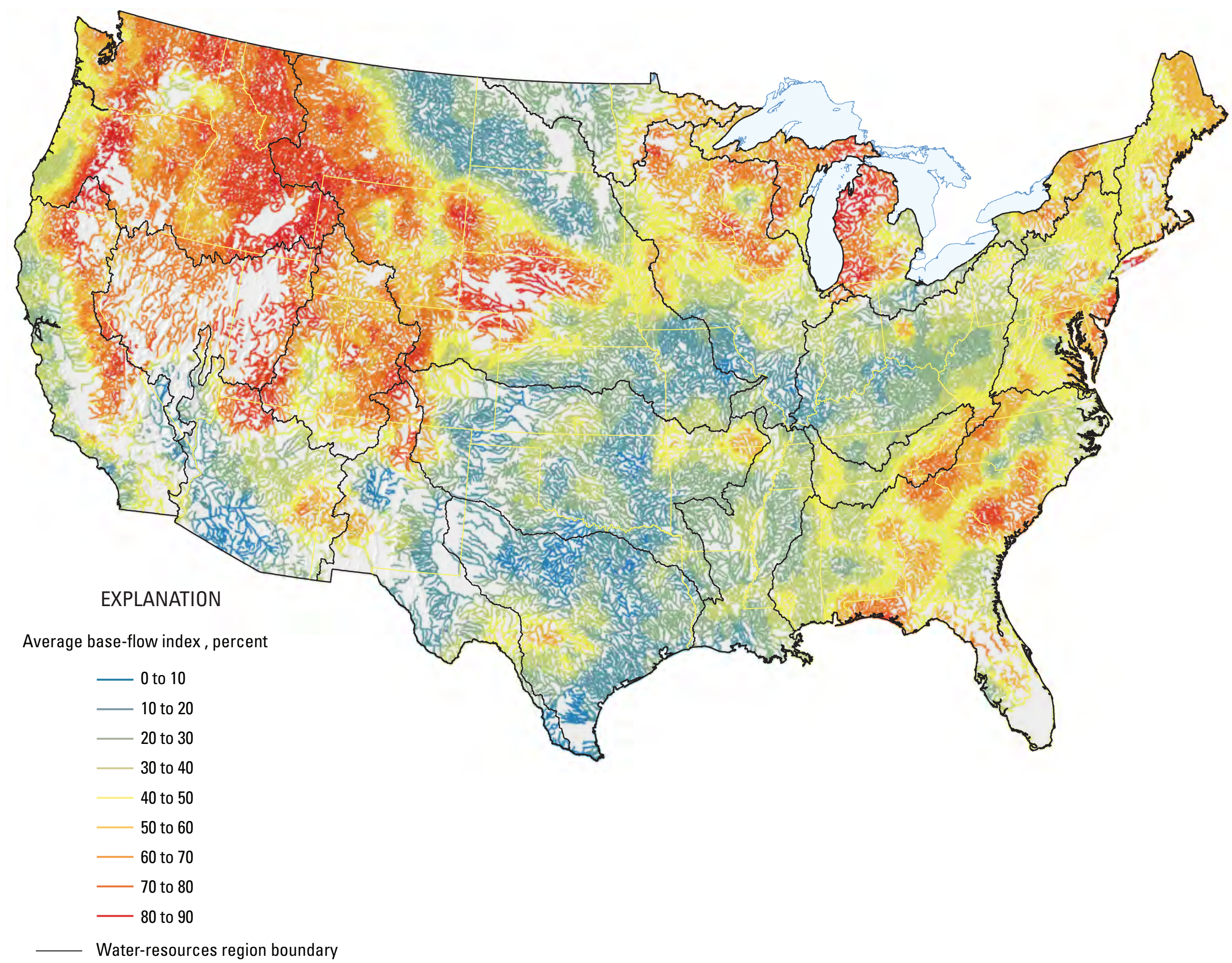
Description: This attribute represents average base-flow index for select streams in the conterminous United States. The index reflects the relative amount of baseflow compared to total flow in a stream.

Units: percent

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-04, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: Base-flow index, 2002” (Wieczorek, M.E., and LaMotte, A.E., 2010c). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_bfi.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model reaches shaded by average base-flow index.



Attribute name: Vegetation growth

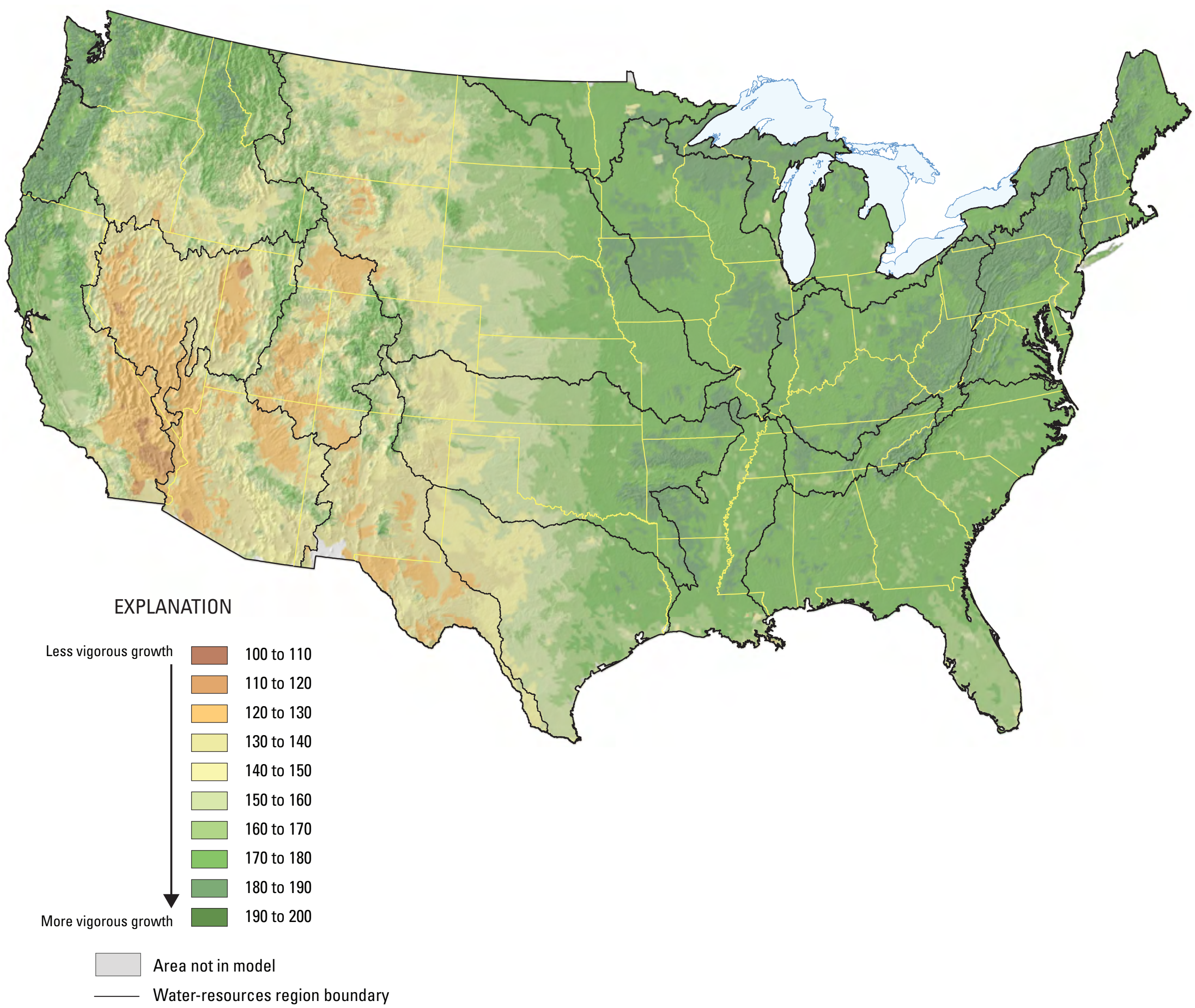
Description: This attribute represents mean vegetation growth for the year 2000 in the conterminous United States.

Units: dimensionless

Data source: The attribute was derived from U.S. Geological Survey National Atlas of the United States, "Average Vegetation Growth 2000" (Center for Earth Resources Obseveration and Science, 2005–2012). Digital data accessed from http://nationalatlas.gov/mld/vgpk90i.html on June 27, 2012.

Processing synopsis: Source image was converted to a grid. GIS tools were then used to calculate the mean vegetation growth by catchment.

Map: Model catchments shaded by mean vegetation growth for the year 2000.



Attribute name: Soil conditions (percent clay)

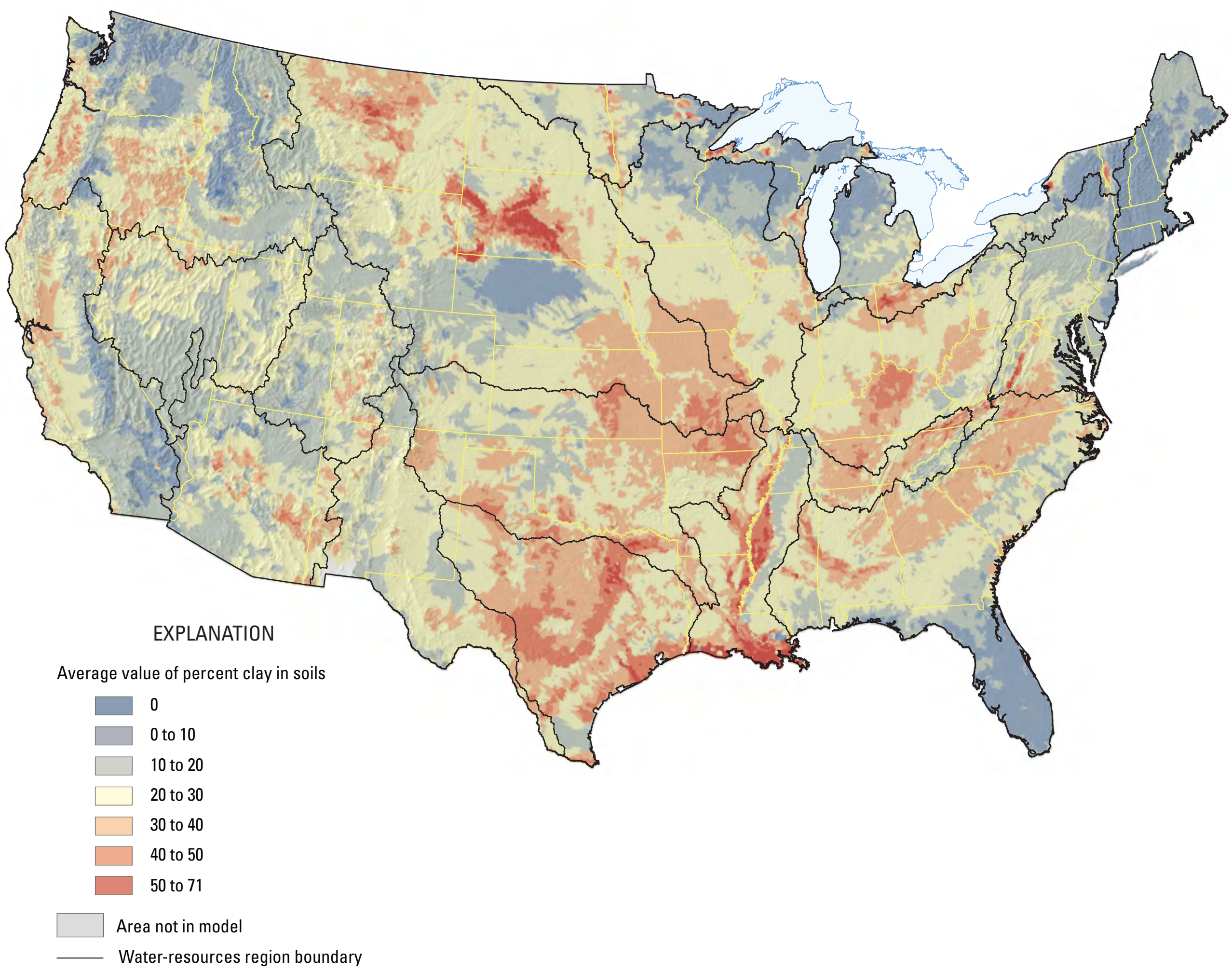
Description: This attribute represents average value of percent of clay in soils in the conterminous United States.

Units: percent

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-26, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: STATSCO soil characteristics” (Wieczorek, M.E., and LaMotte, A.E., 2010l). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_statsgo.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by average value of percent clay in soils.



Attribute name: Soil conditions (percent sand)

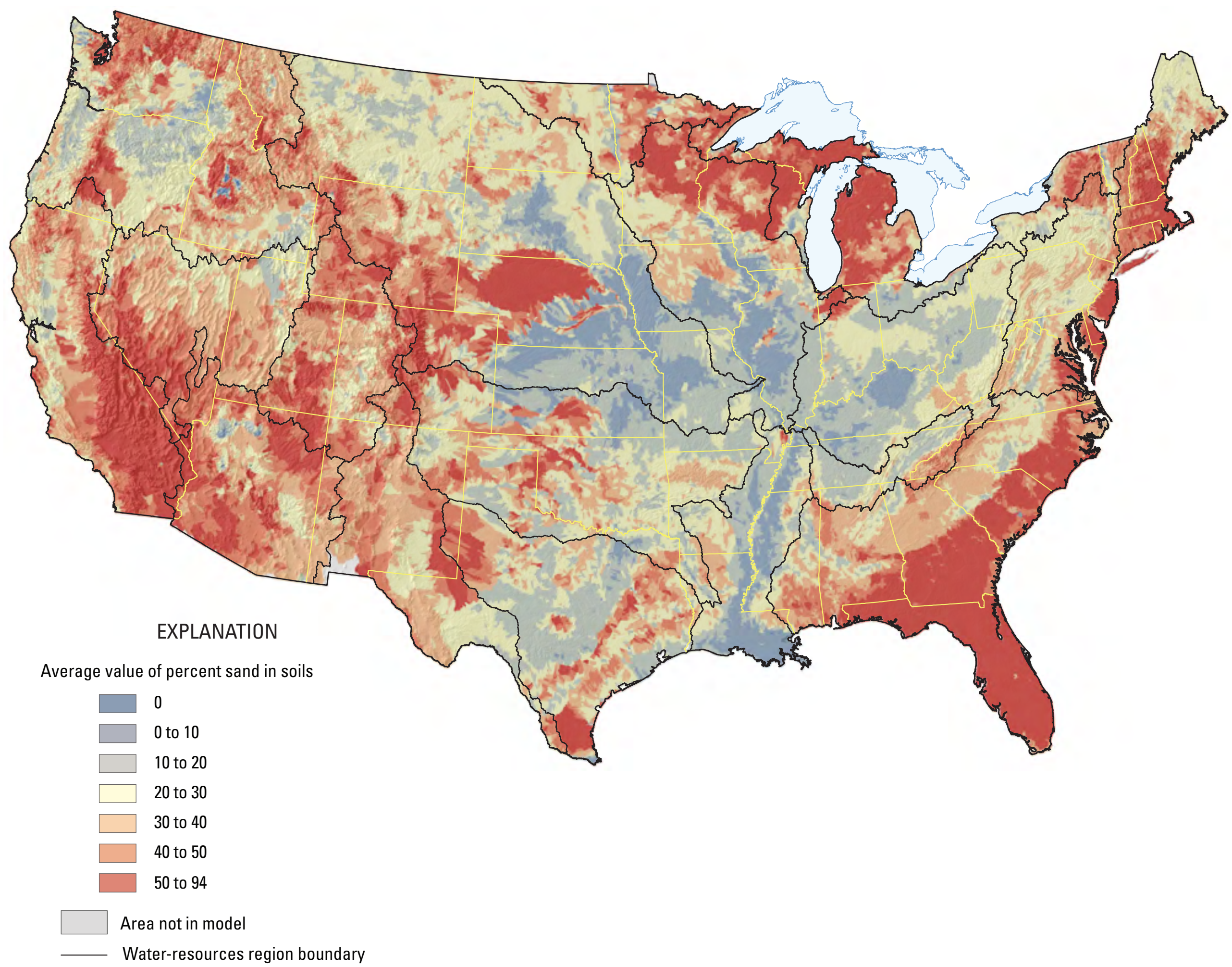
Description: This attribute represents average value of percent sand in soils of the conterminous United States.

Units: percent

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-26, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: STATSCO soil characteristics” (Wieczorek, M.E., and LaMotte, A.E., 2010l). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_statsgo.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by average value of percent sand in soils.



Attribute name: Soil conditions (salinity)

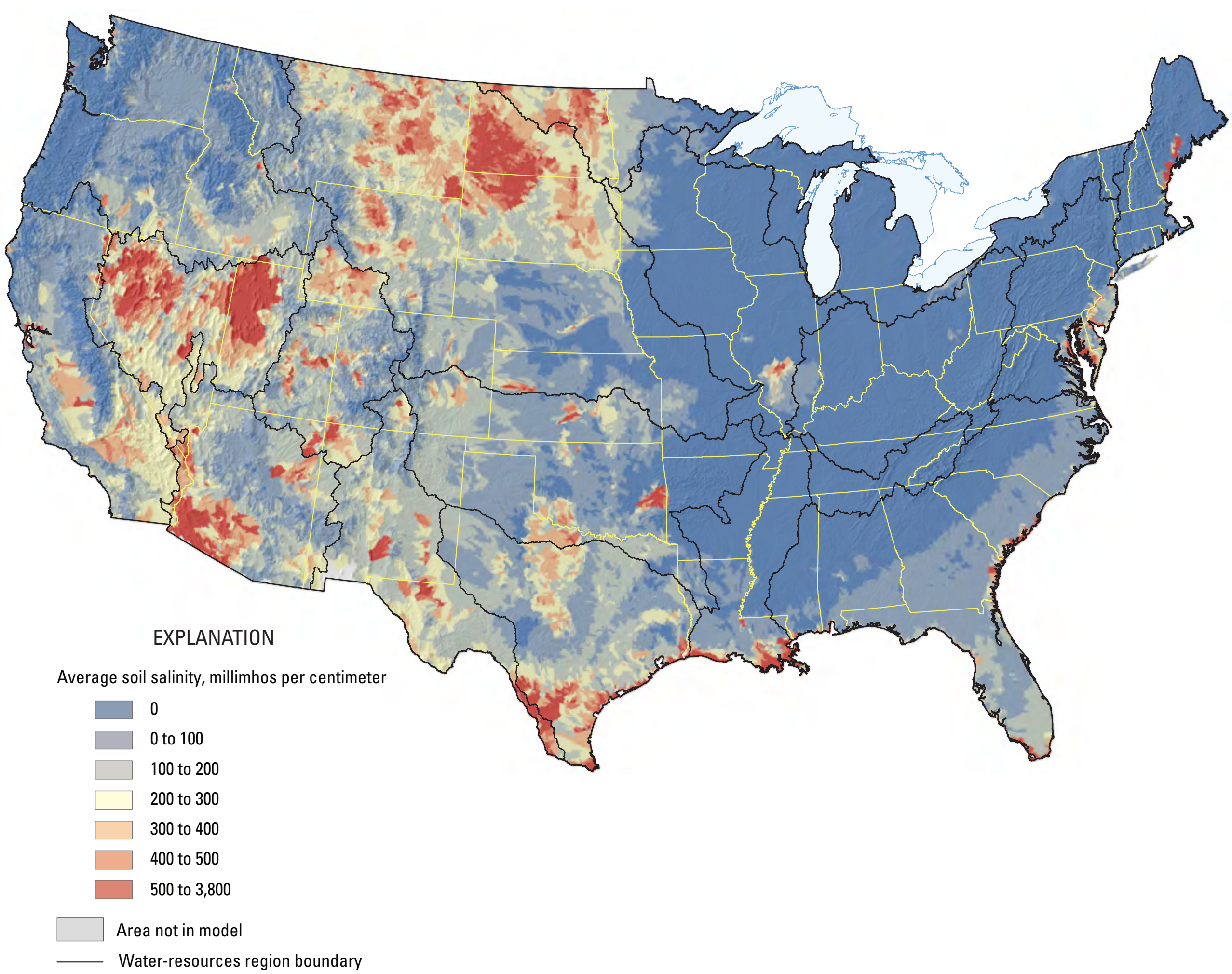
Description: This attribute represents the salinity in soils of the conterminous United States.

Units: mmhos per centimeter

Data source: The attribute was provided as a digital dataset by M.E. Wieczorek, U.S.Geological Survey Geographer, through electronic communication on May 6, 2011. Data were derived in a similar manner as the data for the percent sand and percent clay in soils.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by average soil salinity.



Attribute name: Irrigation and drainage practices (irrigation)

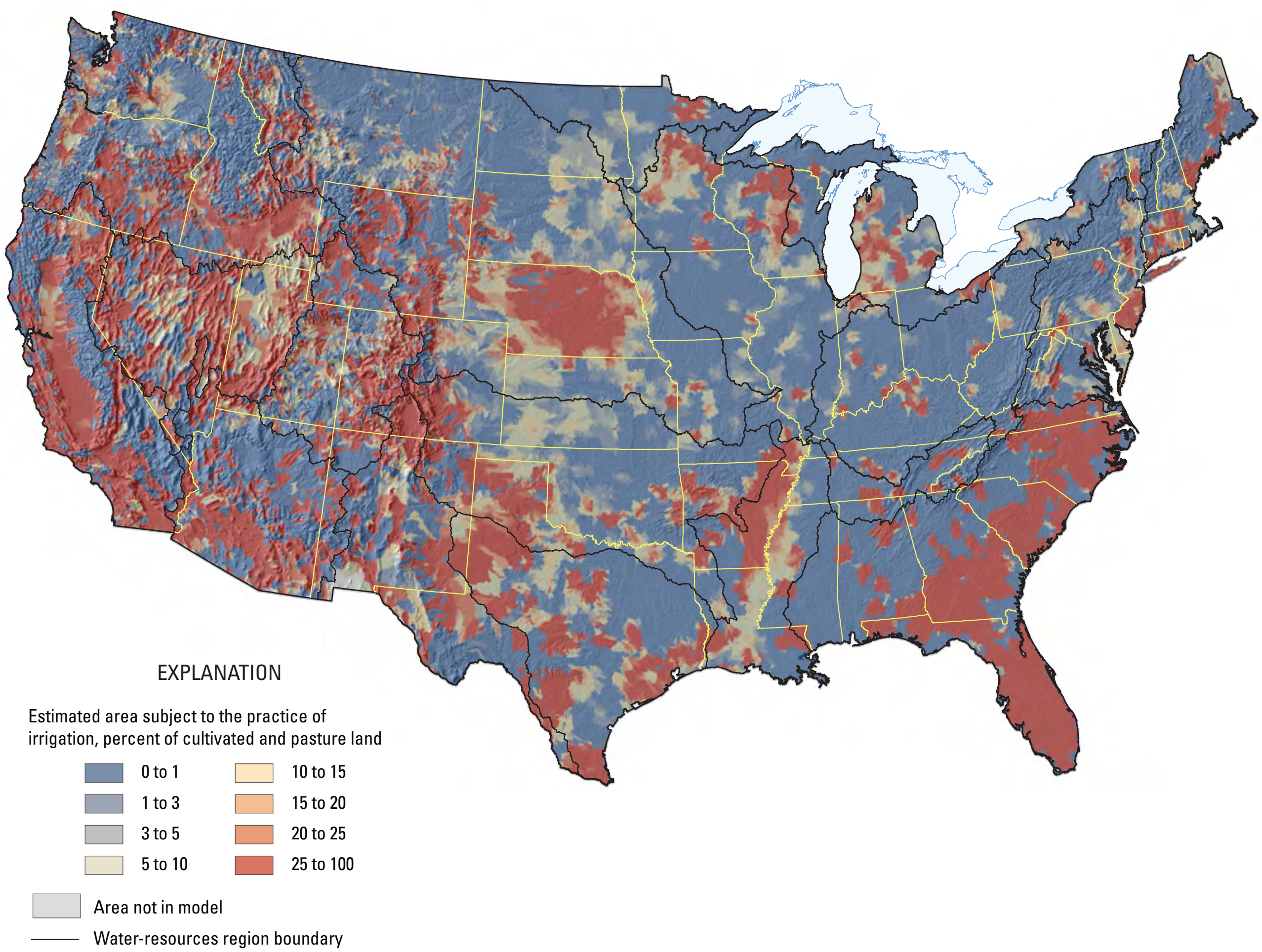
Description: This attribute represents the estimated percent of area subject to the practice of irrigation in the conterminous United States.

Units: percent

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-01, "Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: Artificial drainage (1992) and irrigation (1997)" (Wieczorek, M.E., and LaMotte, A.E., 2010a). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_adrain.xml on September 14, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by the estimated percent of area subject to the practice of irrigation.



Attribute name: Irrigation and drainage practices (ditch drainage)

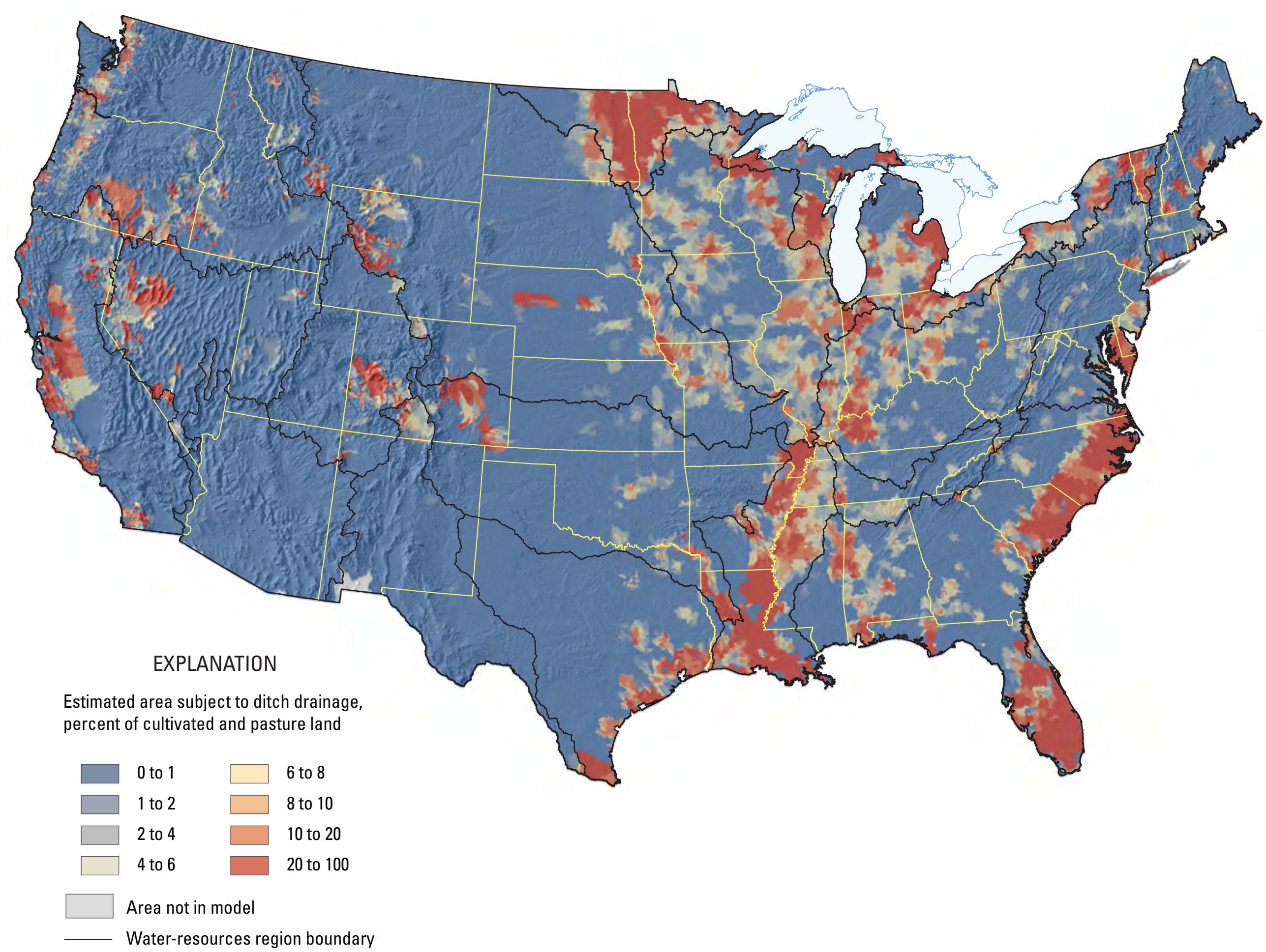
Description: This attribute represents the estimated percent of area subject to ditch drainage in the conterminous United States.

Units: percent

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-01, “Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: Artificial drainage (1992) and irrigation (1997)” (Wieczorek, M.E., and LaMotte, A.E., 2010a). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_adrain.xml on September 14, 2011.

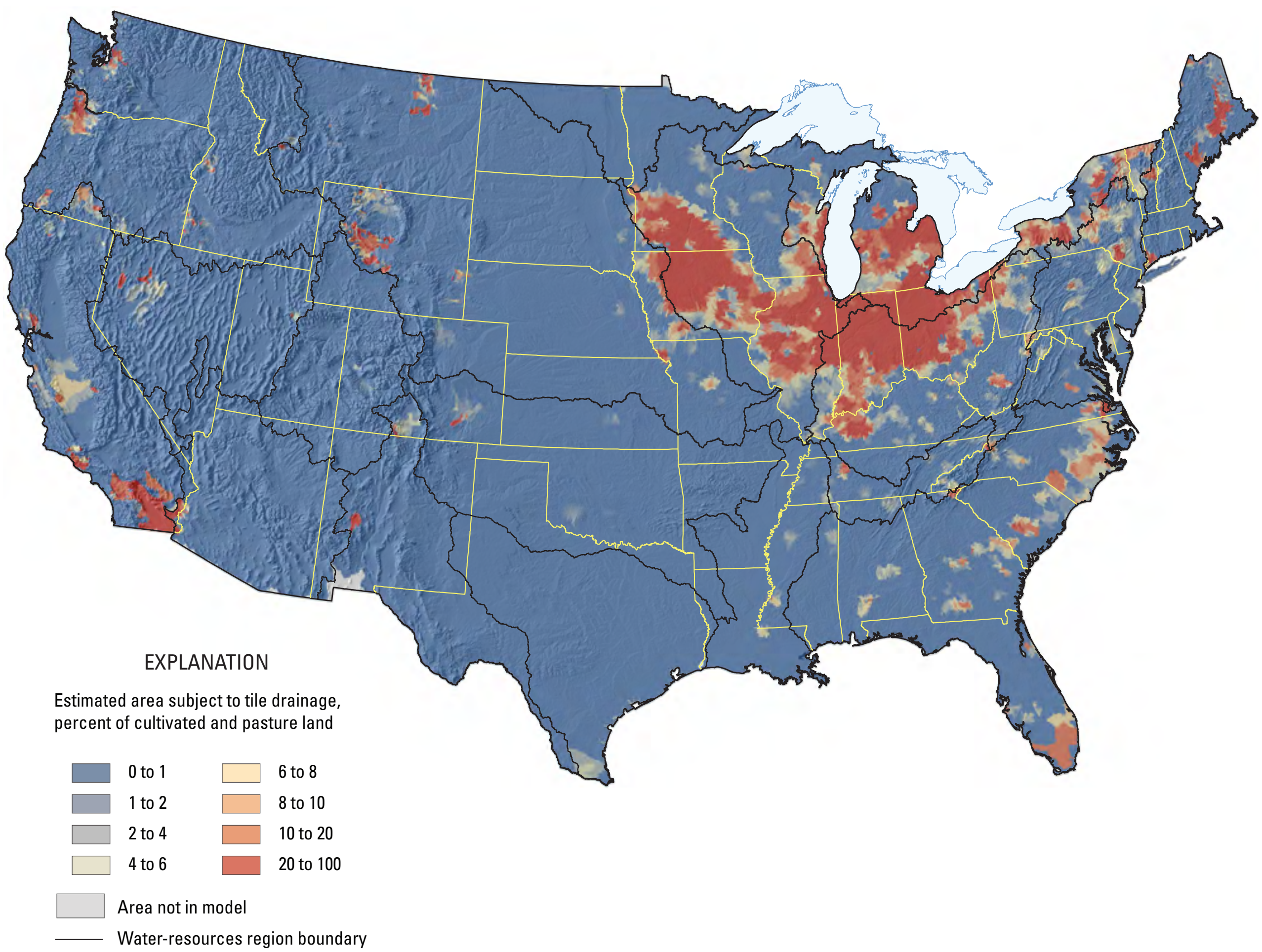
Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by the estimated percent of area subject to ditch drainage.



Attribute name: Irrigation and drainage practices (tile drainage)

Description:	This attribute represents the estimated percent of area subject to tile drainage in the conterminous United States.
Units:	percent
Data source:	The attribute was derived from U.S. Geological Survey Digital Data Series 491-01, "Attributes for MRB_E2RF1 catchments by major river basins in the conterminous United States: Artificial drainage (1992) and irrigation (1997)" (Wieczorek, M.E., and LaMotte, A.E., 2010a). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_adrain.xml on September 14, 2011.
Processing synopsis:	No processing required. Data used in model as provided.
Map:	Model catchments shaded by the estimated percent of area subject to tile drainage.



Attribute name: Water use (irrigation)

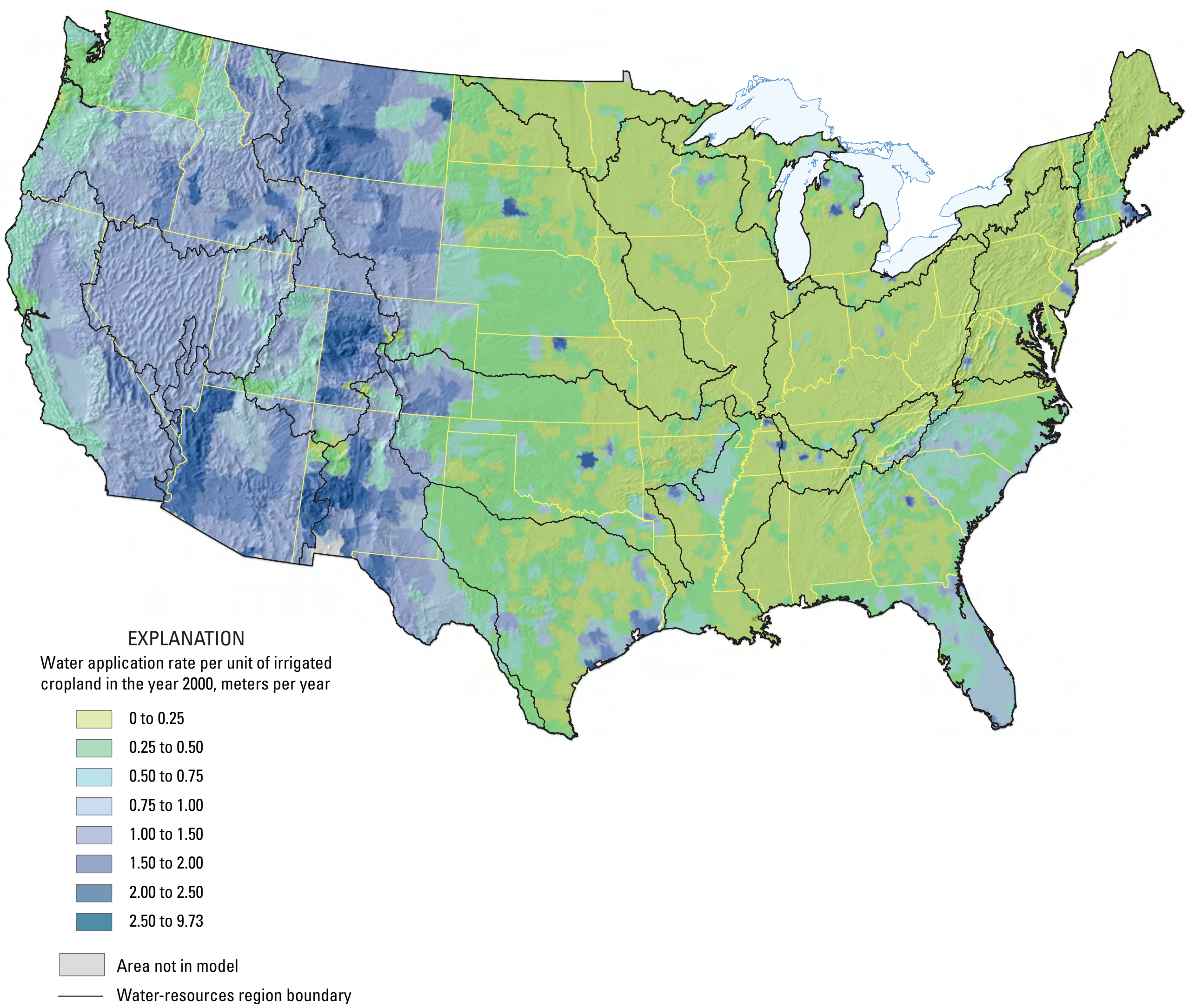
Description: This attribute represents the water application rate per unit of irrigated cropland in the year 2000 in the conterminous United States.

Units: Meters per year

Data Source: The attribute was derived from U.S. Geological Survey's National Water-Use Information Program, "Estimated Use of Water in the United States in 2000" (Hutson and others, 2004). Digital data accessed from http://water.usgs.gov/watuse/data/2000/index.html on March 11, 2011.

Processing synopsis: Using source county-level data for the year 2000, water application rate was computed as irrigation withdrawals divided by irrigated acreage. GIS tools were then used to calculate the mean water application rate per unit of irrigation cropland by catchment.

Map: Model catchments shaded by water application rate per unit of irrigated cropland in the year 2000.



Attribute name: Water use (municipal and industrial)

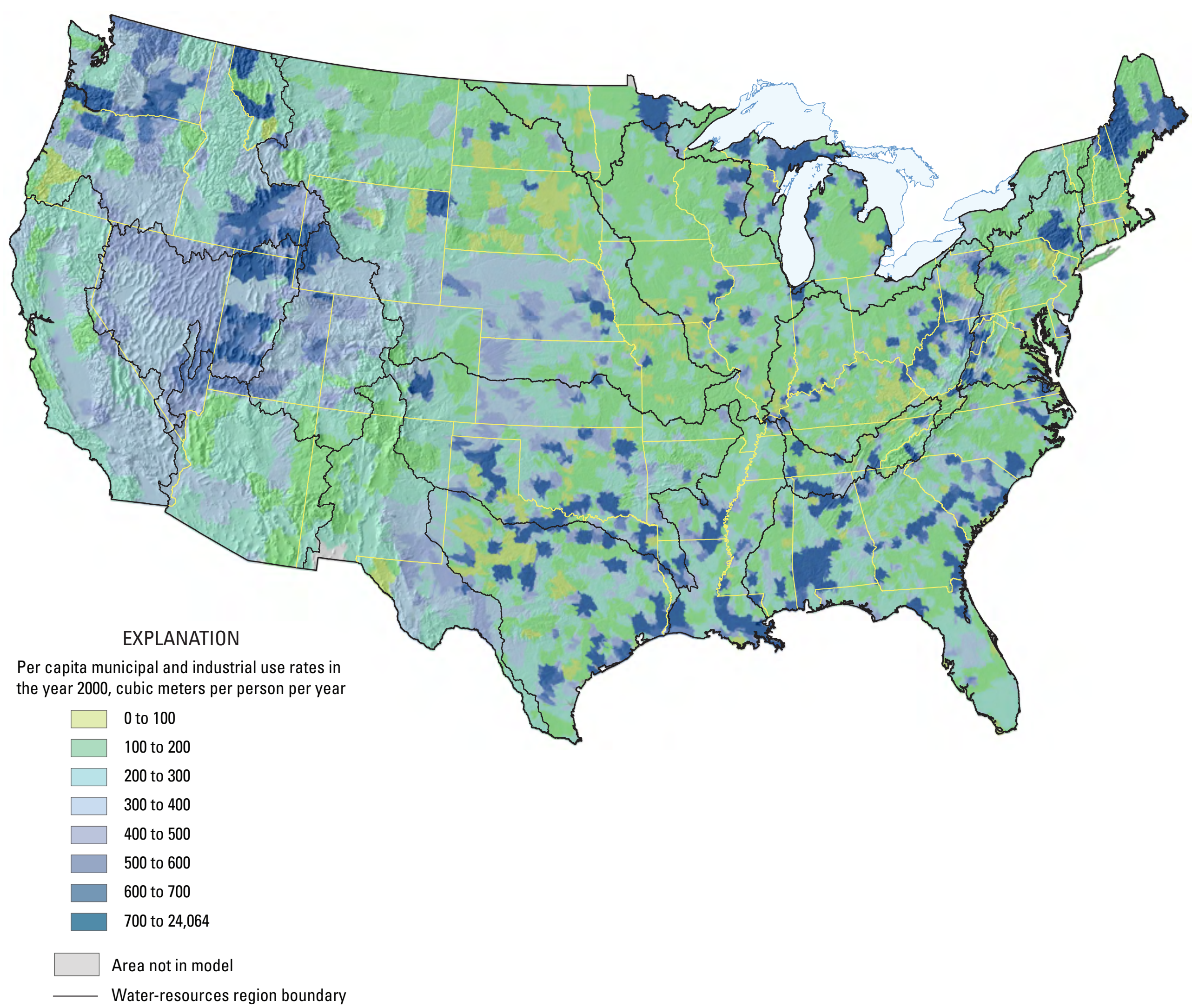
Description: This attribute represents the per capita municipal and industrial use rates in the year 2000 in the conterminous United States.

Units: cubic meters per person per year

Data Source: The attribute was derived from U.S. Geological Survey's National Water-Use Information Program, "Estimated Use of Water in the United States in 2000" (Hutson and others, 2004). Digital data accessed from http://water.usgs.gov/watuse/data/2000/index.html on March 11, 2011.

Processing synopsis: Using source county-level data for the year 2000, per capita municipal and industrial use rates were computed by summing public supply, domestic self-supplied, and industrial use rates and dividing by total population. GIS tools were then used to calculate the mean municipal and industrial use rate by catchment.

Map: Model catchments shaded by per capita municipal and industrial use rates in the year 2000.



Attribute name: Population density

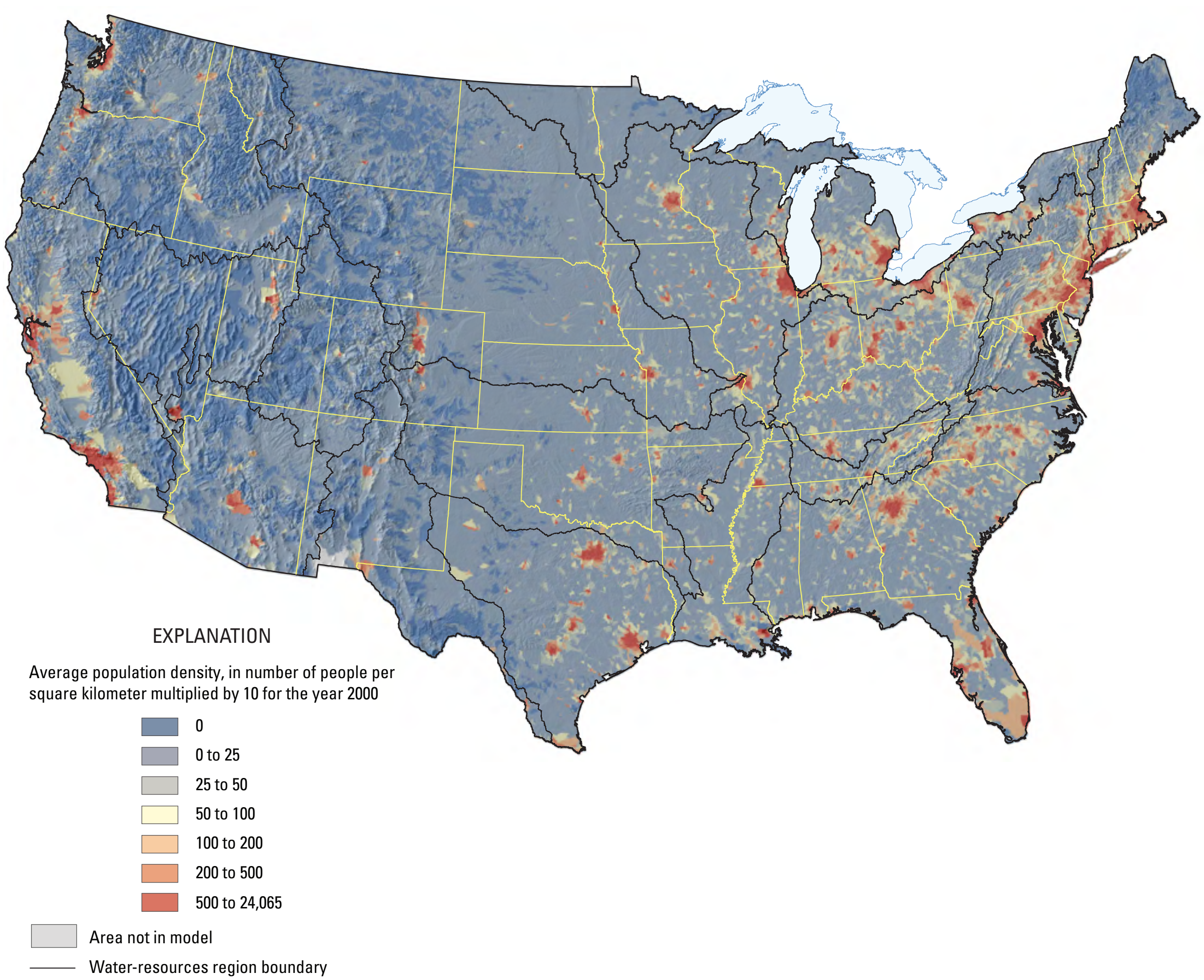
Description: This attribute represents the average population density by model catchment for the year 2000.

Units: number of people per square kilometer multiplied by 10

Data source: The attribute was derived from U.S. Geological Survey Digital Data Series 491-19, “Attributes for MRB_E2RF1 catchments in selected river basins: Population density, 2000” (Wieczorek, M.E., and LaMotte, A.E., 2010i). Digital data accessed from http://water.usgs.gov/GIS/metadata/usgswrd/XML/mrb_e2rf1_popd00.xml on May 6, 2011.

Processing synopsis: No processing required. Data used in model as provided.

Map: Model catchments shaded by the average population density multiplied by 10 for the year 2000.



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