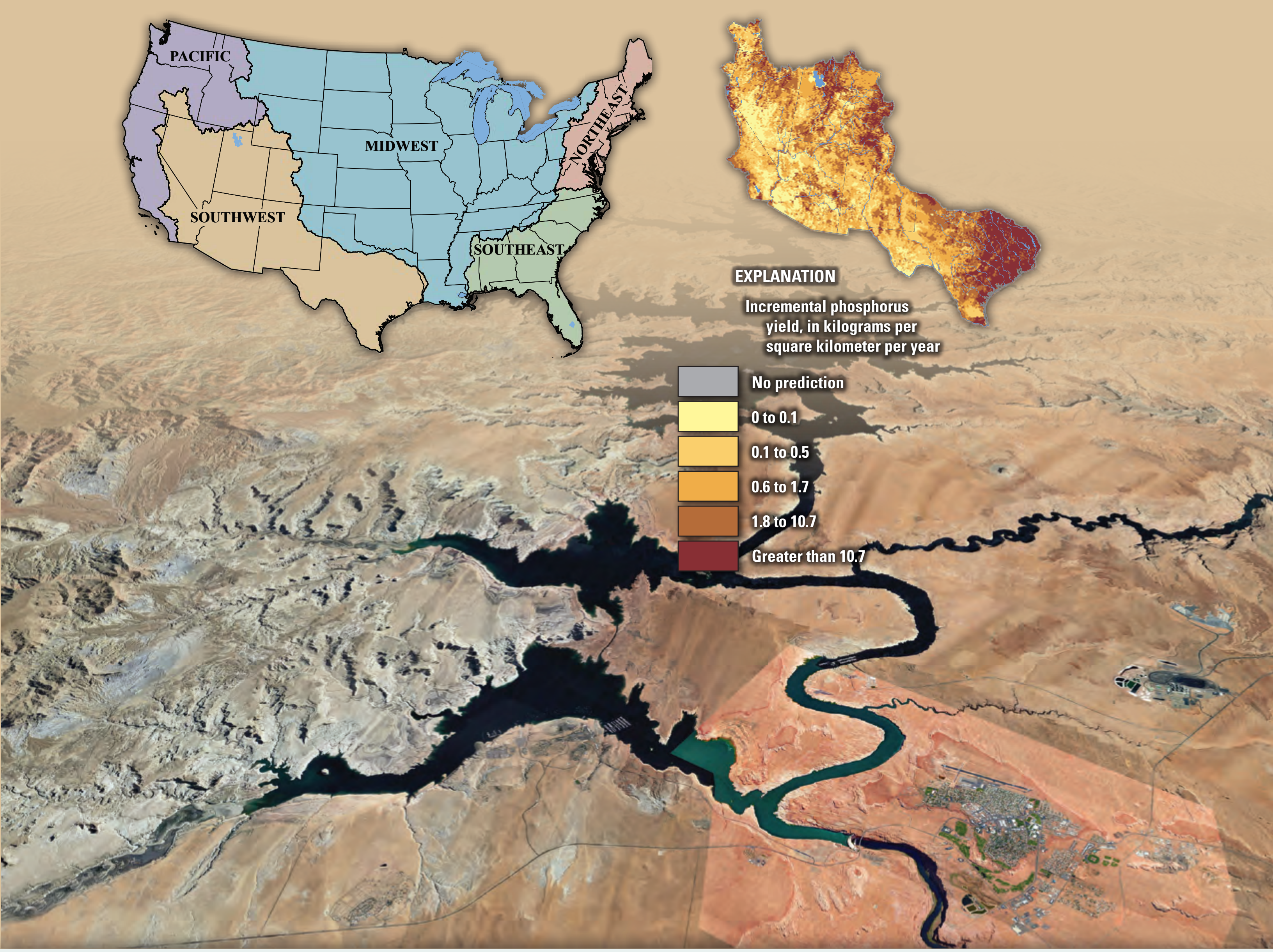
National Water Quality Program

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



Scientific Investigations Report 2019–5106
Version 1.1, June 2020

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

Cover:

Upper left: SPAtially Referenced Regression On Watershed attritutes (SPARROW) modeling regions of the conterminous United States.

Upper right: SPARROW simulated total phosphorus incremental yield, in kilograms per square kilometer per year.

Lower center: Aerial view looking northeast over Lake Powell and Glen Canyon Dam, with the Navajo Reservation to the south, Utah and Arizona. Credit: Satellite image courtesy of Google Earth.

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By Daniel R. Wise, David W. Anning, and Olivia L. Miller

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Foreword

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

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

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

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

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

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
milligram (g)	0.00003527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Yield	
kilogram per square kilometer per year ([kg/km^2]/yr)	0.00892	pound per acre per year ([lb/acre]/yr)
metric tons per square kilometer per year ([t/km^2]/yr)	8.92	pound per acre per year ([lb/acre]/yr)

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

$$°F = (1.8 \times °C) + 32.$$

Datums

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.

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

EPA	U.S. Environmental Protection Agency
NPDES	National Pollutant Discharge Elimination System
ppm	parts per million
SPARROW	SPAtially Referenced Regression On Watershed attributes
USGS	U.S. Geological Survey

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

By Daniel R. Wise, David W. Anning, and Olivia L. Miller

Abstract

Given the predicted imbalance between water supply and demand in the Southwest region of the United States, and the widespread problems with excessive nutrients and suspended sediment, there is a growing need to quantify current streamflow and water quality conditions throughout the region. Furthermore, current monitoring stations exist at a limited number of locations, and many streams lack streamflow and water quality information. SPAtially Referenced Regression On Watershed attributes (SPARROW) models were developed for hydrologic conditions representative of 2012 in order to understand how climate, land use, and other landscape characteristics control the yields of water, total nitrogen, total phosphorus, and suspended sediment across the Southwest region. The calibration data (mean annual streamflow and loads) for each of the four SPARROW models were based on continuous streamflow and discrete water-quality observations from throughout the region. Explanatory variables for the models consisted of regional datasets representing a range of potential sources of streamflow, nitrogen, phosphorous, and sediment, and processes that control the transport from land to water and attenuate loads within streams and waterbodies. Calibration and explanatory data were referenced to a surface water drainage network that allowed for routing and transport of water and loads through the region. The model results showed that wastewater discharge is the largest contributor to total nitrogen and total phosphorus yield from the Southwest region and forest land is the largest contributor to suspended-sediment yield, but that other sources such as atmospheric nitrogen deposition, agricultural runoff, and runoff from developed land are locally important across the region. The results from this study could complement research and inform water-quality management activities in the Southwest region. Examples might include identifying potentially impaired waterbodies and guiding remediation efforts where impairment has been documented, explaining the spatial patterns in harmful algal blooms, and providing estimates of sediment and nutrient loadings where such data are scarce or non-existent.

Introduction

High levels of nutrients and suspended sediments in waterbodies can adversely affect agricultural, domestic, industrial, recreational, and municipal water users and the environment. Excessive nutrients in water can contribute to nuisance aquatic plant growth and harmful algae blooms (HABs) and negatively impact the health of organisms that live in or consume water (U.S. Geological Survey, 1999; U.S. Environmental Protection Agency, 2010). For example, nutrient-enhanced eutrophication and associated oxygen depletion can be fatal to fish. Also, consumption of water with high nitrate concentrations can be toxic to humans–particularly children. Although suspended sediment occurs naturally in streams, high levels can impact flow dynamics, disrupt in-stream photosynthesis through increased turbidity, alter plant, fish, macroinvertebrate, and algal communities, and enhance the transport of pollutants that attach to suspended material (Griffiths and Walton, 1978). Additionally, increased settling of sediment can result in burial of stream features such as fish spawning habitat and lead to reservoir sedimentation, which causes reductions in storage capacity (Morris and Fan, 1998).

Water-quality and water supply are important environmental issues in many areas of the Southwest region of the United States. The U.S. Environmental Protection Agency requires states to monitor streams for pollutant stressors and to assess if such stressors affect water quality and impede designated uses. The results from these biannual stream assessments show that many stream reaches in the Southwest region are impaired by nutrients and sediment (New Mexico Environmental Department, 2012; Colorado Department of Public Health and Environment, 2013; Utah Department of Environmental Quality, 2014; Nevada Division of Environmental Protection, 2014; California Environmental Protection Agency, 2015; Wyoming Department of Environmental Quality, 2015; Arizona Department of Environmental Quality, 2017). Nutrient over-enrichment is also recognized as a serious threat to coastal waters throughout most of the United States and the estuaries in Texas along the Gulf Mexico have been identified as being at risk for such impairment (Bricker and others, 2007). Additionally, water availability is a serious concern in the arid areas of the western United States because of the way surface water is allocated, the depletion of ground water from over-pumping, and diminishing supplies due to drought stress (Anderson and Woosley, 2005).

Understanding the spatial variability of streamflow, nutrients, and suspended sediment and their drivers can help water resource managers and policy makers anticipate, prioritize, and manage water supply and water quality. To that end, statistical modeling can be used to understand how climate, land use, and other landscape characteristics influence streamflow and the transport and fate of nutrients and suspended sediment. SPAtially Referenced Regression On Watershed attributes (SPARROW) models (Schwarz and others, 2006) correlate estimated mean annual streamflow or loads of nutrients or suspended sediment in streams with sources and transport factors. These models extrapolate local monitoring data to unmonitored streams across a large region, predict contaminant loadings to downstream receiving waters, determine the importance of source types and locations, and provide a tool for evaluating proposed improvement strategies such as Total Maximum Daily Load (TMDL) regulations.

SPARROW models offer several advantages for assessing hydrologic and water-quality conditions across large regions. One is that they are developed using statistical algorithms that optimize the fit of model coefficients and, therefore, can be used to objectively identify the environmental factors that have an observable linkage with in-stream conditions. In that way, the models can be used to identify such things as the primary sources of a water-quality constituent. A second advantage is that SPARROW models are designed to utilize the detailed spatial information inherent in digital geographic data sets and synthesize that information in a way that can be related to the spatial scale of available monitoring data, while still retaining the underlying spatial resolution for prediction purposes. In that way, SPARROW models provide a framework for integrating a wide range of different types of data and utilizing all that information to provide spatially detailed estimates of in-stream conditions. A third example of those advantages is that SPARROW models provide estimates that are fully linked in space through a digital stream network so that upstream environmental factors can be related to downstream conditions. All these advantages of SPARROW provide a means of mapping water-quality conditions over large regions while retaining significant spatial detail, mapping the factors that affect in-stream conditions, and relating upstream environmental factors such as sources of model constituents to downstream conditions.

Previous SPARROW models have covered all or part of the Southwest region, but the spatial scope, estimated parameters, and time periods for those models differed from those described in this study. Anning and others (2007) focused on dissolved solids across much of the Southwest region, Kenney and others (2009) and Miller and others (2017) focused on dissolved solids in the Upper Colorado River Basin, and Anning and Flynn (2014) developed a nation-wide dissolved solids model. A SPARROW model of base flow across the Southwest was also developed by Miller and others (2016). Additionally, SPARROW models have been developed for large regions of the conterminous U.S as part of a larger effort conducted by the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) (Preston and others, 2011). These models extended over six large regions that covered all but the Southwest region, were focused on nutrients, and were based on a 2002-time frame. Since those models were developed, technology, scientific understanding and data availability have all advanced and the work described in this report was performed to develop improved models based on those advancements. The new models are based upon many improved data sets, which should provide water-quality information that better supports management agencies as they perform their important work. The new models developed by the USGS NAWQA build upon the previous models in several important ways. First, the new models are based on a 2012 time frame, a full 10 years after the previous set of models, and in that way are more representative of the current decade. The list of water-quality constituents for which models were developed was also expanded from one that includes only nutrients (nitrogen and phosphorus) to one that includes streamflow and suspended sediment. These additional constituents are of value in themselves, but they are also related to nutrient levels and provide a broader basis of information for understanding the factors affecting nutrient conditions in waterbodies.

This report describes SPARROW models developed to simulate long-term mean annual streamflow, total nitrogen, total phosphorus, and suspended-sediment transport in streams and rivers in the Southwest region of the U.S. (fig. 1) based on inputs and management practices centered near 2012, the base year of the models. The Southwest is one of five areas of the U.S. for which SPARROW models for similar constituents were developed as part of a national modeling effort by the U.S. Geological Survey. The other four areas are the Northeast, Southeast, Midwest, and Pacific. The models were based on the most detailed databases available for describing hydrologic and water-quality conditions and the environmental factors affecting them in the 2012 time frame. These databases include hydrologic and water-quality information for streams throughout the region, sources of contaminants such as point-source discharges and agricultural practices, and environmental characteristics that affect fate and transport of contaminants. All these databases were integrated by relating them to a spatial framework defined by a digital stream network. The models were then calibrated to optimize the fit of model coefficients and identify the dominant factors affecting hydrologic and water-quality conditions locally as well as downstream.

The objectives of this study were:

1. To calibrate SPARROW models of streamflow and total nitrogen, total phosphorus, and suspended-sediment load for conditions representative of the 2012 time frame in the Southwest region of the United States;
2. To estimate mean annual yields of water, total nitrogen, total phosphorus, and suspended sediment in monitored and unmonitored stream reaches; and
3. To quantify the contributions from different sources to the estimated yields of water, total nitrogen, total phosphorus, and suspended sediment.

SPARROW models were developed to represent streamflow and the sources, fate, and transport of nutrients and suspended sediment in streams and rivers of the Southwestern United States during 2012 (Miller and others, 2020).

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

Study Area Description

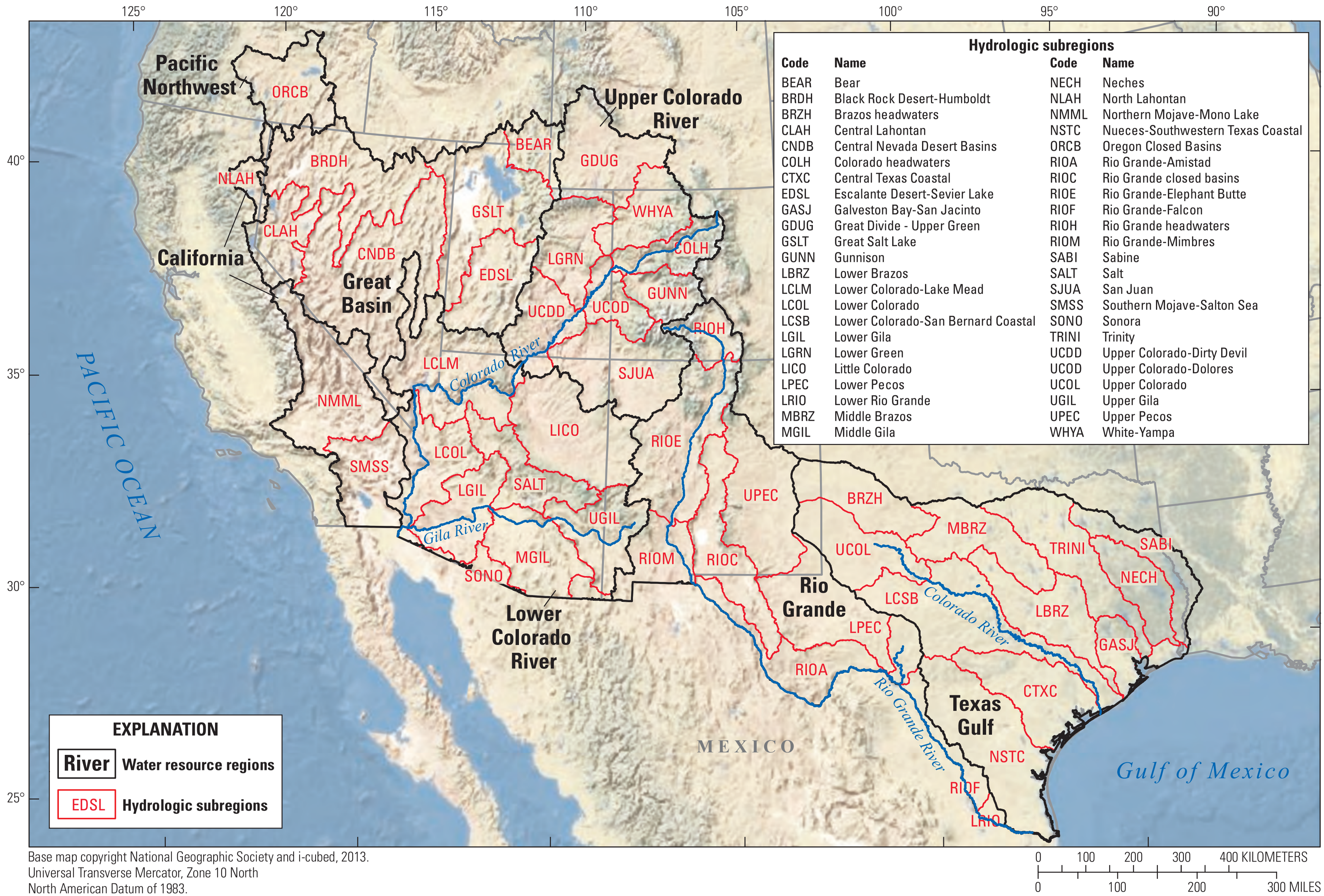
The Southwestern region covers about 2,100,000 square kilometers (km^2) of the United States, contains part or all of seven water-resources regions (fig. 2 and table 1), and includes the U.S. parts of the Rio Grande and Colorado River Basins, several rivers in Texas that drain to the Gulf of Mexico, and many internally-drained basins. Extensive manipulation of the natural hydrology occurs throughout the region, mostly diversions for municipal water supply and irrigation. In 2011, brushland (defined as grassland, shrub/scrub lands, and barren lands) covered 65.8 percent of the U.S. part of the region, forest land covered 13.5 percent, agricultural land covered 6.65 percent, and developed land covered 2.74 percent (fig. 3) (Homer and others, 2015).

The Texas Gulf water-resources region contains several rivers that flow to the Gulf of Mexico. Nearly half the region is brushland and 25 percent is agricultural land, and it contains more developed land than the other water-resources regions in the Southwest (and it includes the cities of Houston, Dallas-Fort Worth, and San Antonio). Precipitation is generally greater in this water-resources region than in the other water-resources regions in the Southwest, averaging 860 millimeters per year (Wieczorek and others, 2019). The Rio Grande water-resources region (about 63 percent of which is within the U.S and drains to the Gulf of Mexico), the Upper Colorado and the lower Colorado River water-resources regions (which drain to the Gulf of California), and the Great Basin water-resources region (which includes internally-drained basins that flow into one of the many playas or large terminal lakes such as the Great Salt Lake) consist mostly of brushland (84, 67, 75, and 79 percent of their U.S. areas, respectively). The Southwest region also includes small areas of the Pacific Northwest and California water-resources regions that do not drain to the Pacific Ocean, and these also consist mostly of brushland (83 and 89 percent of their areas, respectively). These six regions are also generally arid, averaging between 200 and 360 millimeters of precipitation per year (Wieczorek and others, 2019).

Table 1. Selected hydrologic characteristics for the Southwest region of the United States.

[Stream, lake, and reservoir data from NHDPlus Version 2]

Hydrology characteristic	Water resources region							
	Texas Gulf	Rio Grande	Upper Colorado River	Lower Colorado River	Great Basin	Pacific Northwest	California	Southwest region
Two-digit hydrologic unit code	12	13	14	15	16	17	18	19
Count of all reaches	69,241	56,983	85,846	101,574	96,963	9,595	24,342	444,544
Length of all reaches, kilometers	208,721	162,285	196,357	264,128	228,442	21,227	63,585	1,144,744
Length of perennial reaches, kilometers (percentage of total length)	53,249 (26)	14,782 (9.1)	47,514 (24)	11,583 (4.4)	30,453 (13)	5,023 (24)	4,912 (7.7)	167,517 (15)
Length of intermittent reaches, kilometers (percentage of total length)	155,472 (74)	147,503 (91)	148,843 (76)	252,545 (96)	197,988 (87)	16,204 (76)	58,673 (92)	977,227 (85)
Area in lakes and reservoirs, square kilometers (percenage of total area)	5,532 (1.1)	690 (0.1)	1,548 (0.5)	1,169 (0.3)	6,748 (1.6)	625 (1.3)	1,769 (1.3)	18,081 (0.8)



Base map copyright National Geographic Society and i-cubed, 2013.
Universal Transverse Mercator, Zone 10 North
North American Datum of 1983.

Figure 2. Modeling domain for the SPARROW (SPAtially Referenced Regression On Watershed attributes) streamflow, total nitrogen, total phosphorus, and suspended-sediment models developed for the Southwest region of the United States.

Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Universal Transverse Mercator, Zone 10 North. North American Datum of 1983.

Land cover types from National Land Cover Database (2011)

Figure 3. Land cover in the Southwest region of the United States, 2011. [Map taken from Homer and others, 2015].

Methods

Four SPARROW models were developed to identify major factors affecting water supply and water-quality within the Southwest region for 2012. To develop the models, datasets describing water-quality information, sources of contaminants such as point-source discharges and agricultural practices, and environmental characteristics that affect the fate and transport of contaminants were related to a digital stream network and that integrated database was used to calibrate the models and subsequently to estimate streamflow and constituent load.

Data Compilation

Development of the SPARROW models for this study required a substantial amount of data compilation. A SPARROW model is built using:

1. The surface-water drainage network within the modeling domain;
2. The dependent variables of streamflow, nutrient loads, and suspended-sediment loads; and
3. The explanatory variables of watershed attributes including constituent sources and the physical and chemical watershed properties that affect delivery to surface water and loss within free-flowing streams and impoundments.

The streamflow data, load data, and watershed attribute data were spatially referenced to the digital surface-water drainage network which forms the spatial framework of the models.

Surface-Water Drainage Network

The surface-water drainage network used to develop the four SPARROW models for the Southwest region was an enhanced version of the NHDPlus Version 2 (McKay and others, 2017; Brakebill and others, 2020). This enhanced version of NHDPlus Version 2 (hereinafter, “E2NHDPlus2”) represents the water drainage network of the United States with features such as rivers, streams, canals, lakes, ponds, coastlines, and reservoirs. The E2NHDPlus2 data, in digital vector geographic information system (GIS) format, are designed to be used in general mapping and in the analysis of surface water systems. Reach flowlines in the dataset were developed from stream information found on 1:100,000 topographic maps. Each reach in E2NHDPlus2 is a line segment that starts at any point of channel initiation or a tributary junction and ends at the next downstream tributary junction. In addition, the E2NHDPlus2 also contains incremental catchments for each reach in the network that are based on data from the National Elevation Dataset. The incremental catchment for a reach is defined as the area that drains directly to a given reach without passing through another reach. The E2NHDPlus2 includes extensive catchment and reach-level data. These attributes include

1. Topologic information needed to route water and constituents through the network;
2. Information about streams and waterbodies within the network;
3. The area of each incremental catchment and the contributing upstream area for each incremental catchment, along with the portions in the United States and Mexico;
4. Information about the type of catchment and stream (such as if it occurs on the coast, if it originates or terminates within that catchment, or if it is perennial or intermittent); and
5. Stream characteristics such as mean annual streamflow, velocity, and time of travel.

Network Attribute Modifications

Although the E2NHDPlus2 is a comprehensive and detailed representation of the surface hydrology of the Southwest region, some modifications were still necessary before model development could begin. The E2NHDPlus2 identified 15 percent of total stream-reach length in the Southwest region as perennial (table 1). For modeling purposes, a reach was deemed perennial if it was coded in the E2NHDPlus2 as perennial, coastline, or unnamed artificial path that was not a headwater or terminus, or if the catchment for the reach contained an estuary, perennial lake, reservoir, or swamp. Subsequent refinements were made, however, after these general criteria were initially applied. Namely, the perennial status for some reaches (as specified in the E2NHDPlus2) was changed to intermittent when the 7-day low flow, 10-year return period (7D10Q) at nearby USGS streamgage stations was less than a threshold value 0.01 cubic feet per second (ft^3/s). Many of the reaches initially deemed perennial were changed to intermittent because the evaluation period for the 7D10Q (WY 2000–14) was dryer than average for many parts of the Southwest region. In places within the E2NHDPlus2network, where a stream reach is braided the entire flow or contaminant load is generally routed down only one of the two braids, and the other braid has no flow or load. In a small number of cases, flow was re-routed down alternate paths so that it would pass through a reach with a monitoring station, rather than an adjacent reach. This was done to provide better agreement between observed and predicted streamflow or contaminant loads in the models.

Local Diversions And Trans-Basin Transfers

Because of the Southwest regions's dry climate, many artificial conveyance systems have been constructed to transport water from streams to the water's place of use. In many cases such use occurs nearby, while in other cases the water is conveyed tens, if not hundreds, of miles. In some cases, the conveyances divert water from one stream and deliver it to another stream far away, where it flows downstream some distance and is then diverted for its intended use. Several adjustments were made to the E2NHDPlus2 to account for such artificial re-routing of water in the river systems of the Southwest region. For this study, local diversions generally represented water removed from a stream and used in a location such that a fraction of that water could return to the stream somewhere within the six-digit Hydrologic Unit Code (HUC6) watershed in which that stream was located. In contrast, trans-basin transfers generally represented water that was removed and delivered to some location outside the HUC6 watershed of the water's origin. Each one of the local and trans-basin diversions was assigned an attribute that represented the proportion of water remaining in the reach downstream of the diversion. While the E2NHDPlus2 included this value for the trans-basin transfers (in addition to the amount of water transferred), it did not include it for most of the local diversions.

Local diversions for public water supply and irrigation account for most of the consumptive use in the Southwest region (Wieczorek and others, 2019). For those two uses, county-level surface water withdrawals were obtained for 2000, 2005, and 2010 from the USGS Water Use Program (U.S. Geological Survey, 2015) and then averaged to represent the county-level surface water withdrawals for the 2000–14 period. The average county-level withdrawals were then disaggregated to a limited number of reaches in each county—usually just one or two reaches that were identified as likely points of diversion. Counties with average surface water withdrawals less than 1.0 MGD (about 1.5 ft^3/s) were not included, however. The reaches were selected to represent county surface-water withdrawals using the following priority:

1. A reach was known to contain a diversion structure. Such reaches tend to be at the upstream end of a large valley with irrigation in the floodplain. The diversion dams were either in the National Inventory of Dams (U.S. Army Corps of Engineers, 2019) and (or) could be seen in satellite images.

2. A reach was expected to have a diversion, but an actual diversion structure was not identified. For irrigation, this was at the head of the most substantial agricultural valley in the county. For public water supply diversions, the assigned reach contained either a large reservoir (greater than 10 km^2) or had the largest streamflow near the largest city in the county.

3. Where neither of the above occurred, the reach with the largest streamflow in the county was assigned the diversion. This was more typical for cases in the Texas Gulf water-resources region, where there may be many diversions dispersed about the county. While the diversion location was not necessarily precise, this approach ensured that the diversions within those counties were represented in the models.

In total, 157 public water supply diversions and 237 irrigation diversions were identified and quantified for the Southwest region. While the attributes for most local irrigation diversions were estimated as described above, exceptions were made for those in the Lower Gila River and Lower Colorado River subregions of the Lower Colorado water resources region and the Imperial Valley subregion of the California water resources region. For each diversion in those subregions, the E2NHDPlus2 included both an attribute that represented the proportion of water remaining in the reach downstream of the diversion as well as an estimate of the streamflow returned to the hydrologic network, which was included with one of the sources in the streamflow model.

Streamflow And Calibration Load Information

The four Southwest region SPARROW models were calibrated using estimates of long-term mean annual streamflow and total nitrogen, total phosphorus, and suspended-sediment loads, based on available monitoring data. A large and spatially distributed set of streamflow and load monitoring sites, located across the wide range of watershed characteristics found throughout the Southwest region, was required to develop the models. Estimates of long-term mean streamflow required extended periods of streamflow data and estimates of long-term mean annual loads required extended periods of coincident constituent concentration and streamflow data. Water-quality data came from the USGS and several state and local agencies (table 2). Streamflow data largely came from the USGS and, to a lesser extent, from the International Boundary Water Commission for monitoring stations near the U.S.-Mexico border (International Boundary and Water Commission, 2019). A larger number of calibration stations improves SPARROW models by reducing the uncertainty in the estimated model coefficients associated with important constituent sources and transport characteristic (Schwarz and others, 2006; Preston and others, 2009).

SPARROW is a steady-state, mass balance model that relies on the assumption that the dependent and explanatory variables reflect conditions for comparable time periods (Schwarz and others, 2006). Use of a uniform period of record (or closely comparable periods of record) to estimate all variables removes the confounding effect of temporal variability from the SPARROW spatial analysis. For the streamflow model, comparability among estimates of

Table 2. Sources of water-quality data used to estimate calibration loads for total nitrogen, total phosphorus, suspended sediment, total suspended solids used in the SPARROW models developed for the Southwest region of the United States.

Federal agencies		State agencies		Local agencies and other sources		
Agency	**Number of stations**	**Agency**	**Number of stations**	**State**	**Source**	**Number of stations**
U.S. Geological Survey	154	Arizona Department of Environmental Quality	1	Arizona	Cocopah Indian Tribe Environmental Protection Office	2
National Park Service	2	California Department of Water Resources	5	Colorado	Adrian Brown Consultants Incorporated	1
		California Environmental Protection Agency	4		Advanced Sciences Incorporated	2
		Colorado Department of Public Health and Environment	31		CBS Operations, Incorporated	1
		Louisiana Department of Environmental Quality	2		Denver Water Department	2
		Nevada Department of Conservation and Natural Resources	67		The Rivers of Colorado Water Watch Network	9
		Texas Commission on Environmental Quality	314	New Mexico	Pueblo of Jemez	3
		Utah Department of Environmental Quality	44		Pueblo of Taos	3
				Texas	Meadows Center for Water and the Environment	33
				Utah	Utah State University	2

the dependent variable was achieved by using the mean annual value for a common 15-year period (2000–14) for all stations that was based on continuous daily streamflow records. Stations missing more than 2 years of record were excluded from the calibration data set for the streamflow model, however. Where appropriate, comparability between dependent and explanatory variables for the streamflow model was achieved by using mean values for 2000–14.

For the total nitrogen, total phosphorus, and suspended-sediment models, however, comparability of conditions could not be guaranteed using mean values for 2000–14 for the dependent and explanatory variables for two reasons (Schwarz and others, 2006):

1. The water-quality monitoring data used to estimate loads represented different periods of record, sample size, and hydrologic conditions at different sites, or was affected by long-term trends in water quality, thus potentially introducing artificial differences in load among the calibration sites; and

2. Information for some important explanatory variables was not available for multiple periods and, therefore, it was not possible to compute long-term averages over the same period used to summarize the dependent variable. For example, estimates of source inputs from fertilizer and wastewater discharge using the improved estimation methods described in this report were available only for 2012.

To compensate for these limitations, estimates for the dependent variable (constituent load) in the total nitrogen, total phosphorus, and suspended-sediment models were detrended to a selected base year; that is, they were estimated to represent the load that would have been observed during the period 2000–14 if the dynamic factors causing trend in load were held constant throughout that period, equal to their values in the base year (Schwarz and others, 2006). The base year selected for the Southwest region SPARROW models was water year 2012. The watershed attributes used as explanatory variables (for example, source inputs, climatic data, and land management practices) in these models represented 2012 conditions or conditions as close to 2012 as possible. The predictions from the total nitrogen, total phosphorus, and suspended-sediment models, therefore, represented conditions that would have been observed between 2000 and 2014 given the hydrologic conditions throughout that period and given source inputs and management practices that were like the ones occurring in 2012.

The calibration loads used for the Southwest region total nitrogen, total phosphorus, and suspended-sediment SPARROW models were estimated using a three-step process. First, fixed monitoring stations having sufficient water-quality data (Saad and others, 2019) were matched to a nearby streamflow gaging station having mostly continuous records for water years 2000 through 2014. In some cases, the water-quality data associated with a streamflow gaging station came from multiple sites nearby on the same or an adjacent stream reach.

The mean annual load for 2000–14 was then estimated for each monitoring site using one of two methods (Saad and others, 2019). The Beale's Ratio Estimator (BRE) was used to estimate a mean annual load for 2000–14 when there was no trend in the load, because this approach was shown to have little bias and was better at estimating long-term mean annual loads than most regression approaches (Lee and others, 2016). When there was a significant trend in load, however, the USGS Fluxmaster regression method (Schwarz and others, 2006) was used to estimate a mean annual load for 2000–14 that was then detrended to the 2012 base year to account for differences in record length, hydrologic conditions, and sample size among the calibration stations.

This initial set of potential calibration loads was then evaluated for accuracy. Mean load estimates with a standard error greater than 50 percent were removed from the set of potential calibration loads regardless of which estimation method was used, which is consistent with the approach used in previous SPARROW studies. Potential bias in the Fluxmaster-estimated loads were evaluated using the methods described in Saad and others (2019), and those with unacceptable bias were removed from the data set of potential calibration loads. Some of the mean annual streamflow values and mean annual loads were excluded from the calibration dataset so that the area between nested calibration stations was at least 100 km^2 or was 10 percent of the downstream calibration station's total drainage area. This was done to ensure that some parts of the model region were not spatially over-represented. The streamflow model included 867 calibration streamflow values, the total nitrogen model included 289 calibration loads, the total phosphorus model included 389 calibration loads, and the suspended-sediment model included 351 calibration loads.

Catchment Attributes

The catchment attributes in the Southwest region SPARROW models were the explanatory variables that represented the upland and in-stream sources of water, nutrients, and sediment, and the land-to-water delivery and instream loss processes. These catchment attributes were compiled as part of the NAWQA national SPARROW effort described earlier (Wieczorek and others, 2019), and represented a wide variety of physical aspects of the catchments. These attributes fall into one of the following groups of conditions or characteristics: chemical loading, climatological factors, hydrologic components of the water balance, geologic factors, hydrologic modifications, general hydrologic factors, landscape factors, population infrastructure, topically defined regions, soil characteristics, and topographic features. These attributes were processed for use in the SPARROW model by summarizing them for each incremental E2NHDPlus2 catchment as either a total amount or mean value.

The Spatially Referenced Regression On Watershed Attributes (SPARROW) Calibration Process

The goal of the SPARROW calibration process is to iteratively estimate coefficients for each explanatory variable that minimizes the difference between measured and estimated loads (or streamflow). The coefficient estimation process starts at headwater reaches, where an estimate of incremental load for each stream reach is generated using initial model coefficients. Coefficients for permanent losses in streams and impoundments are also estimated. The incremental load is accumulated moving downstream through the surface-water drainage network until a calibration station is reached. The accumulated load is then adjusted to match the measured load at the calibration station. The accumulation process and calibrations station adjustment continue downstream until a terminal reach is encountered (for example, an internal drainage or estuary). At this point, a nonlinear least squares (NLSS) regression is applied to adjust the initial coefficients based on the initial differences between the measured loads at calibration stations and the non-adjust estimated loads at those calibration stations. Accumulated loads are then re-estimated using the adjusted coefficients. This continues until the difference between the measured and estimated loads is minimized. For the application of SPARROW to the Southwest region, 90-percent confidence intervals were estimated for each coefficient using the standard errors from each model and the quantile from its standard t distribution. Ninety-percent confidence intervals were also estimated for the model predictions by using a bootstrap resampling method (Schwarz and others, 2006) that entailed repeated estimation of the model using subsets of the calibration data (200 times in these applications of the model).

Interpreting The Spatially Referenced Regression On Watershed Attributes (SPARROW) Model Coefficients

Model coefficients can be used to understand the major sources and processes controlling water, nutrient, and sediment transport through a watershed. The watershed attributes evaluated in the Southwest region SPARROW models represented spatially variable sources of water, sediment, or nutrients to streams (source terms), and processes that influence their transport from land to water (delivery terms) and in-stream and impoundment loss (loss terms). The significance of all model terms was evaluated at the 5 percent level (alpha = 0.05), using a one-sided t-test for the source and loss terms because they could only be positive and a two-sided t-test for the delivery terms because they could be either positive or negative. The magnitude and sign of model coefficients for sources, delivery terms, and loss terms indicate the nature of the relationship between watershed attributes and load estimates. Source coefficient interpretation depends on source units. Coefficients of sources with units of volume per time or mass per time represent the average volume or mass of that source delivered to streams. Coefficients of sources expressed in areal units describe the mass per unit area delivered to streams from these land areas. The sign of delivery term coefficients indicates the direction of the relationship between delivery terms and load estimates. Loss terms (in streams or impoundments) multiplied by their estimated coefficient represent the ratio between the amount of water, sediment, or nutrients entering a stream reach or impoundment and the amount that discharges from that stream reach or waterbody.

Model Specifications

Streamflow Model

Streamflow represents the net combination of direct surface runoff and groundwater baseflow derived from local precipitation within a watershed, supplemental water that is pumped from deep aquifers and used primarily for irrigation or municipal water supply, and water that is added or removed through human activities such as diversions for municipal water supply and irrigation and trans-basin transfers. Four streamflow sources were evaluated for the Southwest region:

1. Precipitation minus actual evapotranspiration (PME; expressed in ft^3/s to be consistent with the calibration data set) represented the mean difference between precipitation and evapotranspiration for the water years 2000 through 2014 for each E2NHDPlus2 catchment (McCabe and Wolock, 2011) and, as a result, these estimates did not account for consumptive water use or transfers, or the local variations in watershed properties that can influence this parameter.

2. Inflows consisted of streamflow entering from Mexico, trans-basin transfers, and a limited number of return flows from irrigated land. Within Mexico, most of the larger tributaries to the Rio Grande and other rivers are monitored near the border by the International Boundary and Water Commission (2019) and, when possible, this information was used to estimate inflows from Mexico into the Southwest region. The streamflow for non-monitored streams entering from Mexico was estimated by multiplying their Mexican drainage area by a fixed water yield of 0.0268 ft^3/s per km^2. This value represents the average yield for similar U.S. watersheds that was obtained by running a preliminary version of the Southwest region SPARROW streamflow model. Although a few streams flow from the United States into Mexico and then back into the United States, such as the Santa Cruz River and San Pedro River, no additional modifications were required to the network to account for these inflows because the E2NHDPlus2 contains topology for the SPARROW model to account for transport through these reaches.

3. Wastewater discharge represented the total 2012 discharge to surface water within each E2NHDPlus2 catchment from municipal wastewater treatment plants with National Pollutant Discharge Elimination System (NPDES) permits (Skinner and Wise, 2019).

4. Spring discharge represented the discharge from natural springs within each E2NHDPlus2 catchment. The SPARROW model generally reflects modes of surface transport and, as a result, it is built on the assumption that subsurface transport occurs parallel to the surface and is captured within the modeled transport. Larger springs, however, likely originate from regional aquifers that do not necessarily have flow paths congruent with surface drainage. To account for their addition of flow or contaminant load to reaches, data for springs with a mean annual discharge greater than 5 ft^3/s were retrieved from the USGS NWIS database (U.S. Geological Survey, 2015). The purpose of using the 5 ft^3/s flow-threshold was to increase the likelihood that spring discharge (1) was sourced from a regional aquifer, and (2) was somewhat evenly represented across the model space and not influenced by the spatial bias resulting from the priorities of data collection programs.

Both natural and anthropogenic properties and processes were evaluated for their influence on the delivery of water from the land to streams (Wieczorek and others, 2019). Natural water loss from streams through evaporation and groundwater recharge and through engineered diversions were also evaluated. Natural water losses were modeled as a first-order decay rate, based on the reach length (1/km), which represented the fraction of streamflow that was lost to evaporation and groundwater recharge in each reach. Diversions for water supply and irrigation were represented by the proportion of water remaining in an affected reach. Coefficients were estimated for each diversion type, and these coefficients represented scaling factors for those proportions.

The coefficients estimated by the streamflow model for water supply and irrigation diversions were used in the total nitrogen, total phosphorus, and suspended-sediment models rather than estimating coefficients specifically for each one of those models, and this approach was based on two assumptions. First, that the streamflow model provided more accurate estimates of the effects of water diversions compared to the constituent models. The streamflow model had many more calibration stations than the constituent models and, as a result, provided much better spatial coverage. In addition, the calibration data used in the streamflow model were likely more precise than the calibration data used in the constituent models because the streamflow calibration data were based on measured daily values rather than estimated loads. The second assumption was that nitrogen, phosphorus, and suspended-sediment are removed at the diversions in the same proportion as streamflow. There is no information available that shows what proportion of nitrogen, phosphorus, and suspended sediment is removed at diversions compared to streamflow in the Southwest region nor is there information readily available that could be used to make that estimate (for example, the typical design or construction of the diversions, the relative proportion of dissolved and particulate load, or the degree of stream mixing). Therefore, an assumption that the values are equal likely provided the best possible estimates.

Total Nitrogen And Total Phosphorus Transport

Both natural and anthropogenic sources can contribute nitrogen and phosphorus to streams. Nitrogen naturally occurs in streams through soil bacteria fixing atmospheric nitrogen. This nitrogen can then be transported by groundwater flow or overland runoff and discharged to streams. The area of undisturbed land cover types (forest land and brushland) within each catchment was used to represent nitrogen fixation by soil bacteria. Spring discharge to streams was also a potential source of nutrients in the models. Weathering of phosphorous minerals within a watershed and stream channels naturally contributes phosphorous to steams. Two representations of this process were tested. For the first approach, a scaling factor representing the phosphorus content of local rocks and soil (Nardi, 2014) was applied to the catchment area of each reach. For the second approach, a delivery term representing the phosphorous content of local soil and rocks was applied to the area of each catchment. The contribution of phosphorus from stream channels was represented by the length of the E2NHDPlus2 reaches.

Anthropogenic activities such as agriculture, fossil fuel combustion, and urbanization can introduce large amounts of nitrogen and phosphorus into a watershed and were also evaluated in the models. Nutrient sources included commercial fertilizer, livestock manure, atmospheric deposition, developed land, on-site wastewater treatment, and point-source wastewater discharge. The following sections provide more detail on how each anthropogenic nutrient source was estimated.

Commercial Fertilizer

Commercial fertilizer applied to each E2NHDPlus2 catchment in 2012 was estimated from regression models that relate county-level commercial fertilizer sales data to spatially referenced data on incremental catchment attributes (Stewart and others, 2019). Separate regression models for nitrogen and phosphorus were developed to estimate nationally weighted, elemental fertilizer used on agricultural lands for the conterminous United States. This approach built on earlier efforts that used Association of American Plant Food Control Officials data on fertilizer sales to provide county-level estimates of nitrogen and phosphorus fertilizer use (Gronberg and Spahr, 2012). The spatially referenced method improves on these previous efforts by allowing nitrogen to phosphorus ratios to vary at the catchment scale depending on what types of fertilizer were used and expanding the set of variables used to allocate county-level sales data to the catchment scale. The models included catchment-level factors that were either primary determinants of fertilizer use, such as the acreage of different crop types, or measures reflecting the intensity of use.

Livestock Manure

The amount of nitrogen and phosphorus from livestock manure for the Southwest region was based on county-level estimates of nutrient inputs from animal manure that were calculated from animal population inventories in the 2012 Census of Agriculture (Gronberg and Arnold, 2017). The 2012 county-level estimates were disaggregated to the NLCD cultivated crops and pasture land in each county and then summed for each E2NHDPlus2 catchment.

Atmospheric Deposition

The total deposition of atmospheric nitrogen within each E2NHDPlus2 catchment was equal to the mean of the values for 2010–12 estimated by the U.S. Environmental Protection Agency's (EPA's) Community Multiscale Air Quality Modeling System (CMAQ; U.S. Environmental Protection Agency, 2018). The estimates of total atmospheric nitrogen deposition were equal to the sum each of the individual CMAQ parameters:

1. Bias and precipitation adjusted wet deposition of oxidized nitrogen;
2. Bias and precipitation adjusted wet deposition of reduced nitrogen;
3. Mean dry deposition of total oxidized nitrogen; and
4. Mean dry deposition of total reduced nitrogen.

Developed Land

The runoff of nutrients from developed land within each E2NHDPlus2 catchment in 2012 was represented by the total area of National Land Cover Database (NLCD) low, medium, and high intensity developed land (Homer and others, 2015).

Nitrogen From On-Site Wastewater Treatment

The leaching of nitrogen from on-site wastewater treatment systems was estimated by using 1990 census data to obtain a ratio of the number of people using on-site wastewater treatment in a census block group to the total number of people within that census block group. This ratio was then applied to the total 2010 population for each census block group and summed at the catchment scale (LaMotte, 2018).

Wastewater Discharge

Previous SPARROW modeling has shown that some of the largest contributors to surface water nutrient loads are point-source facilities, such as municipal wastewater treatment facilities (WWTFs), that discharge directly to streams (Preston and others, 2009). As part of a nationwide effort, Skinner and Wise (2019) compiled effluent discharge and estimated total nitrogen and phosphorous loads for water year 2012 for 632 major NPDES point-source facilities and 1,354 non-major NPDES point-source facilities that discharged to surface water within the Southwest region. The point-source facility data used to estimate nutrient loads for 2012 were obtained from several sources. These data were primarily obtained from U.S. Environmental Protection Agency's Permit Compliance System (PCS) and Integrated Compliance Information System (ICIS) databases (U.S. Environmental Protection Agency, 1990), but data that were missing from those databases were often available from state databases. The U.S. Environmental Protection Agency Clean Watershed Needs Survey (U.S. Environmental Protection Agency, 2017) was another source of point-source discharge facility information that was not available through the U.S. Environmental Protection Agency's PCS or ICIS databases or state databases. The methods used to compile, check, and calculate the 2012 point-source nutrient loads closely followed those of McMahon and others (2007) and Maupin and Ivahnenko (2011) when they estimated 2002 nutrient loads for the United States. Skinner and Wise (2019) provide detailed descriptions of the methods used to estimate the 2012 nutrient loads, their data quality assurance and quality control procedures, and the ways that their approach differed from previous efforts to estimate point-source nutrient loads. The general approach was to estimate monthly loads of total nitrogen and total phosphorus from each facility based on measured daily discharge and either measured or surrogate total nitrogen and total phosphorus concentrations, and then sum the monthly load estimates for water year 2012.

The 2012 nutrient loads estimated for the NPDES wastewater facilities often relied on surrogate effluent nutrient concentration values because sufficient facility-specific data were often not available. As a result, 82 percent of the total nitrogen load and 72 percent of the total phosphorus load for the Southwest region was estimated using some type of surrogate nutrient concentration. Ideally, the nutrient loads for all the NPDES wastewater facilities would have been based on measured values–but this was not possible and using the surrogate nutrient concentrations not only filled in the data needed to calibrate the SPARROW nutrient models, it allowed for a regional picture of point-source loads (table 1.1). For example, the point-source facilities in the Texas Gulf hydrologic region were responsible for 77 and 69 percent, respectively, of the total nitrogen and total phosphorus discharged from all point source facilities in the Southwest region

Watershed factors were evaluated for their influence on the delivery of nitrogen and phosphorus from upland areas to streams and for the loss of nitrogen and phosphorus in both free-flowing streams and impoundments. The mean incremental water yield predicted by the streamflow model (that is, the water generated exclusively within each incremental catchment), along with other landscape properties that might influence nutrient delivery (Wieczorek and others, 2019), were evaluated as a potential delivery terms in the total nitrogen and total phosphorus models. Particle settling in streams and impoundments can permanently remove nitrogen and phosphorous from waterbodies (although some particles can be re-suspended). Denitrification by benthic bacteria can also permanently remove nitrogen from waterbodies. Plant growth and decay in free-flowing streams and impoundments, however, was assumed to balance for a steady-state model; therefore, no net gain or loss of nutrients was expected from these processes and they were not evaluated in the models (Schwarz and others, 2006). The fraction of nitrogen and phosphorous load lost to in-stream processes was represented in the models through the multiplication of a first-order decay rate (inverse days) by the reach time of travel. The loss of nitrogen and phosphorous in impoundments was represented in the models by a hypothetical settling velocity. The values for reach time of travel and impoundment settling velocity were based on predictions from the Southwest Region SPARROW streamflow model.

Suspended-Sediment Transport

Suspended sediment in streams can come from two general sources: upland erosion and erosion within stream corridors (Swanson and others, 1982). Upland sediment sources include runoff from various land cover types and geologic formations, soil creep, debris avalanches, and slump and earth flow, whereas stream corridor sources include erosion of stream banks and re-suspension of sediment from channel beds in addition to sediment derived from mass wasting where channels intersect valley sides and terrace walls (Gellis and others, 2016). Climate, topography, geology, landslides and wildfire history, stream morphology, and hydrology all influence the amount of suspended sediment.

Stream power, which depends on streamflow and channel slope and was calculated for each reach in the E2NHDPlus2, is the rate at which the potential energy of a stream is dissipated against its bed and banks and is an important control on the amount of suspended sediment in fluvial systems (Yang and Stall, 1974). A stream reach over which there is an increase in stream power would be expected to gain suspended sediment as the energy from the stream erodes the channel. A stream reach over which there is a decrease in stream power would be expected to lose suspended sediment as sediment settles and gets deposited within the channel. Stream power in the suspended-sediment model was evaluated as both a factor affecting stream channel sources (for reaches where there was an increase in stream power) and as a factor affecting net sediment loss (for reaches where there was a decrease in stream power).

Sediment generated by upland sources and within stream corridors were both evaluated in the suspended-sediment model. Upland sediment sources were represented by combining land cover and surface geology. The Southwest region consisted of 9 different NLCD land cover categories (Homer and others, 2015) and 15 different surface geology classes (Soller and others, 2009). Land cover and geology classes were grouped into four generalized classes, respectively. The final land cover classes were agricultural land (6.65 percent of the modeling domain), developed land (2.74 percent), forest land (13.5 percent), and shrubland (65.8 percent). The final geology classes representing similar texture were alluvial sediments (20.4 percent of modeling domain); igneous and metamorphic rocks (14.5 percent), residual material (34.2 percent), and other miscellaneous material (19.6 percent). Open water and wetlands made up 11 percent of the modeling domain, but they were assumed to represent minimal sources of sediment. The intersections of the 4 generalized land cover groups and the 4 generalized surface geology groups produced 16 landscape classes that were initially used to represent upland sources in the suspended-sediment model (table 3). The resulting spatial data set was disaggregated and summed for each E2NHDPlus2 catchment. The sediment generated within stream channels was evaluated as both a function of reach length and as a function of stream power gain.

About 21 percent of the surface geology in the Southwest region consists of material made up of alluvial sediments that are usually found in depositional areas where net sediment generation was expected to be negligible and, as a result, this material was expected to yield much less sediment than the other types of surface geology found across the region. To test this hypothesis, two types of upland sediment sources were evaluated in the model: (1) the area of alluvial sediments inclusive of all land cover groups; and (2) the area of each individual land cover group for all types of surface geology except alluvial sediments.

Watershed factors were evaluated for their influence on the delivery of sediment from upland areas to streams and the permanent loss of sediment in both free-flowing streams and impoundments. The mean incremental water yield predicted by the streamflow model, along with other landscape properties that might influence sediment delivery (Wieczorek and others, 2019), were evaluated as potential delivery terms in the suspended-sediment model. Permanent sediment loss in free-flowing streams was evaluated in the sediment model using two approaches. In the first approach, the fraction of the load that settles to the streambed was calculated by multiplying an estimated first-order decay rate (inverse days) by the reach time of travel (days). The second approach also involved an estimated first-order decay rate but was based on the percentage of stream power lost over each reach. The loss of suspended sediment in impoundments was represented in the models by a hypothetical settling velocity. The values for reach time of travel and impoundment settling velocity were based on predictions from the Southwest Region SPARROW streamflow model.

Accounting For Systematic Differences In Calibration Loads

The water-quality data used to estimate the calibration loads for the suspended-sediment model were collected by the USGS and state and local water-quality agencies and those agencies often have different techniques for collecting and processing water-quality samples. All USGS samples are collected using cross-sectionally integrated and flow-integrated techniques, whereas most other agencies use surface grab sampling. Additionally, the calibration loads used in the suspended-sediment model were based on two different analytical techniques: (1) the standard suspended sediment method (American Society for Testing and Materials, 2006) used by the USGS and (2) the total suspended solids (TSS) method (Rice, 2012) generally used by other state and local water-quality agencies. Standard suspended-sediment concentration is the mass of all the sediment within a known volume of a water-sediment mixture collected directly from a waterbody (Guy, 1969). In contrast, TSS is the mass of suspended material within a subsample of a water-sediment mixture collected from a waterbody. Such subsampling introduces negative bias and more variability, especially when the percentage of sandsize sediment is high because of sediment settling before subsampling (Gray and others, 2000).

Measurements of suspended sediment determined by the two analytical methods described above are generally not used interchangeably (Gray and others, 2000), but limiting SPARROW model estimation to include only loads determined by a single analytic method would induce spatial biases and have too-few observations to produce reasonable model accuracy. An alternative approach is to include suspended-sediment load estimates based on both analytical methods, but also specify a term in the model that can account for relative bias. The study by Gray and others (2000) identified a proportional downward bias in TSS measurements by as much as 20 percent. Given this finding, the presumption in the SPARROW model is that TSS loads are smaller than the equivalent suspended-sediment load by a fixed proportion.

The SPARROW model includes a technique to account for systemic differences between two groups of calibration loads (Gregory Schwarz, U.S. Geological Survey, written commun., April 7, 2017). The model evaluates an independent variable that takes either a value of one (to indicate one group) or a value of zero (to indicate the other group). During model calibration SPARROW estimates a coefficient for this independent variable and, because it only applies to reaches associated with the first group of loads, it can be interpreted as a scaling factor for converting between the two groups. The inverse of the exponential function of the estimated coefficient represents

Table 3. Generalized land cover and surface geology combinations evaluated as upland sources in the SPARROW suspended-sediment model for the Southwest Region of the United States.

[**Contribution from the combined land cover and surface geology group to the total area of the model domain**: 11.3 percent of the modeling domain consists of open water and wetlands]

Generalized land cover group	Contribution from the land cover group to the total area of the model domain (percent)	Generalized surface geology group	Contribution from the surface geology group to the total area of the associated land cover group (percent)	Contribution from the combined land cover and surface geology group to the total area of the model domain (percent)
Agricultural land[1]	6.65	Alluvial sediments	25.0	1.66
		Igneous and metamorphic rocks	0.33	0.02
		Residual material[5]	34.2	2.28
		Glaciofluvial, proglacial, glacial till, colluvial, lacustrine, eolian, coastal zone, playa, and calcareous biological sediments	40.5	2.69
Developed land[2]	2.74	Alluvial sediments	33.6	0.92
		Igneous and metamorphic rocks	2.65	0.07
		Residual material[5]	35.8	0.98
		Glaciofluvial, proglacial, glacial till, colluvial, lacustrine, eolian, coastal zone, playa, and calcareous biological sediments	27.9	0.77
Forest land[3]	13.5	Alluvial sediments	7.05	0.95
		Igneous and metamorphic rocks	29.3	3.96
		Residual material[5]	55.8	7.53
		Glaciofluvial, proglacial, glacial till, colluvial, lacustrine, eolian, coastal zone, playa, and calcareous biological sediments	7.86	1.06
Brushland[4]	65.8	Alluvial sediments	25.6	16.8
		Igneous and metamorphic rocks	15.9	10.5
		Residual material[5]	35.6	23.4
		Glaciofluvial, proglacial, glacial till, colluvial, lacustrine, eolian, coastal zone, playa, and calcareous biological sediments	22.9	15.1

[1]Cultivated crops and pasture in 2011.

[2]Low, medium, and high intensity developed land and other cleared areas in 2011.

[3]Deciduous, evergreen, and mixed forest land in 2011.

[4]Shrub, scrub, grass, and barren land in 2011.

[5]Soil parent material which has formed in its place of origin.

an average conversion factor between the two groups of loads.

Addressing Spatial Bias In The Model Calibration

SPARROW calibration stations are often nested within the basin of downstream stations. When this occurs, the model prediction at each upstream calibration station is replaced during the model calibration process with its monitored value to eliminate errors from propagating down the stream network and to reduce the correlation across the sub-basin error terms (Smith and others, 1997). The resulting downstream value that is estimated using the upstream measured value is referred to as the “conditioned” value used in model calibration, whereas the value estimated without adjustment is referred to as the “unconditioned” value. This use of conditioned values reduces the potential influence of the downstream sites on the coefficients in the SPARROW model and can result in an underestimation of the residuals compared to when the model is used to completely estimate value throughout the basin (Wellen and others, 2015). During calibration, it is optimal for each monitoring station to have similar influence on the determination of coefficient estimates in the SPARROW model. However, because calibration stations with small nested shares (the fraction of drainage area that is downstream of other calibration stations) tend to have lower residual variance, these stations may be under-represented in the SPARROW statistical calibration process.

To address for the potential unequal influence of the nested basins during SPARROW model calibration, a statistical algorithm was developed in which weights are computed for each calibration station based on its nested share and, if necessary, these weights are used in a subsequent re-estimation of the model using weighted NLLSR (WNLLSR; Schwarz and others, 2006, eq. 1.55). The models were first calibrated with equal weights applied to all calibration stations and the squares of the residuals were then regressed on the nested share. If the nested share was found to be a statistically significant predictor of the squares of the residuals the WNLLSR was then used to re-calibrated the models, using the inverse of the predicted values from this regression as weights. The potential bias related to nested calibration stations was also accounted for by calculating two different RMSE values. A conditioned RMSE value was calculated for each model that reflected the difference between the measured calibration value and the estimated accumulated value that was reset to the measured value during model calibration. An unconditioned RMSE was calculated for each model that reflected the difference between the measured calibration value and the estimated accumulated value without such adjustments.

Because SPARROW model predictions are spatially distributed across a landscape, it is important to consider the spatial pattern of model error. Spatial autocorrelation among model residuals, which may introduce bias into the model parameterization, can be either positive (meaning the residual values at nearby sites are similar) or negative (meaning they are dissimilar). Autocorrelation in the calibration residuals was evaluated for three types of spatial structures or patterns, which corresponded to three different types of modeling or measurement error. The results from these evaluations were then used to make corrections to the model input when spatial correlation was found to be statistically significant at the 5 percent level.

1. Spatial correlation among loose clusters of calibration sites–for example, those located within the same large watershed or ecoregion or within a large area having homogenous land cover, was evaluated using the Moran's I statistic. A positive and significant value for the Moran's I statistic indicated that important watershed processes or sources were not included in the model. This type of spatial correlation can be addressed by including additional predictor variables in the model when possible.

2. Spatial correlation among tight clusters of nested calibration sites–those within 5 km of each other, with similar drainage areas (a ratio less than a factor of two) was evaluated using the Pearson correlation coefficient. A negative and significant Pearson coefficient indicated that the calibration value was mis-estimated at the upstream site in the nested pairs. This type of spatial correlation can be addressed by removing the upstream site in each pair from the calibration data set.

3. Spatial correlation among tight clusters of nonnested calibration sites and nested calibration sites with dissimilar drainage areas (a ratio greater than a factor of two) was also evaluated using the Pearson correlation coefficient. A negative and significant Pearson coefficient indicated that the spatial scale of a source variable was coarser than the spatial scale of the catchment network. This type of spatial correlation can be addressed by randomly selecting one site in each pair and removing it from the calibration data set.

Types of Model Predictions

The SPARROW predictions of streamflow, nitrogen, phosphorus, and suspended-sediment loads across the Southwest region are presented in the following ways for this report:

1. The models were first used to estimate the mean annual incremental yield of water (millimeters per year [mm/yr]), total nitrogen ([kg/km^2]/yr), total phosphorus ([kg/km^2]/yr), and suspended sediment (metric ton per square kilometer per year [(t/km^2)/yr]) for each of the 444,544 E2NHDPlus2 catchments. Incremental yield was equal to the estimated water or load generated within each incremental catchment divided by the catchment area. The mean annual incremental yields are useful for comparing the relative intensity of the streamflow and load generated within catchments because they are normalized for contributing area. The incremental yields were also expressed in two ways: (1) total incremental yield, which represents the total amount generated within each incremental catchment and (2) delivered incremental yield, which represents the amount generated within each catchment that was delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins. The difference between the two values reflects permanent losses such as attenuation in free-flowing streams, losses in impoundments, and diversions for consumptive use, as well as in-stream transfers. The contribution from each source to the total amount of nitrogen, phosphorus, and suspended sediment delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins was also estimated.

   - The contribution from each source to the total amount of nitrogen, phosphorus, and suspended sediment generated within the Southwest Region was also estimated.

2. The total mean annual yields of water, total nitrogen, total phosphorus, and suspended sediment were estimated for each of the 46 hydrologic subregions within the study domain along with the relative contribution from each modeled source to those total yields. These values were equal to the total load generated within each subregion divided by the subregion area.

3. And finally, the median yields of water, total nitrogen, total phosphorus, and suspended sediment were estimated for catchments dominated by specific land cover types.

Model Calibration Results and Predictions

Streamflow

The streamflow model included four source terms, five delivery terms, and four aquatic loss terms (table 4). The coefficient for PME (0.381) indicated that about 38 percent (on average) of the estimated amount of this source reaches streams. The model results implied that the actual discharge from inflows was greater than the estimated discharge (the coefficient was greater than one), whereas the actual discharge from wastewater treatment and springs was less than the estimated discharge for each source (the coefficients were less than one). The streamflow model included two delivery terms with negative coefficients and three terms with positive coefficients. The negative coefficient for air temperature was expected, as was the negative coefficient for flow distance, which was the mean distance between all points within an incremental catchment and the reach that flows through that catchment. Areas with higher mean temperatures would likely experience greater evaporation than areas with lower temperature and longer mean flow distances should allow water to be evaporated, transpired, or otherwise removed compared to shorter mean flow distances. The positive coefficients for impervious surface and soil clay content were likely due to lower infiltration and increased surface runoff in urbanized areas and areas with relatively impermeable clayey soils. The positive coefficient for precipitation intensity, which was equal to the mean annual precipitation divided by the mean length of precipitation events, likely reflected that same process–shorter storm events should result in lower infiltration and increased surface runoff than longer ones with the same amount of precipitation. Many other climate and landscape factors were evaluated as potential delivery terms but were not included because they were not significant.

The streamflow model included a term representing the combined effect of evaporation and streambed infiltration from intermittent streams (those processes were not significant, however for perennial streams), separate terms representing irrigation diversions and municipal water-supply intakes, and a term representing evaporation from impoundments. The coefficients for both irrigation diversions and municipal water-supply intakes were less than one. Because these variables were expressed as the ratio between the streamflow downstream and upstream of each diversion, the values less than one indicated that there was a general under-estimation of the amount of water removed at the diversions or that some water diverted for irrigation comes back to streams through irrigation returns.

The streamflow model was generally successful at matching the mean annual streamflow measured at the 867 stream gages used in the calibration–the model explained about 89 percent of the variability in measured water yield (based on the yield R^2 value in table 4). Figure 4 shows the diagnostic plots for the calibration of the streamflow model. Residual variance decreased slightly as conditioned predicted streamflow (4A) and conditioned predicted water yields (4B) increased, meaning that the model residuals were slightly heteroskedastic. The conditioned RMSE (0.586) and unconditioned RMSE (0.664) were close in value, which is reflected in the similarities between the plots shown in fig. 4*C* and fig. 4D and the similarities between the conditioned and unconditioned residuals shown in figure 5. The nested areas for the calibration stations were not a significant predictor of the squares of the residuals from the streamflow model and, therefore, were not used as weights in its calibration. There was no significant spatial correlation among loose clusters of residuals or significant spatial correlation among tight clusters of nonnested residuals and nested residuals that had dissimilar drainage areas, but there was significant spatial correlation among 12 pairs of nested residuals that had similar drainage areas. The upstream station in each one of these nested pairs was removed from the calibration data set, leaving 867 calibration stations in the final model (and no significant spatial correlation among nested residuals).

The mean incremental yields predicted by the streamflow model are shown in figure 6, where the total incremental yields represent the total amount of water generated within each incremental catchment and the delivered incremental yields represent the amount generated within each catchment that was delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins. The difference between the two values reflects permanent losses in free-flowing streams, losses in impoundments, and diversions for consumptive use, as well as in-stream transfers. As expected, the largest water yields were predicted for areas with the highest precipitation–specifically, the Sabine (SABI), Neches (NECH), Trinity (TRINI), and Galveston-Bay-San Jacinto (GASJ) hydrologic subregions. PME is by far the largest source of streamflow in the Southwest region, but wastewater discharge and the combination of inter-basin transfers, inflows from Mexico, and local irrigation returns are also substantial sources in some hydrologic subregions. This is apparent in figure 7 and table 2.1, which show the total yields predicted for each of the hydrologic subregions within the Southwest region along with the contribution from the modeled sources to those yields. Because of the large range in yields across the watersheds, the main plot in figure 7 includes

Table 4. Model statistics for the explanatory variables included in the SPARROW streamflow model for the Southwest region of the United States.

[ft³/s, cubic foot per second; km, kilometer; m/yr, meter per year; ln, natural logarithm; *p*-value, probability value; RMSE, root mean square error; R^2, coefficient of determination; SPARROW, SPAtially Referenced Regression On Watershed attributes; yr/m, year per meter; <, less than; –, not applicable]

Variable	Variable units	Coefficient units	Model coefficient value	90-percent confidence interval for the model coefficient: Low	90-percent confidence interval for the model coefficient: High	Standard error of the model coefficient	*p*-value	*t*-statistic	Variance inflation factor
Source									
Precipitation minus evapotranspiration[a]	ft³/s	Fraction, dimensionless	0.381	0.335	0.428	0.028	<0.0001	13.5	7.59
Wastewater discharge[b]	ft³/s	Fraction, dimensionless	0.823	0.399	1.25	0.257	0.001	3.20	1.10
Spring discharge[c]	ft³/s	Fraction, dimensionless	0.481	0.258	0.705	0.136	0.000	3.54	1.02
Inflows[d]	ft³/s	Fraction, dimensionless	1.06	0.625	1.50	0.266	0.000	3.99	1.01
Land-to-water delivery									
Ln(air temperature)[e]	Unitless	Unitless	–0.441	-0.510	–0.371	0.042	<0.0001	–10.4	2.61
Ln(Impervious surface)[f]	Unitless	Unitless	0.318	0.245	0.392	0.044	<0.0001	7.17	1.62
Ln(precipitation intensity)[g]	Unitless	Unitless	1.219	1.025	1.414	0.118	<0.0001	10.3	4.39
Ln(flowline distance)[h]	Unitless	Unitless	–0.260	-0.383	–0.136	0.075	0.001	–3.45	5.71
Ln(soil clay content)[i]	Unitless	Unitless	0.301	0.176	0.425	0.076	0.000	3.98	1.67
Aquatic loss									
Loss from intermittent streams[j]	km	km^{-1}	0.011	0.009	0.012	0.001	<0.0001	10.5	1.79
Withdrawals for irrigation[k]	Unitless	Unitless	0.357	0.245	0.468	0.068	<0.0001	5.27	1.03
Withdrawals for municipal water supply[l]	Unitless	Unitless	0.699	0.319	1.080	0.231	0.003	3.03	1.06
Evaporative loss from impoundments[m]	yr/m	m/yr	1.218	0.702	1.734	0.313	0.000	3.89	1.13

Spatial test	Number	Correlation/ value	*p*-value	Model summary statistic	Model summary statistic value
Nested sites (weighting)–Coefficient for nested share[n]	867	<0.001	0.492	Conditioned RMSE[o], in natural logarithm units	0.586
Loose clusters–Moran's *I*	867	0.047	0.405	Conditioned RMSE[o], percent in real space units[q]	63.9
Tight clusters–Pairs of nested sites within 5 km	–	–	–	Unconditioned RMSE[p], in natural logarithm units	0.664
Tight clusters–Pairs of nonnested sites (and dissimilarly sized nested sites) within 5 km	74	-0.003	0.979	Unconditioned RMSE[p], percent in real space units[q]	74.4
				Mean exponentiated weighted error	1.142
				R^2	0.920
				Yield R^2	0.891
				Number of calibration stations	867

[a]Mean annual difference between precipitation and evapotranspiration for water years 2000 through 2014.

[b]Mean discharge to surface water from municipal wastewater treatment facilities in 2012.

[c]Mean spring discharge.

[d]Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water.

[e]Natural log of the mean air temperature for water years 2000 through 2014 (degrees Celsius × 10).

[f]Natural log of the area of land consisting of impervious surface in 2011 (percent).

[g]Natural log of the mean intensity of precipitation events (mm/day).

[h]Natural log of mean distance to flowline within catchment (km).

[i]Natural log of mean soil clay content (percent).

[j]The combined effect of evaporation and streambed infiltration expressed as a function of the reach length (km).

[k]Estimated removal of surface water for irrgation expr=essed as a proportion of total streamflow subtracted from one.

[l]Estimated removal of surface water for municipal water supply expressed as a proportion of total streamflow subtracted from one.

[m]Estimated mean annual evaporation from ponds, lakes, and reservoirs expressed as a function of wetted area.

[n]The ratio of the nested drainage area to the total drainage area, where the nested area is the area upstream of a calibration station that drains exlusively to that calibration station.

[o]Conditioned RMSE: root mean square error of the difference between the natural log of measured calibration streamflow and the natural log of predicted accumulated streamflow that was reset to the measured streamflow at the calibration stations.

[p]Unconditioned RMSE is similar to the conditioned RMSE except the predicted accumulated streamflow was not reset to the measured streamflow at the calibration stations.

[q]RMSE in terms of percent in real space units was computed as: $100 \times (\exp(RMSE^2) - 1)^{0.5}$; RMSE is in this equation is in natural log units.

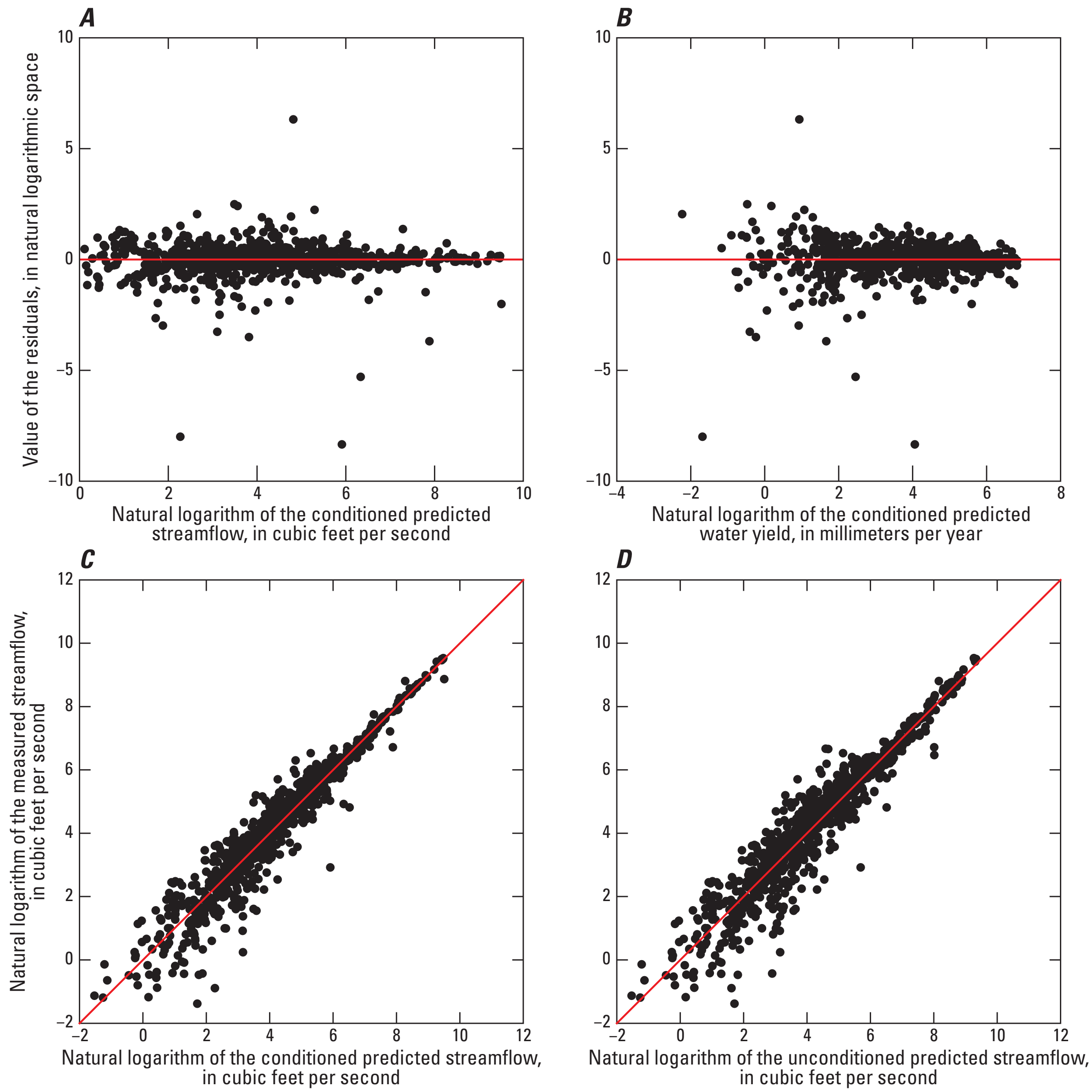


Figure 4. Diagnostic plots for the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) streamflow modelshowing (*A*) Residuals versus predicted streamflow; (*B*) Residuals versus predicted yield; (*C*) Measured streamflow versus conditioned predicted streamflow (model calibration); and (*D*) Measured streamflow versus unconditioned predicted streamflow (full prediction).

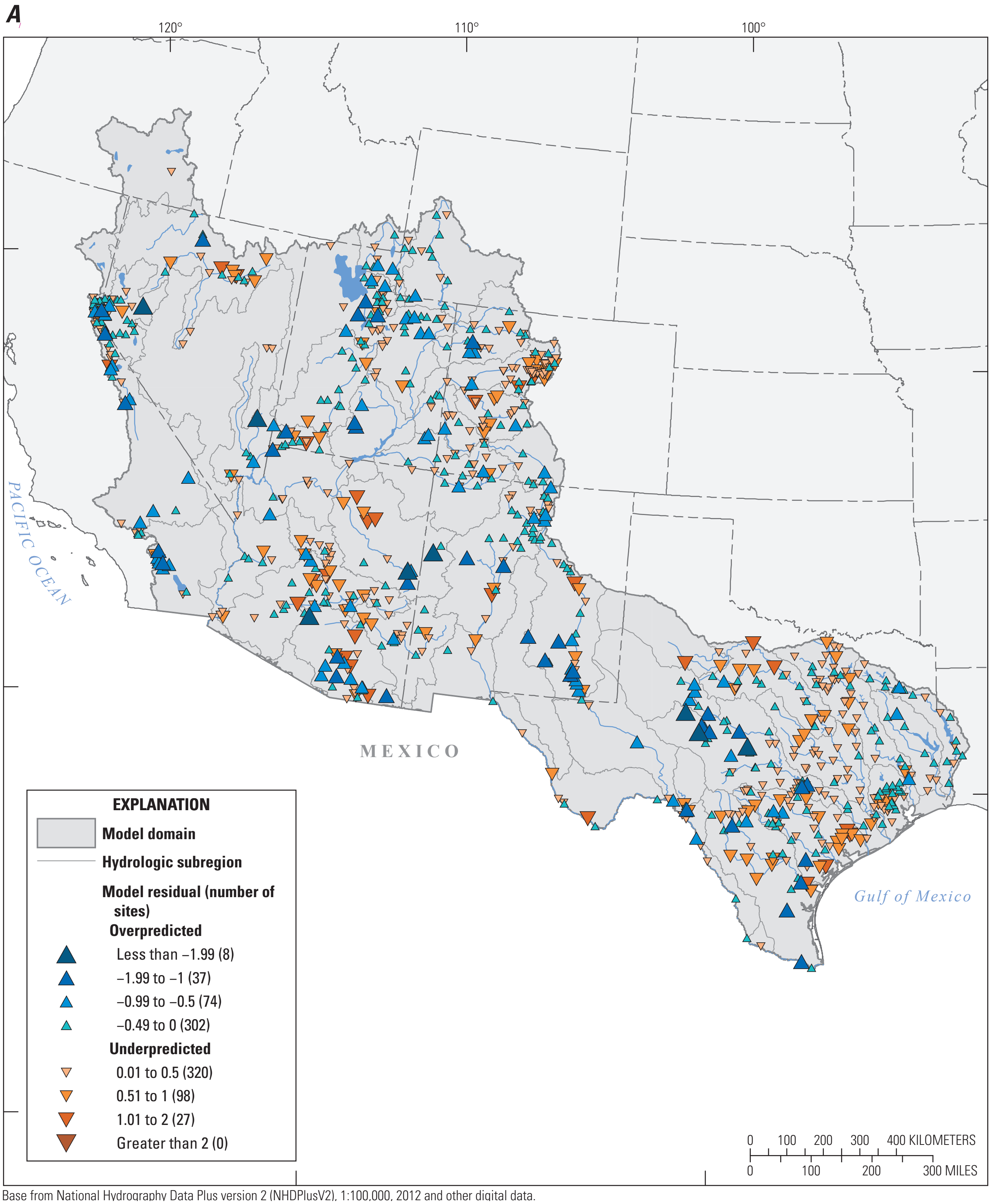
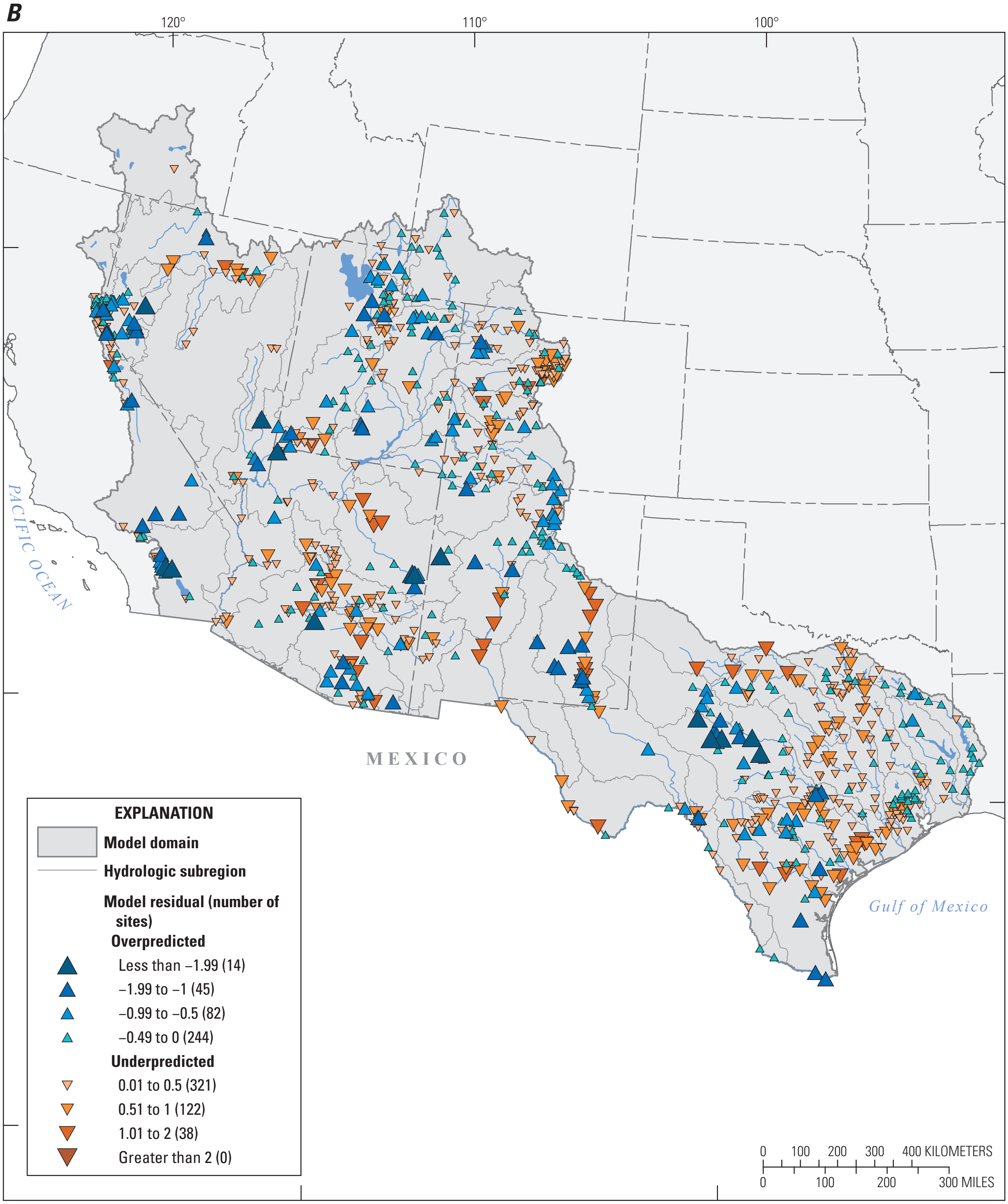
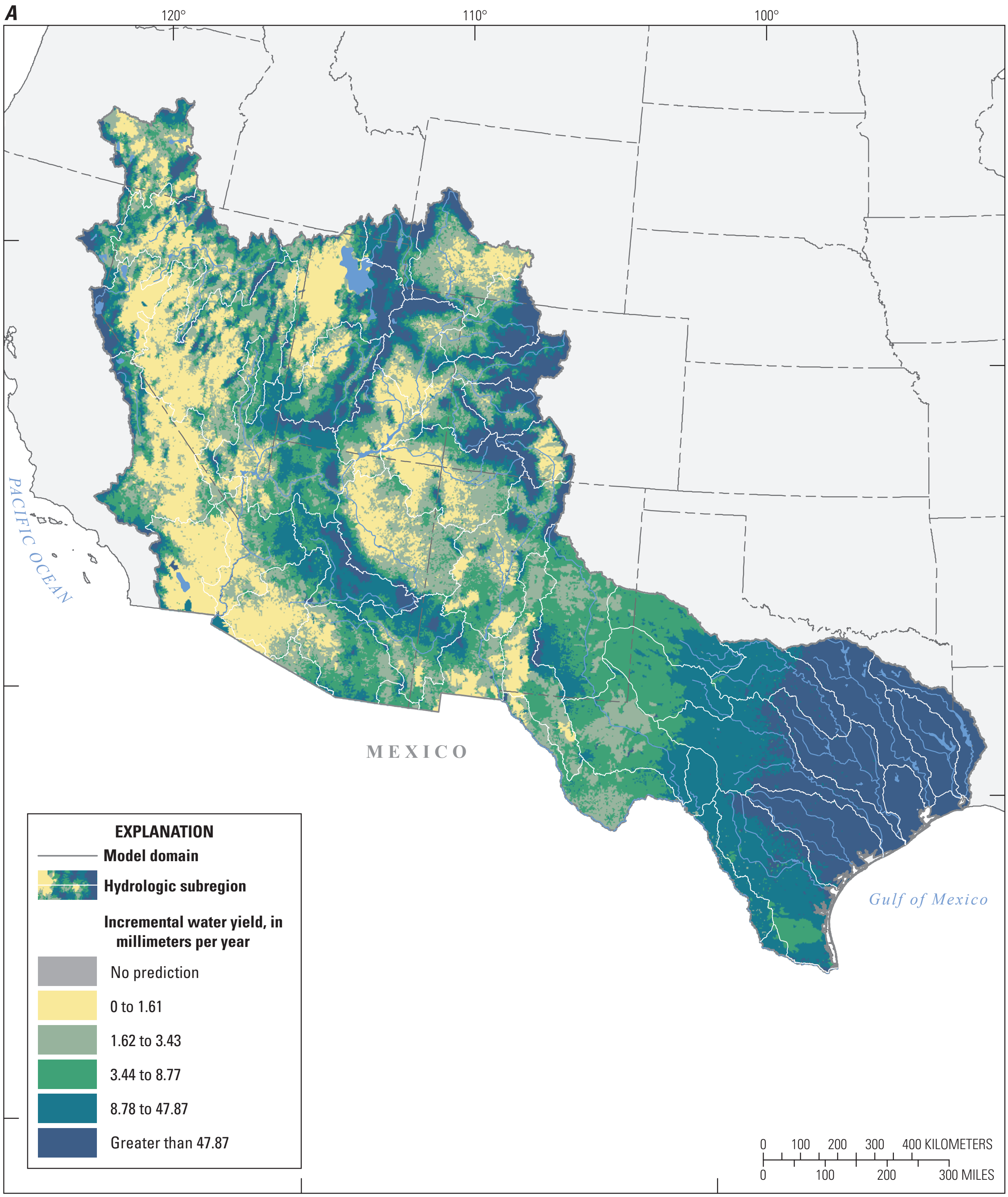


Figure 5. Spatial distribution of conditioned (*A*) and unconditioned (*B*) Residuals from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) streamflow model. [Conditioned residuals are based on the difference between the log of measured calibration streamflow and the log of predicted accumulated streamflow that was reset to the measured streamflow at the calibration stations. Unconditioned residuals are based on the difference between the log of measured calibration streamflow and the log of predicted accumulated streamflow that was not reset to the measured streamflow at the calibration stations.]



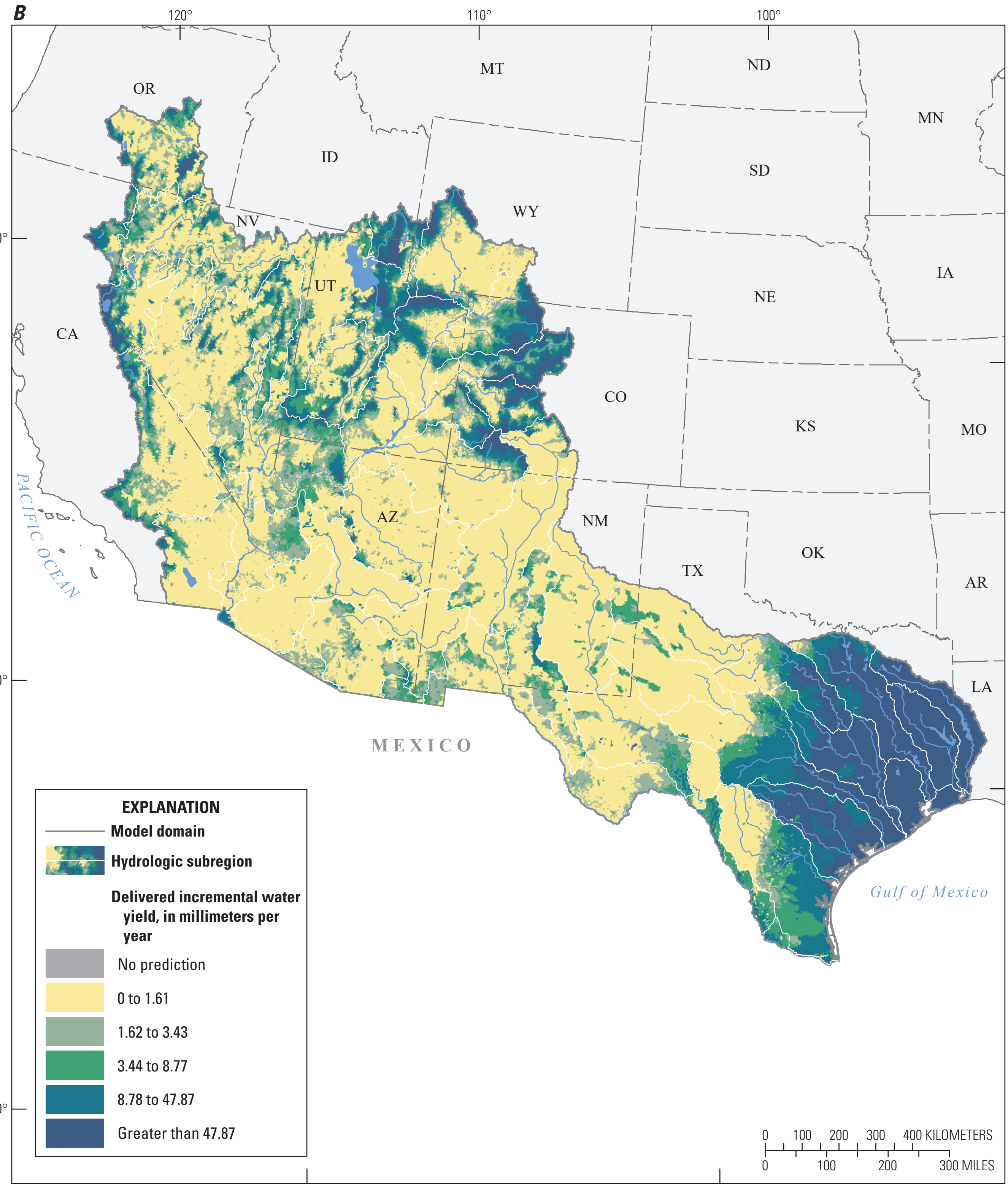
Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 5.—Continued.



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 6. Predicted mean annual incremental yield (*A*) and delivered incremental yield (*B*) of water from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) streamflow model.



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 6.—Continued.

a break at 100 mm/yr. The inset plot, however, shows the full range of water yields without any axis breaks.

Total Nitrogen

The total nitrogen model included six source terms, two delivery terms, and four aquatic loss terms (table 5). The model results indicated that on average less than 3 percent of the nitrogen from atmospheric deposition, commercial fertilizer, and livestock manure reaches streams and that developed land yields an average of 136 (kg/km^2)/yr of nitrogen to streams. The coefficient for inflows (2.41 mg/l) represents the mean total nitrogen concentration in that source, which was obtained by converting the model results in kg/yr per ft^3/s to mg/l. The coefficient was 1.321 for wastewater discharge, implying that the actual total nitrogen discharge to streams in 2012 was greater than that reflected by the point source discharge estimates. The results showed that spring discharge was not a significant source of surface-water nitrogen across the Southwest region and, as a result, this term was not included in the model. Background fixation of nitrogen on forest land (represented by the area of forest land) was not significant, but this did not necessarily mean that it is a negligible source of nitrogen. The lack of significance for forest land was likely due to the strong, positive relation between this source and the amount of atmospheric nitrogen deposited in a catchment. On-site wastewater treatment was also not a significant source but, as was the case for forest

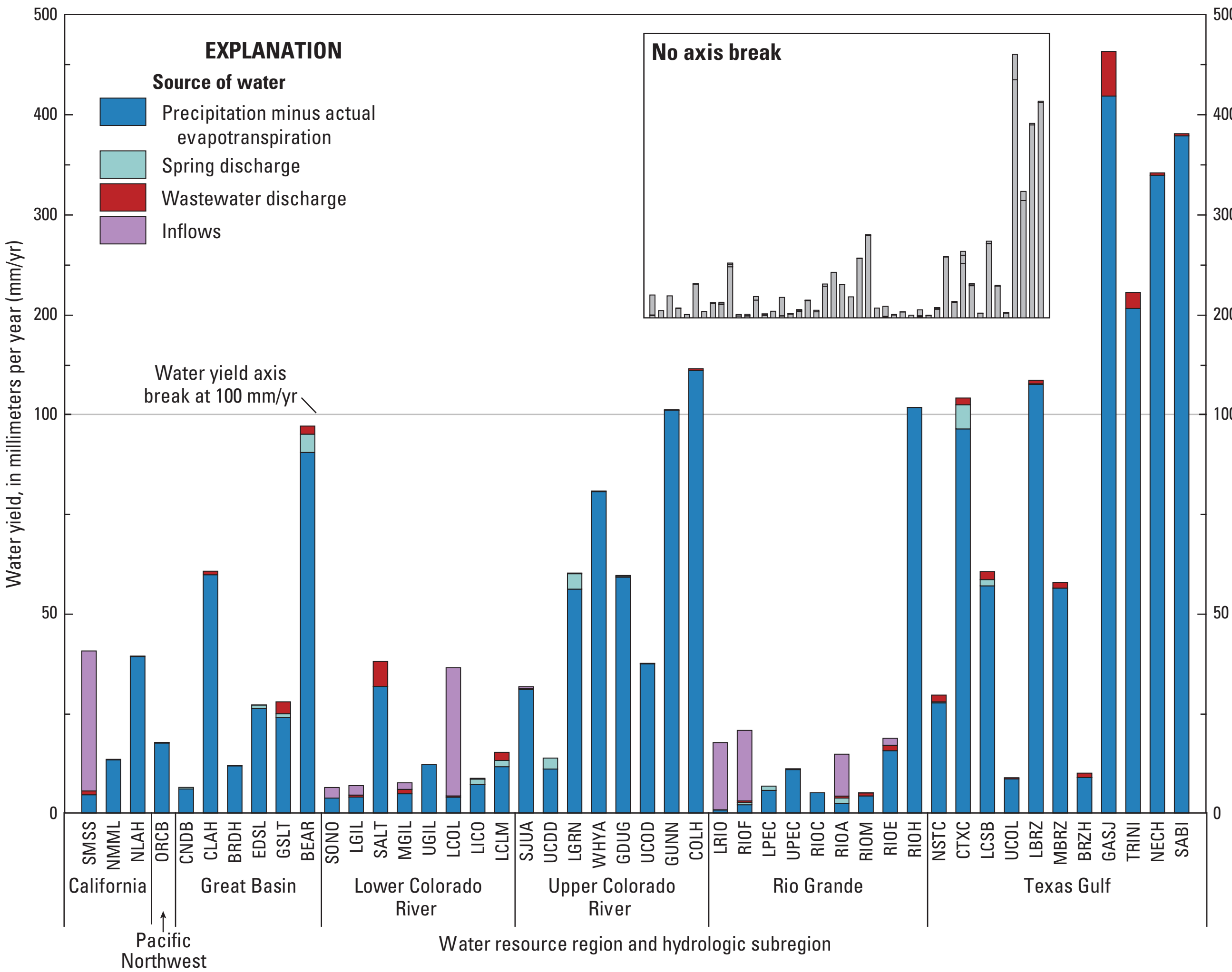


Figure 7. Predicted mean annual water yield, by source, for hydrologic subregions in the Southwest region of the United States.

Table 5. Model statistics for the explanatory variables included in the SPARROW total nitrogen model for the for the Southwest region of the United States.

[kg/yr, kilogram per year; km, kilometer; km^2, square kilometer; l, liter; yr/l, year per liter; *p*-value, probability value; RMSE, root mean square error; R^2, coefficient of determination; –, not applicable]

Variable	Variable unit	Coefficient unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value	*t*-statistic	Variance inflation factor
				Low	High				
Source									
Atmospheric deposition[a]	kg/yr	Fraction, dimensionless	0.022	0.015	0.029	0.004	<0.0001	4.98	6.21
Developed land[b]	km^2	kg/km^2/yr	136	32.53	240	63.0	0.031	2.17	1.59
Commercial fertilizer[c]	kg/yr	Fraction, dimensionless	0.028	0.010	0.045	0.011	0.010	2.59	3.05
Livestock manure[d]	kg/yr	Fraction, dimensionless	0.014	0.003	0.024	0.006	0.032	2.16	2.62
Wastewater discharge[e]	kg/yr	Fraction, dimensionless	1.321	0.918	1.724	0.244	<0.0001	5.41	1.16
Inflows[f]	yr/l	mg/l	2.41	0.96	3.85	0.875	0.006	2.75	1.02
Land-to-water delivery									
Ln(Incremental water yield)[g]	Unitless	Unitless	0.617	0.523	0.711	0.057	<0.0001	10.9	7.24
Ln(Base flow index)[h]	Unitless	Unitless	0.454	0.193	0.714	0.158	0.004	2.87	3.02
Aquatic loss									
Loss from intermittent streams[i]	Day	Days^{-1}	0.206	0.112	0.301	0.057	0.000	3.60	2.04
Withdrawals for irrigation[j]	Unitless	Unitless	0.357	–	–	–	–	–	–
Withdrawals for municipal water supply[k]	Unitless	Unitless	0.699	–	–	–	–	–	–
Loss within impoundments[l]	yr/m	m/yr	3.231	1.935	4.526	0.782	<0.0001	4.13	1.19

Spatial test	Number	Correlation/ Value	*p*-value	Model summary statistic	Model summary statistic value
Nested sites (weighting)–Coefficient for nested share[m]	289	0.013	0.651	Conditioned RMSE[n], in natural logarithm units	0.589
Loose clusters–Moran's *I*	289	0.022	0.820	Conditioned RMSE[n], percent in real space units[p]	64.4
Tight clusters–Pairs of nested sites within 5 km	6	0.569	0.238	Unconditioned RMSE[o], in natural logarithm units	0.633
Tight clusters–Pairs of nonnested sites (and dissimilarly sized nested sites) within 5 km	14	–0.093	0.752	Unconditioned RMSE[o], percent in real space units[p]	70.1
				Mean exponentiated weighted error	1.208
				R^2	0.926
				Yield R^2	0.861
				Number of calibration stations	289

[a]Mean wet and dry atmospheric deposition of oxidized and reduce nitrogen for water years 2010–12.

[b]Area of developed land in 2011.

[c]Commercial fertilizer applied to cultivated crops and pasture in 2012.

[d]Manure from livestock applied to cultivated crops and pasture land in 2012.

[e]Discharge to surface water from municipal wastewater treatment facilities in 2012.

[f]Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water.

[g]Natural log of the incremental water yield predicted by the streamflow model (mm/yr).

[h]Natural log of base flow index (percent).

[i]Loss due to denitrification in intermittent streams expressed as a function of the reach time of travel.

[j]Estimated removal of surface water for irrgation expressed as a proportion of total streamflow subtracted from one (fixed to value estimated in streamflow model).

[k]Estimated removal of surface water for municipal water supply expressed as a proportion of total streamflow subtracted from one (fixed to value estimated in streamflow model).

[l]Loss due to denitrification in ponds, lakes, and reservoirs expressed as the inverse hydraulic load.

[m]The ratio of the nested drainage area to the total drainage area, where the nested area is the area upstream of a calibration station that drains exlusively to that calibration station.

[n]Conditioned RMSE: root mean square error of the difference between the natural log of measured calibration loads and the natural log of predicted accumulated loads that were reset to the measured loads at the calibration stations.

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

[p]RMSE in terms of percent in real space units was computed as: $100 \times (\exp(RMSE^2) - 1)^{0.5}$; RMSE is in this equation is in natural log units.

land, this result does not mean that it is not an important source of surface-water nitrogen in some areas. Rather, the lack of significance was likely due to the strong, positive relation between this source and the area of developed land. And while it was possible to build models that included forest land without atmospheric deposition or on-site wastewater treatment without developed land, the resulting models would be missing important sources of nitrogen across the entire modeling domain.

Both delivery terms in the total nitrogen model had positive coefficients, which were consistent with expectations. The positive coefficient for incremental water yield (as predicted by the streamflow model) was expected because greater water yields should enhance nitrogen delivery to surface water via overland and subsurface flow. The positive coefficient for base flow index (BFI) was expected because BFI was likely a surrogate for groundwater redox condition. Lower BFI values are generally found in areas underlain by aquifers that are less oxic, where soil denitrification removes nitrogen that otherwise would be delivered to streams. These include the semi-consolidated sand and gravel aquifers along the Texas Gulf coast and the sandstone aquifers around the four corners area of Utah, Colorado, Arizona, and New Mexico (DeSimone and others, 2014). Higher BFI values, in contrast, are generally found in areas underlain by aquifers that are more oxic, where soil denitrification is not expected to remove a substantial amount of nitrogen. These include the igneous and metamorphic rock and unconsolidated sand and gravel aquifers in the Great Basin and the sandstone and the carbonate rock aquifers in central Texas (DeSimone and others, 2014). Many other climate and landscape factors were evaluated as potential delivery terms but were not included because they were not significant.

The total nitrogen model included an aquatic loss term for intermittent streams and impoundments, but aquatic loss was not significant in perennial streams. The total nitrogen model also included loss terms representing municipal water supply intakes and irrigation diversions with coefficients that were set to the values estimated in the streamflow model.

Figure 8 shows the diagnostic plots for the calibration of the total nitrogen model, which explained about 86 percent of the variability in measured total nitrogen yield. The variance of the model residuals was relatively constant across the range of conditioned predicted total nitrogen loads (8*A*) and conditioned total nitrogen yields (8*B*). The conditioned RMSE (0.589) and unconditioned RMSE (0.633) were close in value, which is reflected in the similarities between the plots shown in fig. 8C and fig. 8D and the similarities between the conditioned and unconditioned residuals shown in figure 9. The nested areas for the calibration stations were not a significant predictor of the squares of the residuals from the total nitrogen model and, therefore, were not used as weights in its calibration. There was no significant spatial correlation among either loose clusters of residuals or tight clusters of nested or nonnested residuals.

The mean incremental yields predicted by the total nitrogen model are shown in figure 10, where the total incremental yields represent the total amount of nitrogen generated within each incremental catchment, and the delivered incremental yields represent the amount generated within each catchment that was delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins. Wastewater discharge is the largest contributor to the total nitrogen generated within the Southwest region (about 40 percent of the total amount) and, together with atmospheric deposition, accounts for about 61 percent of the total amount. There are nine hydrologic subregions, however, where agricultural sources (commercial fertilizer and livestock manure) are the largest source of total nitrogen and 18 where they are responsible for at least 25 percent of the total nitrogen (fig. 11 and table 2.2). This type of information can be helpful when evaluating the total nutrient loads delivered to impaired waterbodies. For example, the results from this study showed that the combination of agricultural sources and wastewater discharge contributes 80 percent of the total nitrogen loading to the estuaries along the Texas Gulf coast.

Total Phosphorus

The total phosphorus model included seven source terms, three delivery terms, no aquatic loss term for free-flowing stream, but a loss term for impoundments (table 6). The model results indicated that on average less than 1 percent of the phosphorus in commercial fertilizer and livestock manure is delivered to streams, developed land yields on average 3.28 $(kg/km^2)/yr$ to streams, and the mean total phosphorus concentration in inflows is 0.366 mg/l. The average

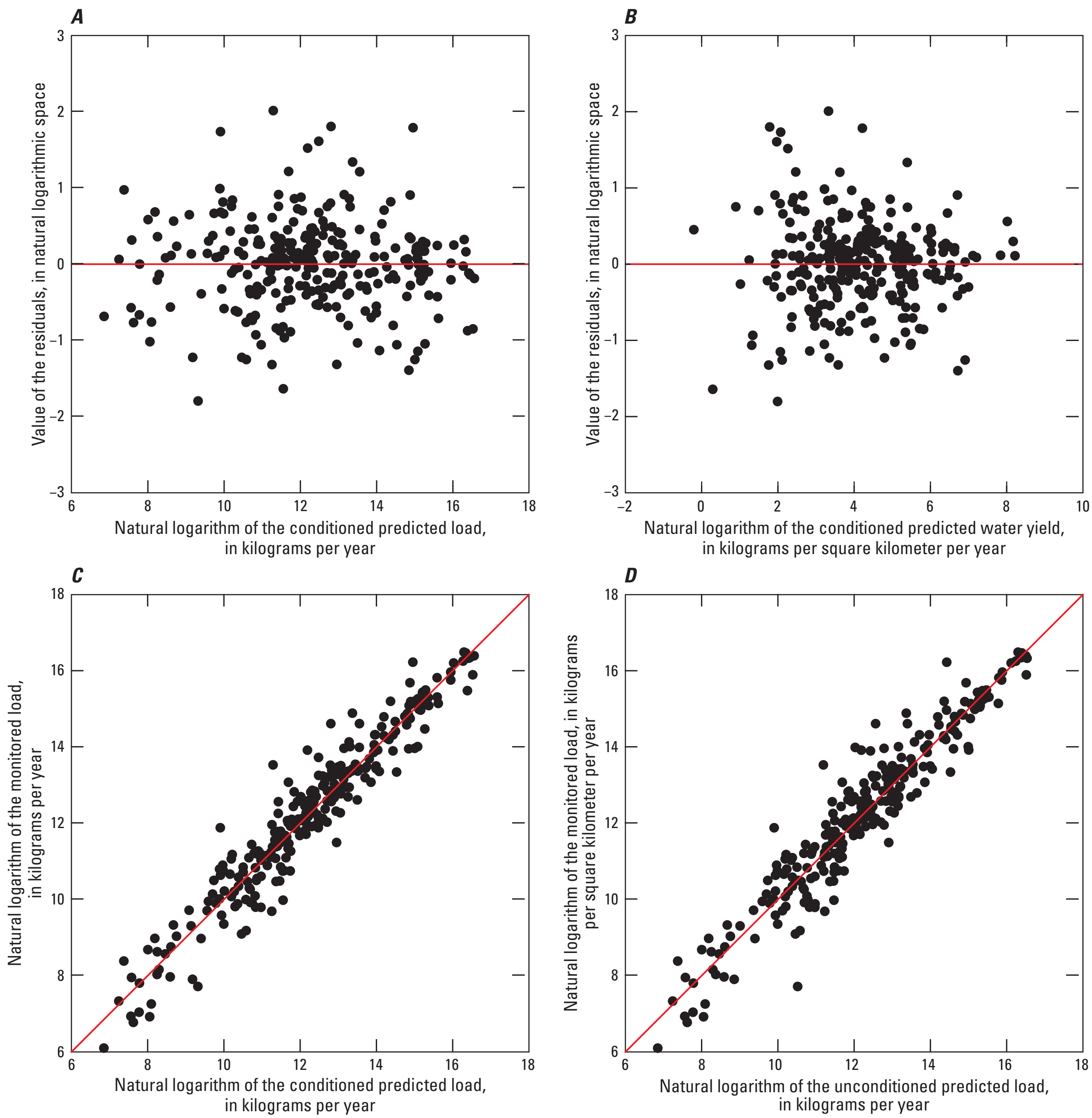
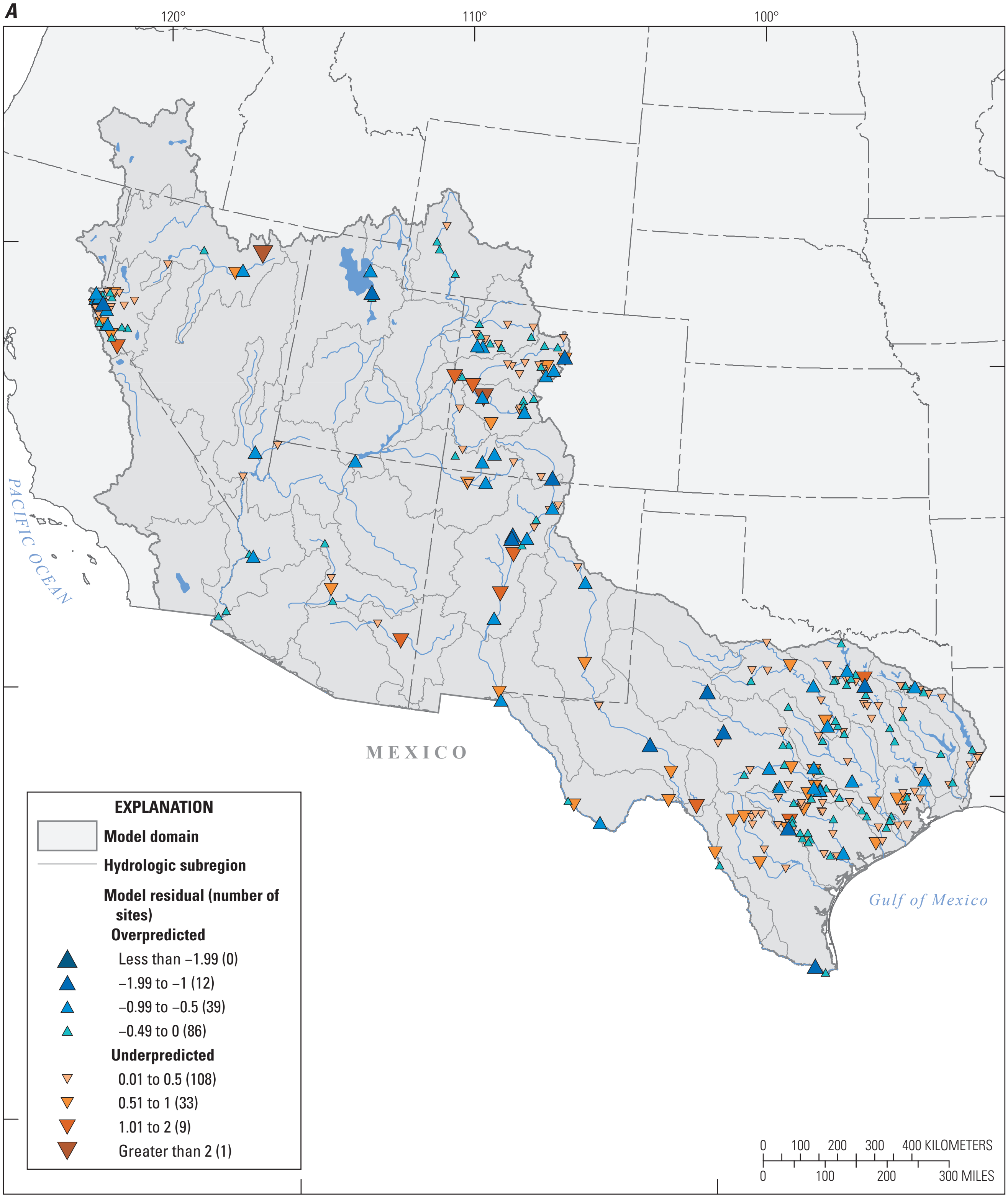
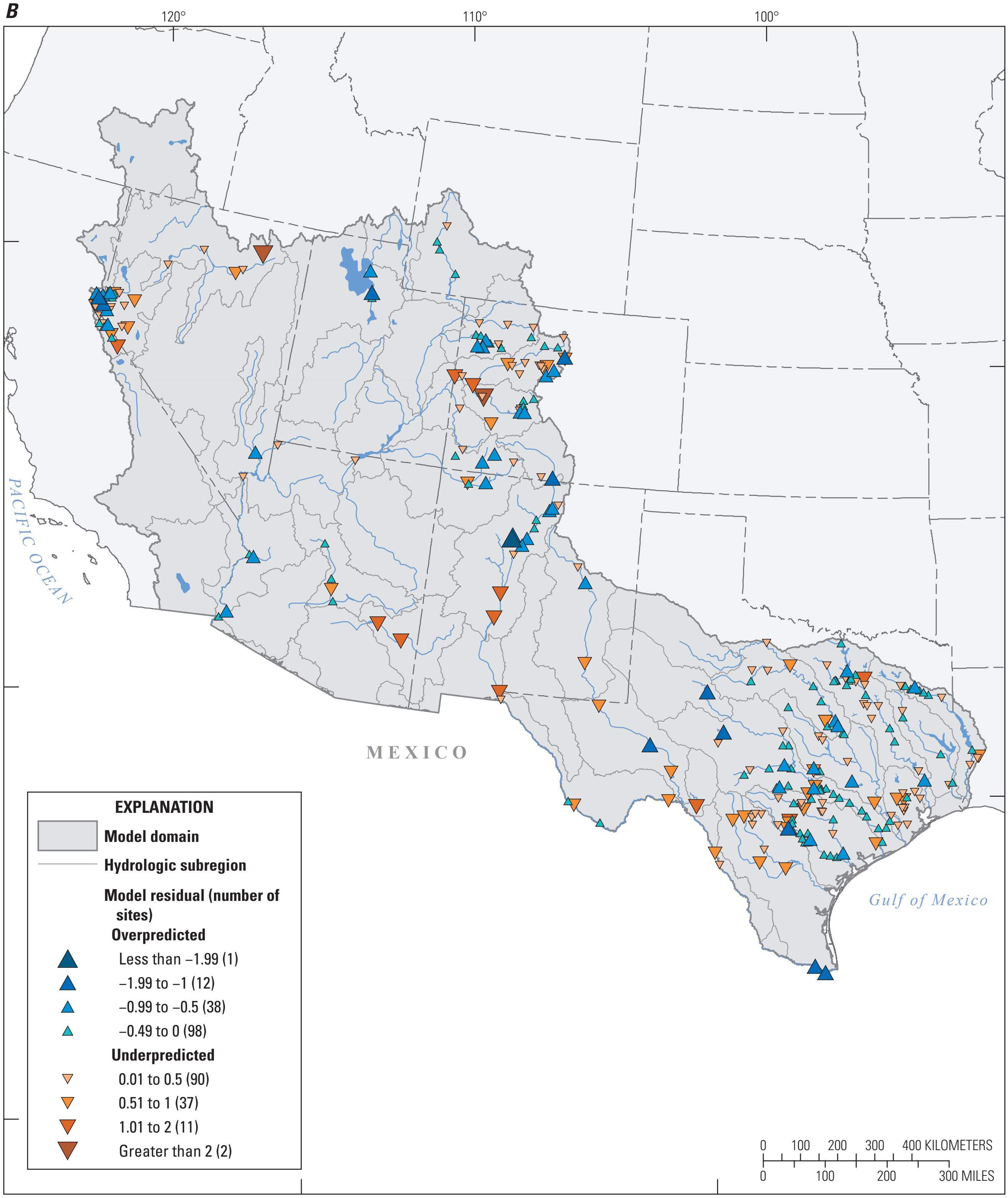


Figure 8. Diagnostic plots for the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total nitrogen model. (*A*) Residuals versus predicted load; (*B*) Residuals versus predicted yield; (*C*) measured streamflow versus conditioned predicted load (model calibration); and (*D*) measured load versus unconditioned predicted load (full prediction).



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 9. Spatial distribution of conditioned (*A*) and unconditioned (*B*) residuals from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total nitrogen model. [Conditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were reset to the measured loads at the calibration stations. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at the calibration stations.]



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 9.—Continued.

Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 10. Predicted mean annual incremental yield (*A*) and delivered incremental yield (*B*) of total nitrogen from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total nitrogen model.

Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 10.—Continued.

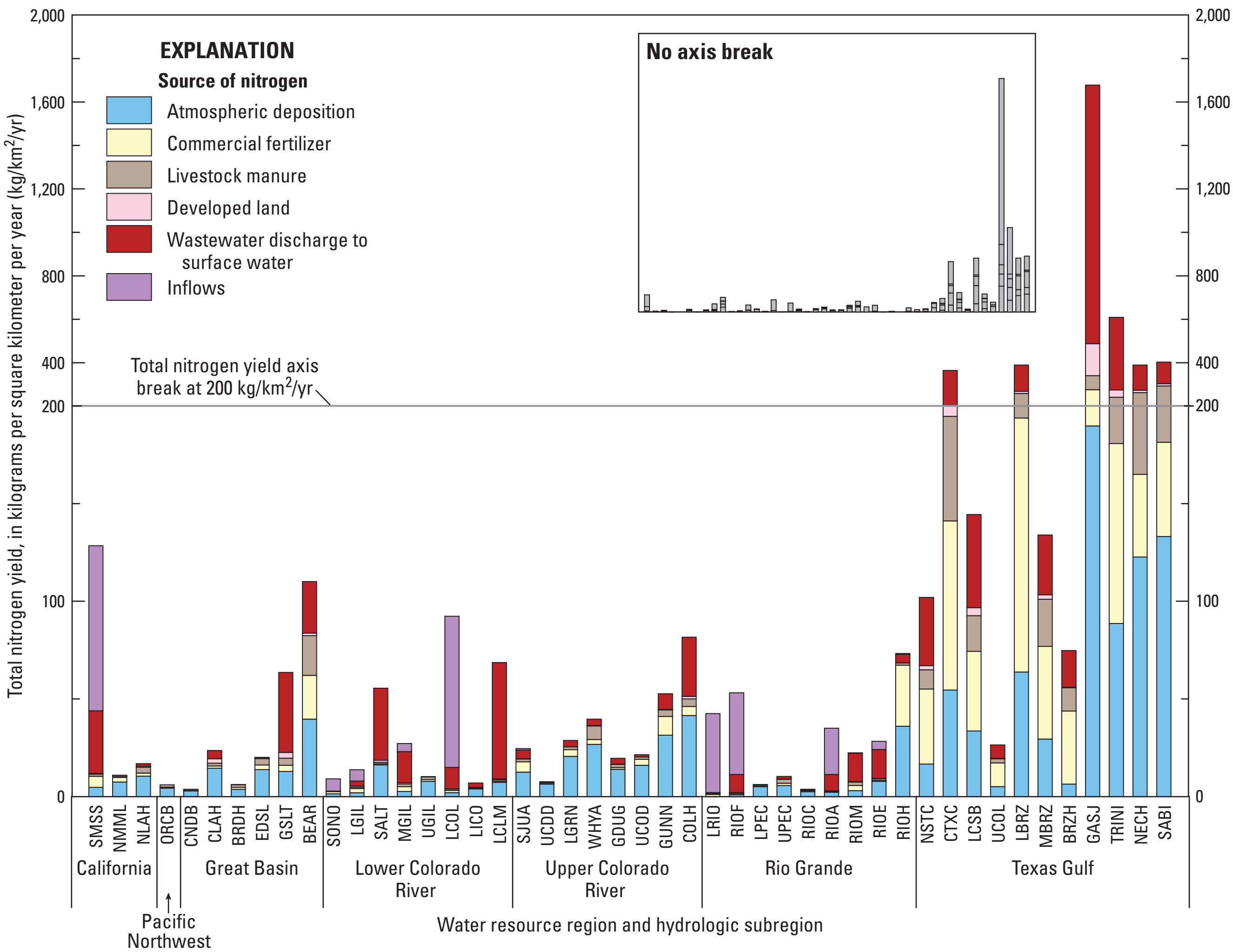


Figure 11. Predicted mean annual total nitrogen yield, by source, for hydrologic subregions in the Southwest United States.

phosphorus contribution from perennial streams is 14.9 (kg/km)/yr and the average contribution from geologic phosphorus is 0.934 (kg/km^2)/yr. The coefficient was 0.653 for wastewater discharge, implying that the actual total discharge to streams in 2012 was less than that reflected by the point source discharge estimates. Spring discharge was not a significant source of surface-water phosphorus nor were intermittent streams, but this did not necessarily mean that intermittent streams are not an important source in some areas. This lack of significance was likely due to spatial correlation between intermittent stream length and catchment area (which was used in part to represent geologic phosphorus). The coefficient for intermittent streams was significant when geologic phosphorus was excluded from the model, however, which suggests that the contribution from intermittent stream to in-stream load was likely accounted for in the geologic phosphorus source term.

Two of the delivery terms in the total phosphorus model (incremental water yield and soil erodibility) had significant positive coefficients, meaning that they acted to enhance the delivery of phosphorus from land. The positive coefficients for these watershed attributes were expected because wetter areas, especially those with more erodible soils, should enhance phosphorus delivery to surface water. The third delivery term (soil clay content) had a negative coefficient, meaning that it acted to attenuate the delivery of phosphorus from land. This was also expected since soils with high clay content are more cohesive and stable than soils that have low clay content and, therefore, are at lower risk of erosion by water and wind. Many other climate and landscape factors were evaluated as potential delivery terms but were not included because they were not significant.

The model calibration results showed that impoundments were important locations for net phosphorus loss but that free-flowing streams were not. The total phosphorus model also included loss terms representing municipal water supply

Table 6. Model statistics for the explanatory variables included in the SPARROW total phosphrous model for the Southwest region of the United States.

[(kg/km)yr, kilogram per kilometer per year; (kg/km^2)/yr, kilogram per square kilometer per year; km, kilometer; km^2, square kilometer; l, liter; R^2, coefficient of determination; *p*-value, probability value; RMSE, root mean square error; –, not applicable]

Variable	Variable unit	Coefficient units	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value	*t*-statistic	Variance inflation factor
				Low	High				
Source									
Perennial streams[a]	km	(kg/km)/yr	14.9	9.30	20.5	3.41	<0.0001	4.38	2.50
Geologic phosphorus[b]	km^2	(kg/km^2)/yr	0.934	0.439	1.428	0.300	0.002	3.12	3.56
Developed land[c]	km^2	(kg/km^2)/yr	3.28	0.07	6.49	1.95	0.093	1.68	4.95
Commercial fertilizer[d]	kg/yr	Fraction, dimensionless	0.001	0	0.001	0.000	0.067	1.84	4.12
Livestock manure[e]	kg/yr	Fraction, dimensionless	0.001	0	0.002	0.000	0.115	1.58	3.87
Wastewater discharge[f]	kg/yr	Fraction, dimensionless	0.653	0.305	1.00	0.211	0.002	3.10	1.18
Inflows[g]	yr/l	mg/l	0.366	0.091	0.642	0.167	0.029	2.19	1.01
Land-to-water delivery									
Ln(incremental water yield)[h]	Unitless	Unitless	0.803	0.647	0.960	0.095	<0.0001	8.47	7.79
Ln(soil erodibility)[i]	Unitless	Unitless	4.16	3.06	5.26	0.666	<0.0001	6.24	7.26
Ln(soil clay content)[j]	Unitless	Unitless	–1.05	–1.59	–0.499	0.332	0.002	–3.15	2.23
Aquatic loss									
Withdrawals for irrigation[k]	Unitless	Unitless	0.357	—	—	—	—	—	—
Withdrawals for municipal water supply[l]	Unitless	Unitless	0.699	—	—	—	—	—	—
Loss within impoundments[m]	yr/m	m/yr	13.9	10.8	16.9	1.856	<0.0001	7.47	1.12

Spatial test	Number	Correlation/ value	*p*-value	Model summary statistic	Model summary statistic value
Nested sites (weighting)–Coefficient for nested share[n]	389	0.003	0.952	Conditioned RMSE[o], in natural logarithm units	0.832
Loose clusters–Moran's *I*	389	0.115	0.161	Conditioned RMSE[o], percent in real space units[q]	100
Tight clusters–Pairs of nested sites within 5 km	16	0.213	0.427	Unconditioned RMSE[p], in natural logarithm units	0.898
Tight clusters–Pairs of nonnested sites (and dissimilarly sized nested sites) within 5 km	18	0.344	0.162	Unconditioned RMSE[p], percent in real space units[q]	111
				Mean exponentiated weighted error	1.425
				R^2	0.862
				Yield R^2	0.819
				Number of calibration stations	389

[a]Contribution from perennial stream channels.

[b]Contribution from geologic material represented by the incremental catchment area scaled by an estimate of the natural phosphorus content of local soil and rock.

[c]Area of developed land in 2011.

[d]Commercial fertilizer applied to cultivated crops and pasture in 2012.

[e]Manure from livestock applied to cultivated crops and pasture in 2012.

[f]Discharge to surface water from municipal wastewater treatment facilities in 2012.

[g]Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water.

[h]Natural log of the incremental water yield predicted by the streamflow model (mm/yr).

[i]Natural log of mean soil erodibility as measured by the K-factor (unitless).

[j]Natural log of the mean soil clay content (percent).

[k]Estimated removal of surface water for irrgation expressed as a proportion of total streamflow subtracted from one (fixed to value estimated in streamflow model).

[l]Estimated removal of surface water for municipal water supply expressed as a proportion of total streamflow subtracted from one (fixed to value estimated in streamflow model).

[m]Loss due to settling in ponds, lakes, and reservoirs expressed as the inverse hydraulic load.

[n]The ratio of the nested drainage area to the total drainage area, where the nested area is the area upstream of a calibration station that drains exlusively to that calibration station.

[o]Conditioned RMSE: root mean square error of the difference between the natural log of measured calibration loads and the natural log of predicted accumulated loads that were reset to the measured loads at the calibration stations.

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

[q]RMSE in terms of percent in real space units was computed as: $100 \times (\exp(RMSE^2) - 1)^{0.5}$; RMSE is in this equation is in natural log units.

intakes and irrigation diversions with coefficients that were set to the values estimated in the streamflow model.

Figure 12 shows the diagnostic plots for the calibration of the total phosphorus model, which explained about 82 percent of the variability in measured total phosphorus yield. The variance of the model residuals was relatively constant across the range of conditioned predicted total phosphorus loads (fig. 12A) and conditioned total phosphorus yields (fig. 12B). The conditioned RMSE (0.823) and unconditioned RMSE (0.898) were close in value, which is reflected in the similarities between the plots shown in figs. 12C and 12D and the similarities between the conditioned and unconditioned residuals shown in figure 13. The nested areas for the calibration stations were not a significant predictor of the squares of the residuals from the total phosphorus model and, therefore, were not used as weights in its calibration. There was no significant spatial correlation among either loose clusters of residuals or tight clusters of nested or nonnested residuals.

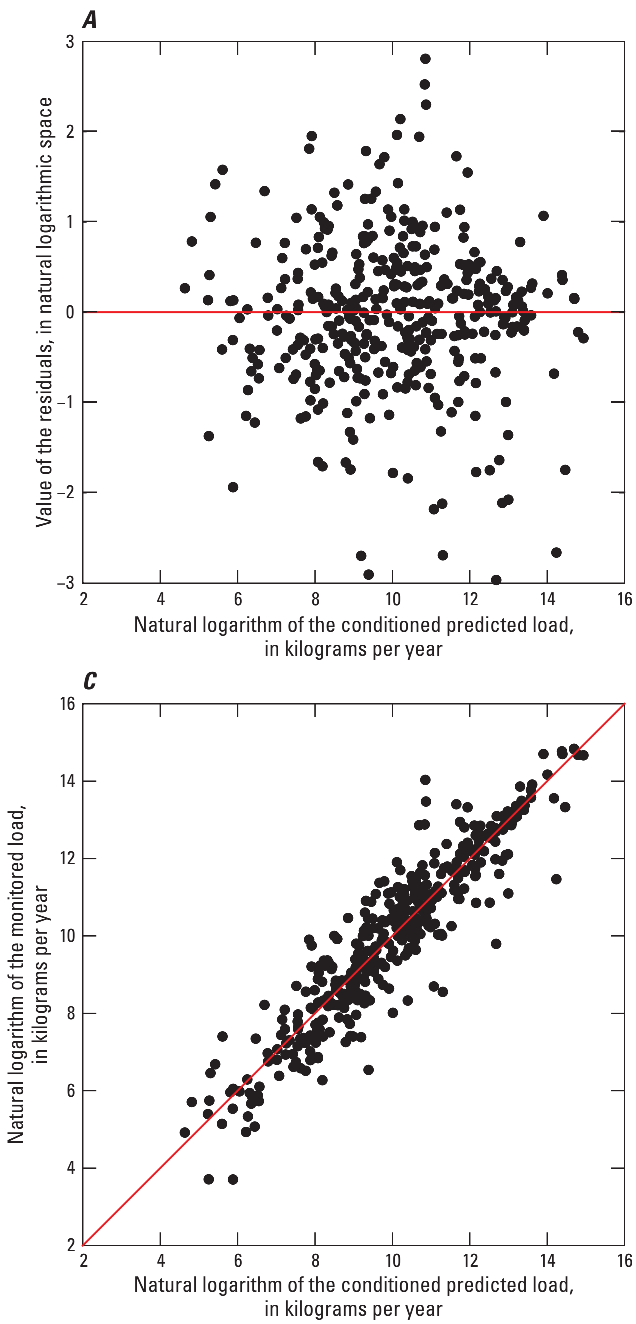


Figure 12. Diagnostic plots for the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total phosphorus model. (*A*) Residuals versus predicted load; (*B*) Residuals versus predicted yield; (*C*) measured streamflow versus conditioned predicted load (model calibration); and (*D*) measured load versus unconditioned predicted load (full prediction).

The mean incremental yields predicted by the total phosphorus model are shown in figure 14, where the total incremental yields represent the total amount of phosphorus generated within each incremental catchment and the delivered incremental yields represent the amount generated within each catchment that was delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins. Though wastewater discharge is the largest contributor to the total phosphorus generated in the Southwest region (about 19 percent of the total amount), there is no one dominant source, but there are regional patterns with regards to locally important sources (fig. 15 and table 2.3). For example, commercial fertilizer, livestock manure, wastewater discharge, and developed land contribute in aggregate most of the total phosphorus generated in the Texas Gulf Coast water resource region whereas perennial stream channels and geologic phosphorus are the sources of most of the total phosphorus generated in the other water resource regions.

Suspended Sediment Transport

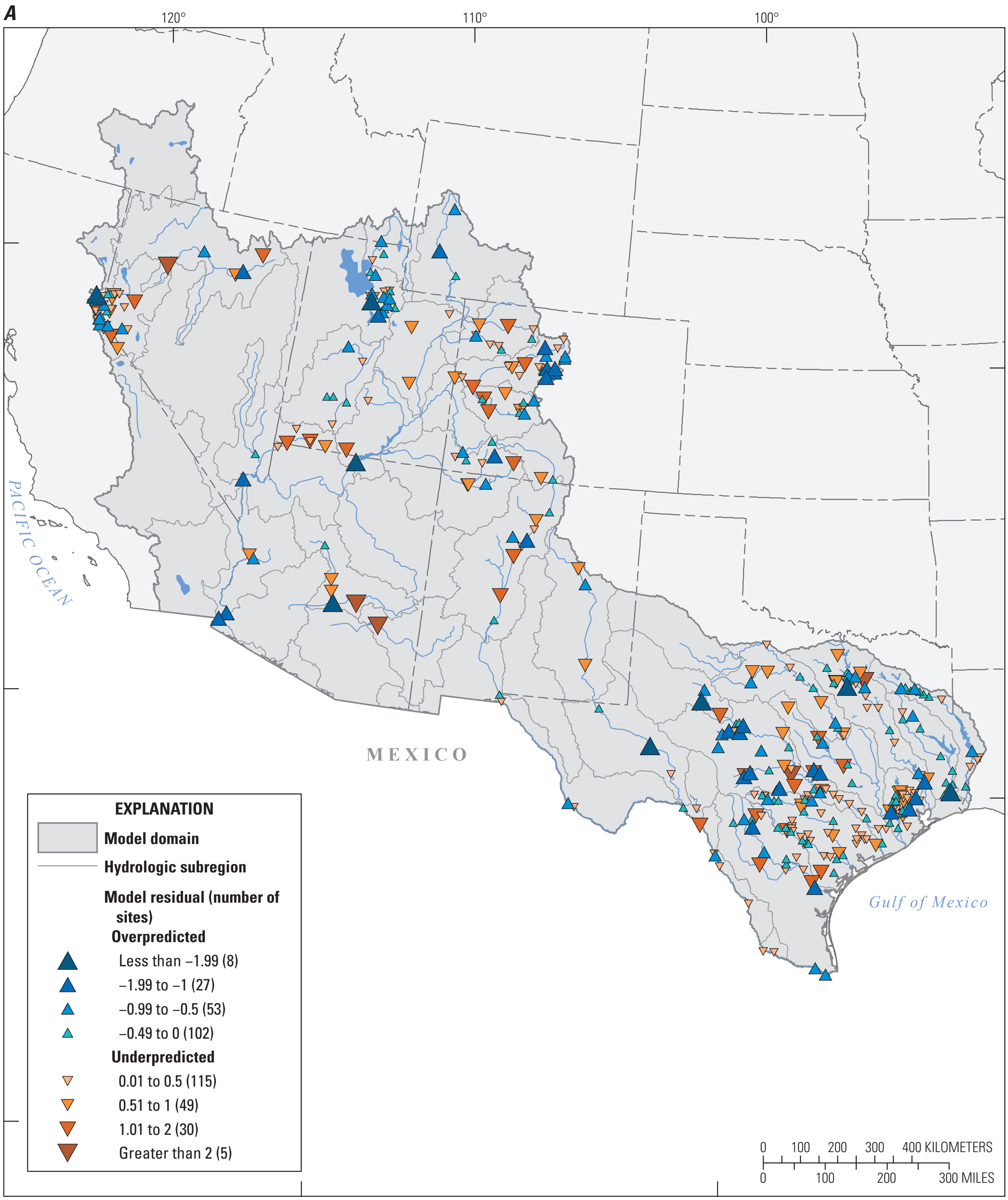
The suspended-sediment model included six source terms, two delivery terms, four aquatic loss terms, and a calibration load conversion term (table 7). The model results indicated that, as expected, alluvial sediments generally yield on average much less sediment to streams (0.744 [(t/km^2)/yr]) than areas represented by other types of surface geology. Sediment yields from agricultural, developed, and forest land not consisting of alluvial sediments average 3.40, 8.91, and 15.1 (t/km^2)/yr, respectively. The exception was brushland, which yields almost exactly the same amount of sediment as alluvial sediments. The model results also indicated that the average sediment contribution from perennial streams is 13.4 (t/km^2)/yr, but that stream power gain did not have a significant effect on this source and that inflows were not a significant source of sediment.

Intermittent streams were not included as a source in the model because the estimated coefficient was very close to zero and had very little significance. These results did not necessarily mean, however, that intermittent streams do not contribute to in-stream suspended-sediment load across the Southwest region. These results might be due to spatial correlation between intermittent stream length and sources that were expressed as an area (specifically, brushland and forest land). The coefficient for intermittent streams was significant when both brushland and forest land were excluded from the model, which suggests that its contribution to in-stream load was accounted for in those area-based source terms. There are characteristics of intermittent streams, however that might also help explain their low significance as a modeled source of suspended sediment. The suspended-sediment loads generated in intermittent streams, which typically occur in pulses on the order of hours or days in response to short precipitation events, might not have been recorded by the routine monitoring on which the calibration loads were based or might not even have reached the perennial streams where the monitoring stations were located. The precipitation-driven flows in many intermittent streams in the arid areas of the Southwest region are completely absorbed by downstream dry channels or lost to evapotranspiration due to the short duration and small areal extent of the summer thunderstorms that produce runoff (Hadley, 1968). Therefore, water yield can decrease moving downstream despite an increase in drainage area, and some headwater tributaries that experience only ephemeral flows seldom contribute any sediment to perennial streams because of these losses by absorption.

The suspended-sediment model included one delivery term with a positive coefficient (soil erodibility) and one delivery term with a negative coefficient (soil clay content) and, as expected, these results were consistent with those from the total phosphorus model. Unlike the total phosphorus model, however, the suspended-sediment model did not include incremental water yield as a delivery term because that landscape property was not significant. This result does not mean that local runoff (as represented by incremental water yield) was not a factor in the transport of suspended sediment through Southwest region watersheds. Rather, there were likely issues with correlation between incremental water yield and other landscape properties that were included in the model–specifically, soil erodibility and the area of brushland and forest land. Many other climate and landscape factors were evaluated as potential delivery terms but were not included because they were not significant.

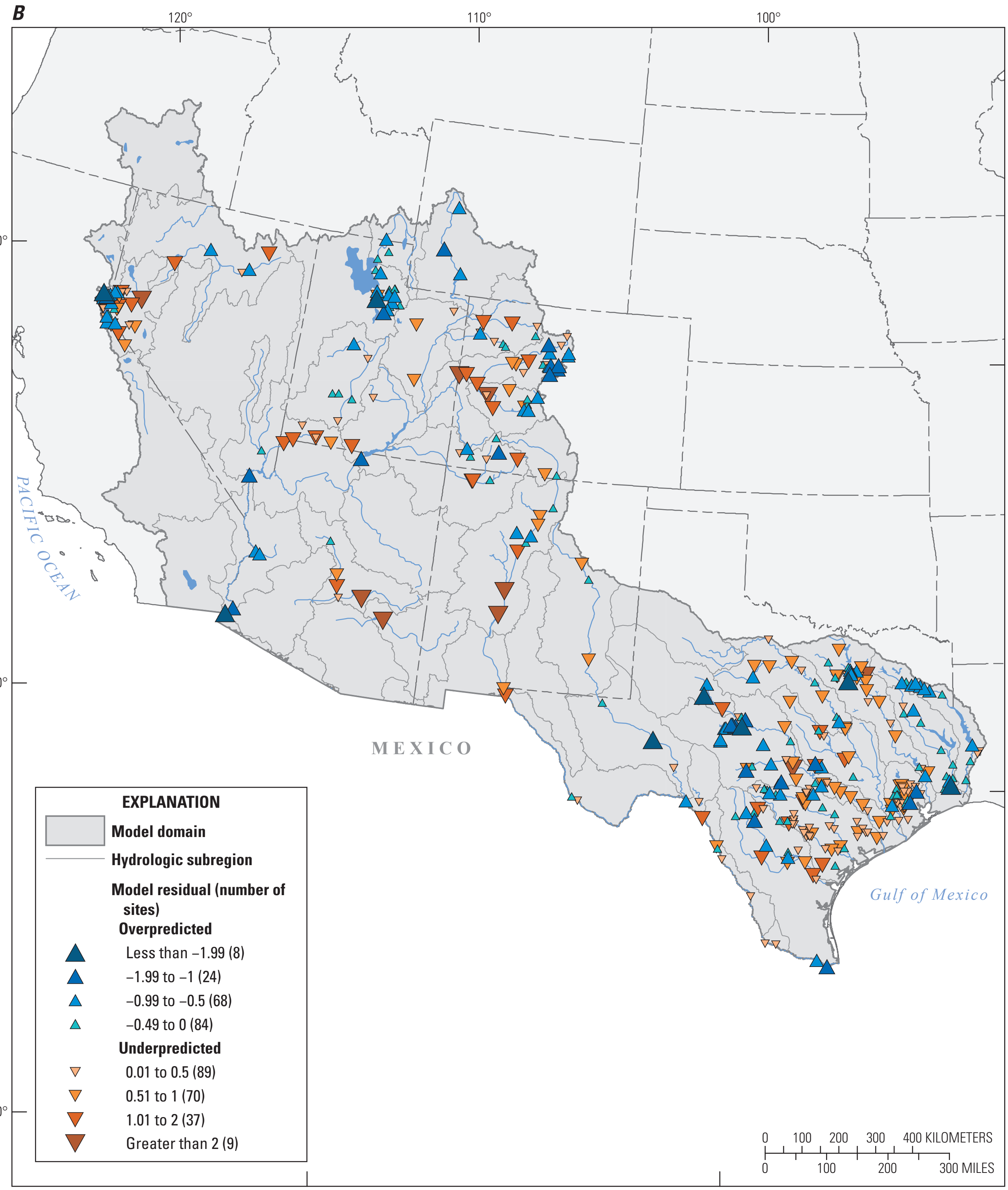
The model results showed that free-flowing streams were an important location for net sediment loss, and these losses were a function of the percentage decrease in stream power. The suspended-sediment model included loss terms representing municipal water supply intakes and irrigation diversions with coefficients that were set to the values estimated in the streamflow model. The model results also showed that impoundments were an important location for net sediment loss.

The model identified a significant difference between the TSS and suspended-sediment loads in the calibration data



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 13. Spatial distribution of conditioned (*A*) and unconditioned (*B*) residuals from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total phosphorus model. [Conditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were reset to the measured loads at the calibration stations. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at the calibration stations.]



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 13.—Continued.

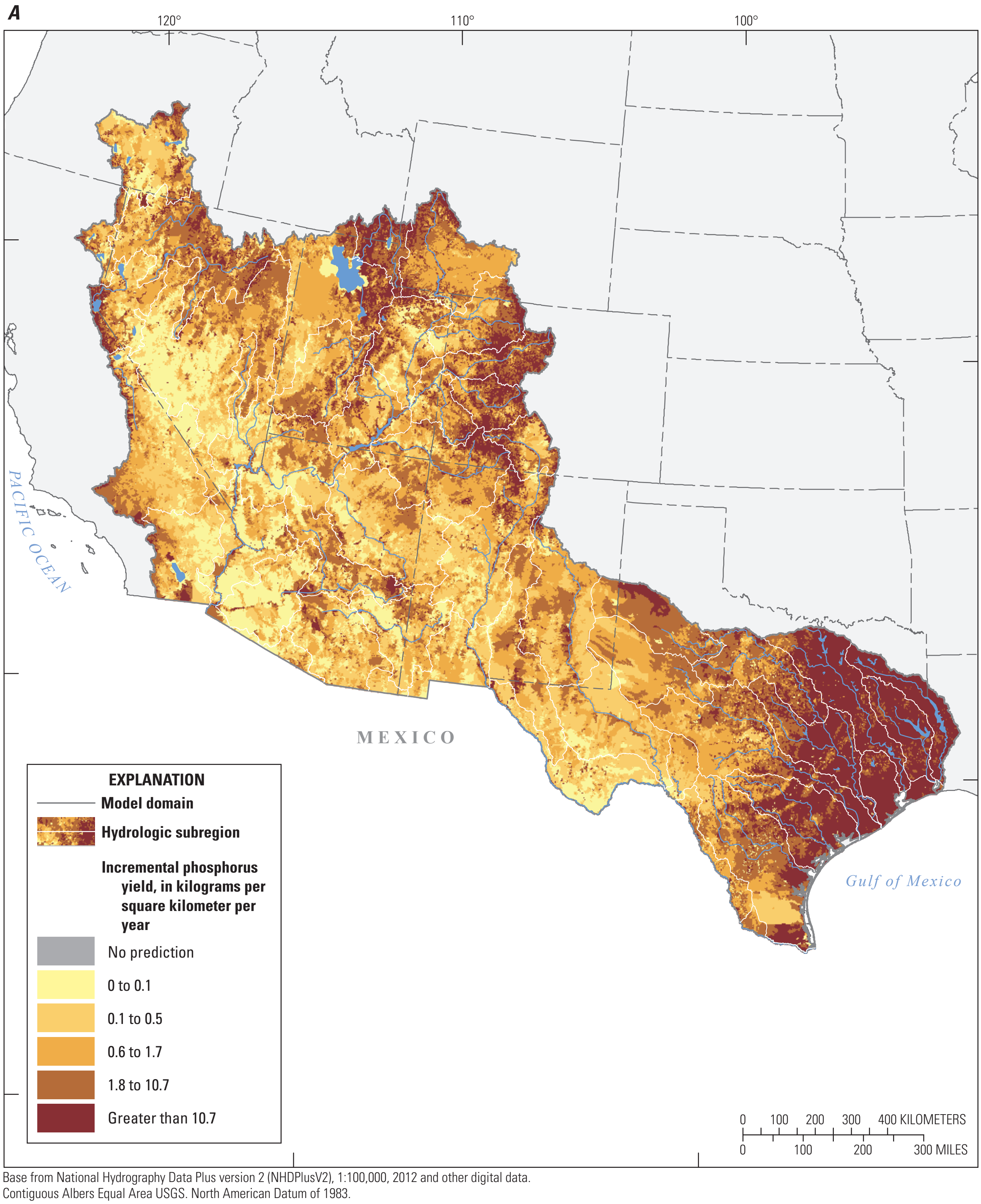
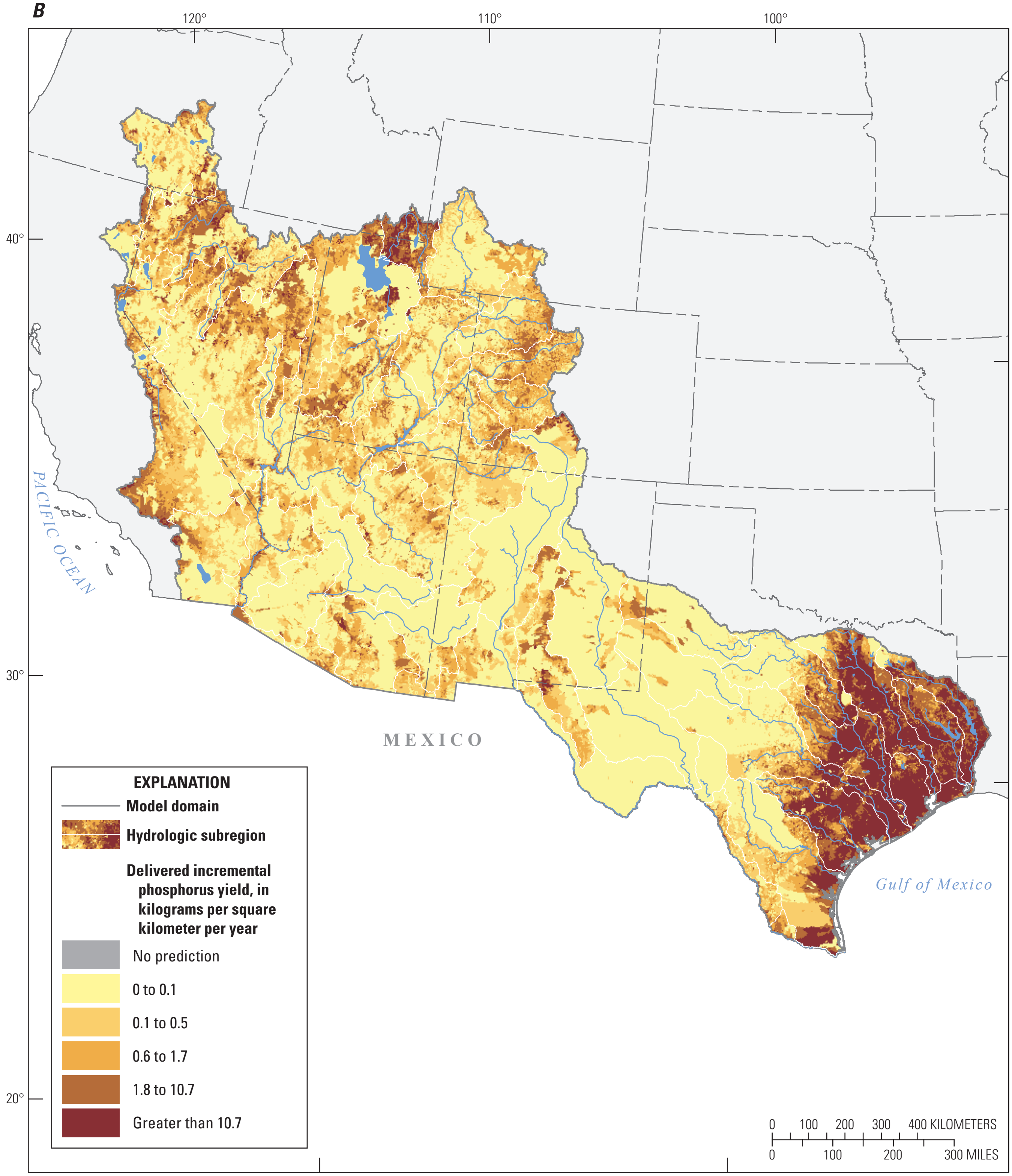


Figure 14. Predicted mean annual incremental yield (*A*) and delivered incremental yield (*B*) of total phosphorus from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) total phosphorus model.

B



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 14.—Continued.

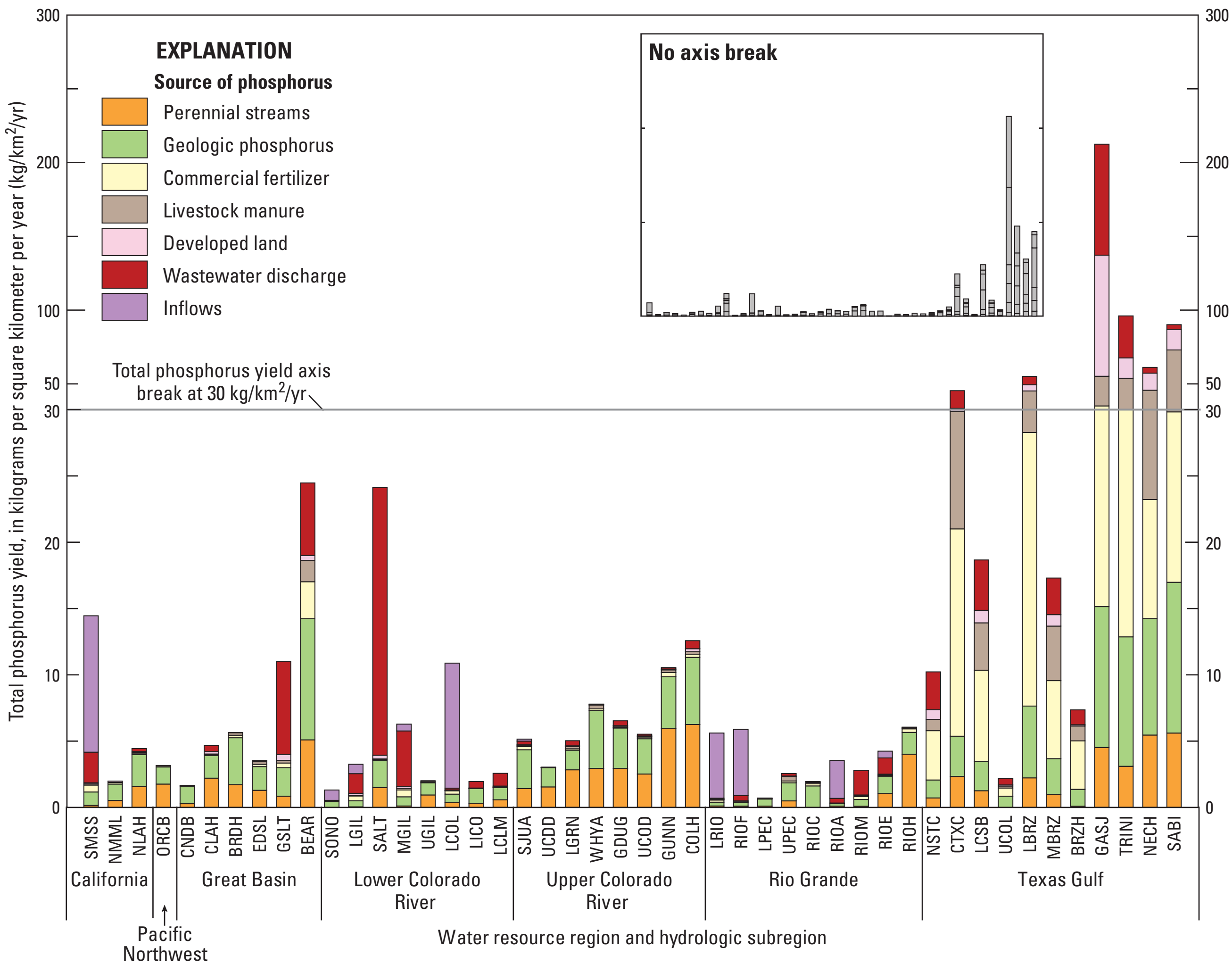


Figure 15. Predicted mean annual total phosphorus yield, by source, for hydrologic subregions in the Southwest region of the United States.

set, and this is presumed to be the combination of differences in field sampling techniques (surface grab sampling versus depth and width integrated sampling) and laboratory analytical techniques (SS compared to TSS). The estimated coefficient of -1.180 was equivalent to an average conversion factor of 3.25 between TSS and SS loads, and this factor was substantially higher than the average value (1.622) for the only other results found in the literature (Groten and Johnson, 2018, for streams in Minnesota where the results ranged from 1.000 – 3.888). The reason for such a large difference between the results for the Southwest region and the average value for the streams in Minnesota is not known, but one possibility is that the Southwest region streams contain a larger fraction of sand compared to the Minnesota streams.

Figure 16 shows the diagnostic plots for the calibration of the suspended-sediment model, which explained about 66 percent of the variability in measured suspended-sediment yield. The values shown on the plots reflect any scaling necessary to convert TSS loads to equivalent SS loads. The variance of the model residuals was relatively constant across the range of conditioned predicted suspended-sediment loads (16A) and conditioned suspended-sediment yields (16B). The conditioned RMSE (1.322) was substantially less than the unconditioned RMSE (1.572), which is reflected in the difference between the plots shown in fig. 16 (there is more spread around the 1:1 line in fig. 16D compared to fig. 16C) and the differences between the conditioned and unconditioned residuals shown in figure 17 (for example, the natural logs of 119 conditioned residuals were greater than 1.0 or less than -1.0, whereas the natural logs of 166 unconditioned residuals were greater than or less than those values). The nested areas for the calibration stations were not a significant predictor of the squares of the residuals from the suspended-sediment model and, therefore, were not used as weights in its calibration. There was no significant spatial correlation among either loose clusters of residuals or tight clusters of nested or nonnested residuals. Although significant spatial correlation was not found among tight clusters of nested residuals,

Table 7. Model statistics for the explanatory variables included in the SPARROW suspended-sediment model for the Southwest region of the United States.

[m/yr, meter per year; (t/km)/yr, ton per kilometer per year; *p*-value, probability value; RMSE, root mean square error; R^2, coefficient of determination; (t/km²)/yr, ton per square kilometer per year; yr/m, year per meter; –, not applicable]

Variable		Coefficient unit	Variable unit	Model coefficient value	90-percent confidence interval for the model coefficient		Standard error of the model coefficient	*p*-value	*t*-statistic	Variance inflation factor
					Low	High				
Source										
Perennial streams[a]		km	(t/km)/yr	13.4	5.78	20.97	4.60	0.004	2.90	1.67
Land cover group	Surface geology									
All land cover types	Alluvial sediments	km²	(t/km²)yr	0.744	0	1.51	0.463	0.109	1.61	2.15
Agricultural land	All other types[b]	km²	(t/km²)/yr	3.40	0	7.93	2.74	0.216	1.24	2.50
Developed land		km²	(t/km²)/yr	8.91	0.44	17.4	5.14	0.084	1.73	2.38
Forest land		km²	(t/km²)/yr	15.1	6.02	24.3	5.53	0.007	2.74	3.35
Brushland		km²	(t/km²)/yr	0.737	0	1.64	0.549	0.181	1.34	1.76
Land-to-water delivery										
Ln(soil erodibility)[c]		Unitless	unitless	7.37	6.01	8.74	0.827	<0.0001	8.92	7.66
Ln(soil clay content)[d]		Unitless	unitless	–1.45	–2.11	–0.79	0.398	0.000	−3.64	2.00
Aquatic loss										
Loss in streams[e]		Percent	Percent^{-1}	0.002	0	0.004	0.001	0.086	1.72	1.57
Withdrawals for irrigation[f]		Unitless	Unitless	0.357	—	—	—	—	—	—
Withdrawals for municipal water supply[g]		Unitless	Unitless	0.699	—	—	—	—	—	—
Loss in impoundments[h]		yr/m	m/yr	13.7	9.67	17.7	2.44	<0.0001	5.61	1.17
Conversion										
Conversion between TSS and SSC loads[i]		—	—	–1.180	–1.526	-0.834	0.210	<0.0001	–5.62	4.23

Spatial test	Number	Correlation/ value	*p*-value	Model summary statistic	Model summary statistic value
Nested sites (weighting)–Coefficient for nested share[j]	351	0.029	0.834	Conditioned RMSE[k], in natural logarithm units	1.322
Loose clusters–Moran's *I*	351	0.020	0.832	Conditioned RMSE[k], percent in real space units[m]	218
Tight clusters–Pairs of nested sites within 5 km	11	–0.159	0.640	Unconditioned RMSE[l], in natural logarithm units	1.572
Tight clusters–Pairs of nonnested sites (and dissimilarly sized nested sites) within 5 km	17	0.117	0.655	Unconditioned RMSE[l], percent in real space units[m]	329
				Mean exponentiated weighted error	4.478
				R^2	0.765
				Yield R^2	0.656
				Number of calibration stations	351

[a]Contribution from perennial stream channels.

[b]Igneous and metamorphic rock, residual material, and glaciofluvial, proglacial, glacial till, colluvial, lacustrine, eolian, coastal zone, playa, and calcareous biological sediments.

[c]Natural log of mean soil erodibility as measured by the K-factor (unitless).

[d]Natural log of the mean soil clay content (percent).

[e]Removal in streams expressed as a function of the reduction in stream power (percent).

[f]Estimated removal of surface water for irrgation expressed as a fraction of stream discharge (fixed to value estimated in streamflow model).

[g]Estimated removal of surface water for municipal water supply expressed as a fraction of stream discharge (fixed to value estimated in streamflow model).

[h]Loss due to settling in impoundments such as ponds, lakes, and reservoirs expressed as the inverse hydraulic load.

[i]Conversion term between TSS and suspended sediment calibration loads.

[j]The ratio of the nested drainage area to the total drainage area, where the nested area is the area upstream of a calibration station that drains exlusively to that calibration station.

[k]Conditioned RMSE: root mean square error of the difference between the natural log of measured calibration loads and the natural log of predicted accumulated loads that were reset to the measured loads at the calibration stations.

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

[m]RMSE in terms of percent in real space units was computed as: $100 \times (\exp(RMSE^2) - 1)^{0.5}$; RMSE is in this equation is in natural log units.

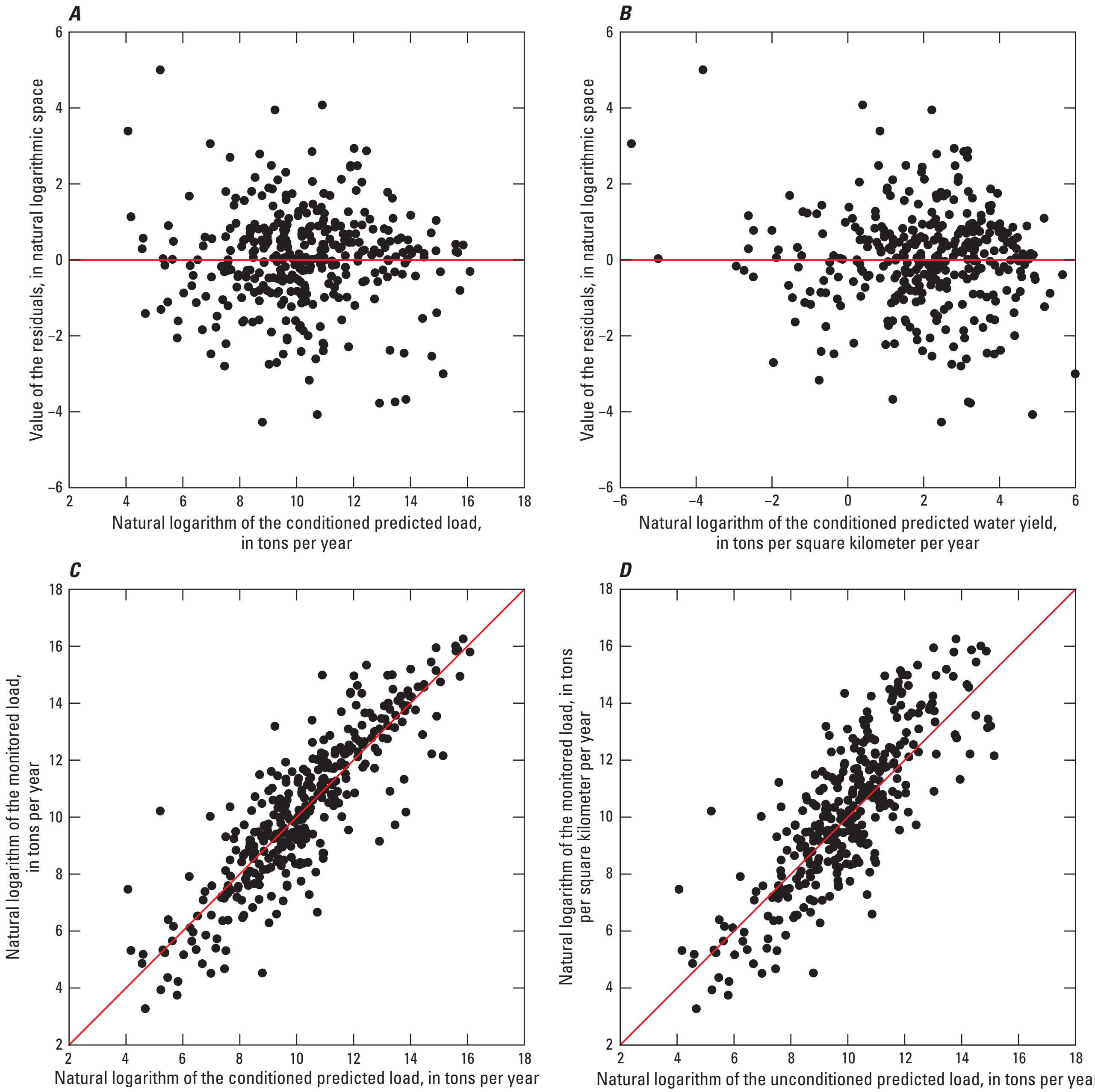
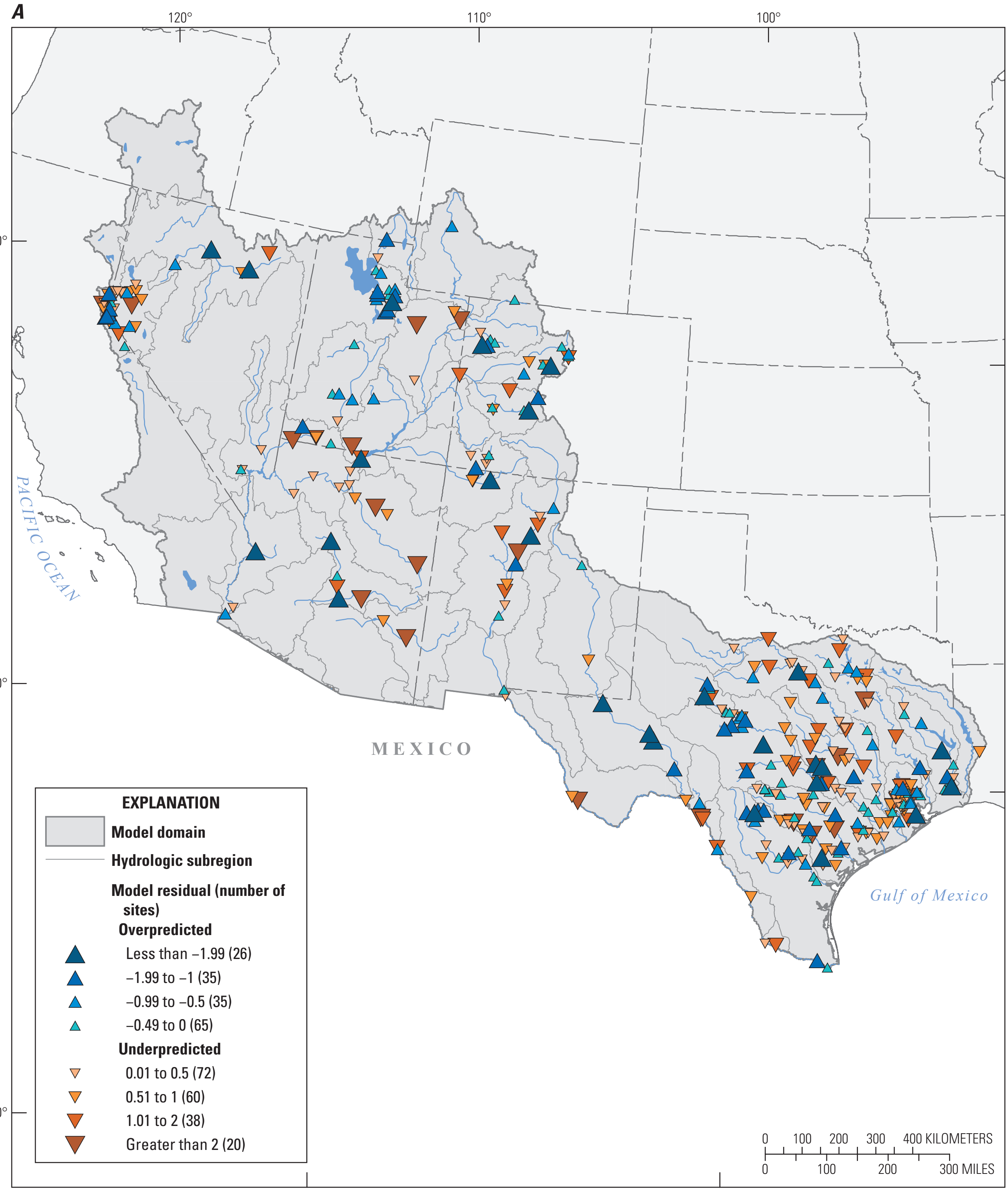


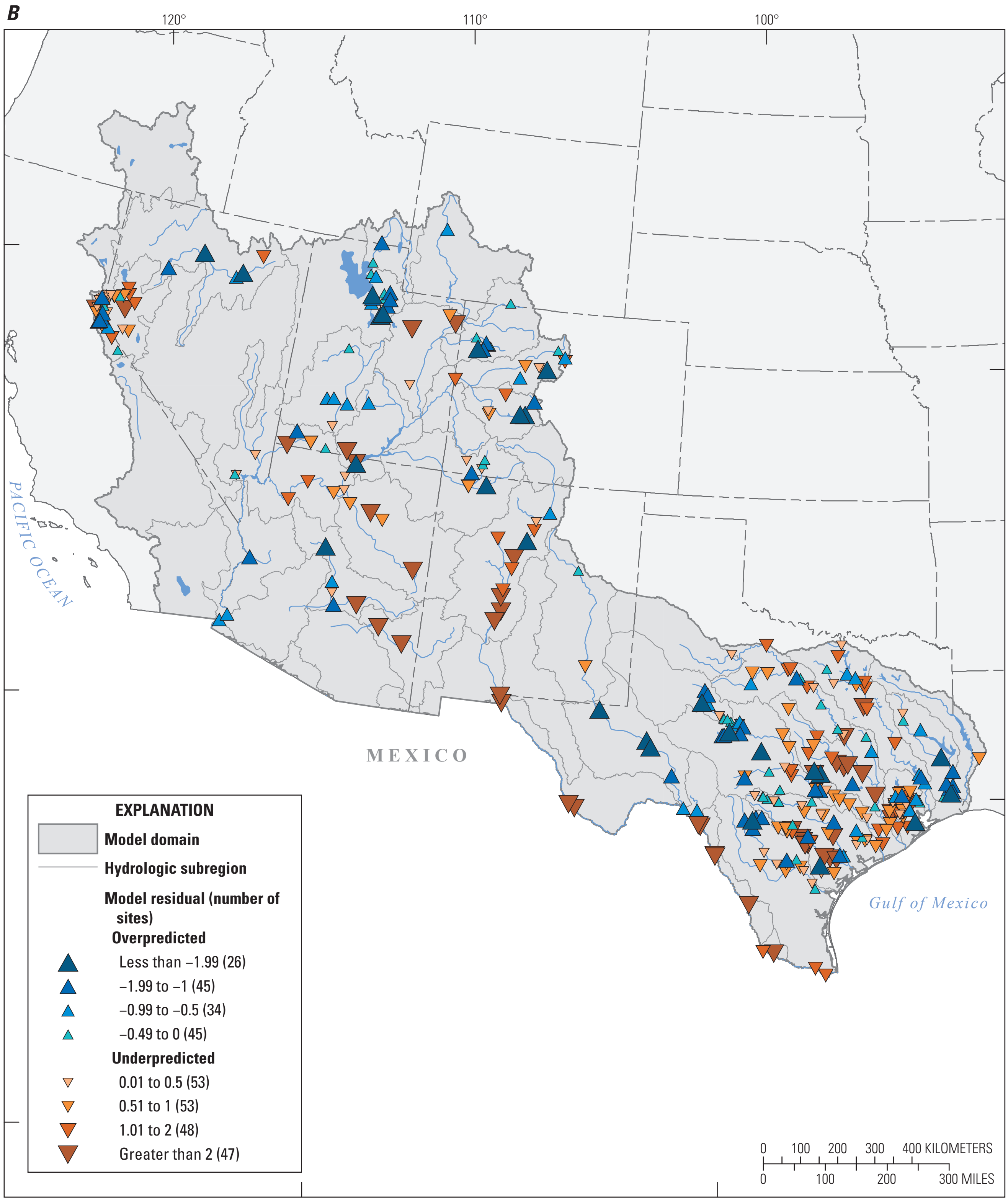
Figure 16. Diagnostic plots for the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) suspended-sediment model. (*A*) Residuals versus predicted load; (*B*) Residuals versus predicted yield; (*C*) measured streamflow versus conditioned predicted load (model calibration); and (*D*) measured load versus unconditioned predicted load (full prediction).

the substantial difference between the conditioned and unconditioned RMSE was an indication that calibration station nesting still affected the model calibration even though the nested areas for the calibration stations were not a significant predictor of the squares of the residuals.The mean incremental yields predicted by the suspended-sediment model are shown in figure 18, where the total incremental yields represent the total amount of suspended sediment generated within each incremental catchment, and the delivered incremental yields represent the amount generated within each catchment that was delivered to the Mexican border, the Gulf of Mexico, or delivered to internal receiving waters for closed basins. The highest suspended-sediment yields were generally predicted for the Texas Gulf water resources region where water yields are also generally highest. Forest land is the largest contributor to the suspended sediment generated within the Southwest region, accounting for about 55 percent of the total amount, and this is



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 17. Spatial distribution of conditioned (*A*) and unconditioned (*B*) residuals from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) suspended-sediment model. [Conditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were reset to the measured loads at the calibration stations. Unconditioned residuals are based on the difference between the log of measured calibration loads and the log of predicted accumulated loads that were not reset to the measured loads at the calibration stations.]

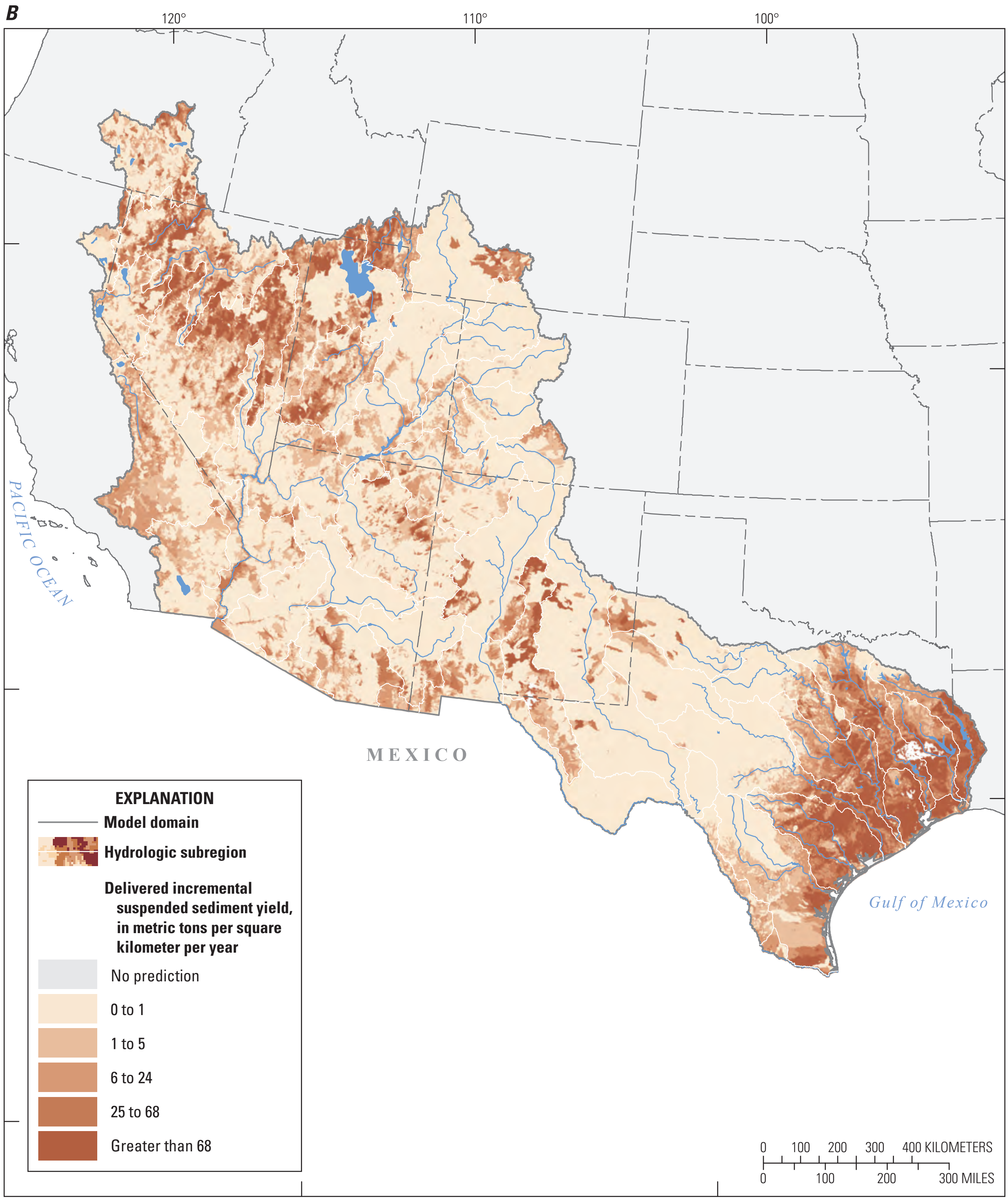


Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 17.—Continued.

Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 18. Predicted mean annual incremental yield (*A*) and delivered incremental yield (*B*) of suspended sediment from the Southwest region SPARROW (SPAtially Referenced Regression On Watershed attributes) suspended-sediment model.



Base from National Hydrography Data Plus version 2 (NHDPlusV2), 1:100,000, 2012 and other digital data.
Contiguous Albers Equal Area USGS. North American Datum of 1983.

Figure 18.—Continued.

the case in almost all the hydrologic subregions (fig. 19 and table 2.4).

There were substantial differences between the predicted total and the delivered incremental suspended-sediment yields (fig. 18), and these differences reflect losses in free-flowing streams, impoundments (such as reservoirs, lakes, and ponds), and water diversions for irrigation and municipal water supply. On average, about 33 percent of the total amount of suspended-sediment load generated within each of the hydrologic subregions in the Southwest region reaches its terminal waterbody, meaning that the load is exported out of a subregion or (for the case of closed basins) delivered to internal receiving waters–and the values range from close to zero for the Rio Grande-Amistad (RIOA) subregion to 82 percent for the Sonora subregion (SONO). The amount of suspended sediment that reaches terminal waterbodies is influenced by the combined effect of different watershed properties. An example of this relationship is shown in figure 20, where the percentage of suspended sediment reaching a terminal waterbody is plotted against the total impoundment area within each subregion normalized by the total length of streams within the subregion. As expected, subregions with a higher value for normalized impoundment area generally have a lower percentage of suspended sediment reaching a terminal waterbody compared to subregions with a lower value for normalized impoundment area. This relationship is complicated, however, by the presence of major stream diversions within a subregion or a large reservoir upstream of a terminal waterbody, which act to reduce the amount of suspended sediment exported from a subregion. There is a group of subregions with low values for normalized impoundment area that also have low percentages of suspended sediment reaching a terminal waterbody (most below 10 percent), but almost all these subregions either contain a major stream diversion and/or have a large reservoir located near their outlet or internal receiving waters. Without these alterations to the natural hydrology these subregions would deliver a much higher percentage of their suspended sediment to terminal waterbodies.

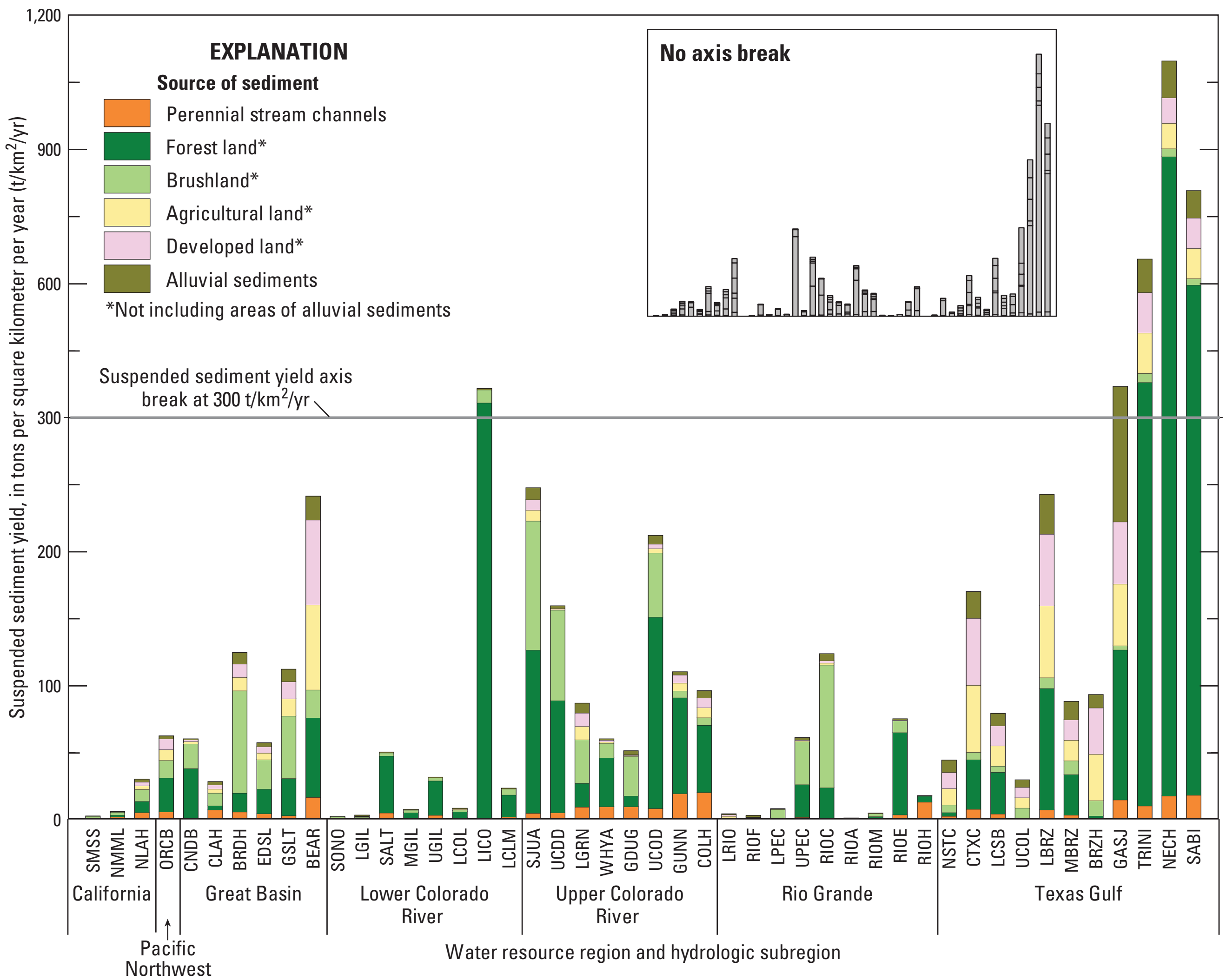


Figure 19. Predicted mean annual suspended-sediment yield, by source, for hydrologic subregions in the Southwest region of the United States.

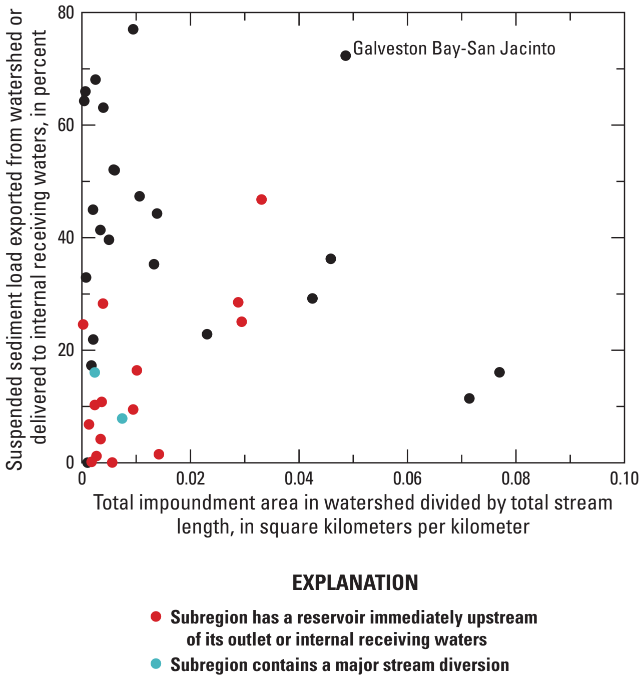


Figure 20. Suspended-sediment generation in hydrologic subregions of the Southwest Region of the United States.

The one major outlier on figure 20 is the Galveston Bay-San Jacinto subregion, which exports a greater share of its suspended sediment (72 percent) than all but one other subregion even though it has the third highest value for normalized impoundment area. The high percentage of suspended sediment reaching Galveston Bay at the outlet of this subbasin likely reflects three factors: a high percentage of the suspended sediment exported from the subbasin originates on the developed land covering the Houston metropolitan area, this developed land has few impoundments to trap sediment, and almost all the impoundments in the subbasin are upstream of the Houston metropolitan area.

Yields Summarized By Land Cover

The SPARROW model can estimate the yields for catchments that are dominated by different types of land cover, even land cover types that are not represented in a model as a source. For this report, yields were summarized for catchments that were predominately one type of land cover. Table 8 shows the median incremental yields of total nitrogen, total phosphorus, and suspended sediment for catchments where at least 90 percent of the total area is covered by forest land, shrubland, agricultural land, or developed land. The median total nitrogen, total phosphorus and suspended-sediment yields were highest for agricultural and developed land and lowest for forest land and shrubland.

Discussion

The assumptions and simplifications in model specification need to be considered when using the results from any SPARROW application, with the primary assumption being that the quantity and quality of the explanatory and calibration data are adequate. Every effort was made to identify and quantify the sources of streamflow, nutrients, and sediment in the Southwest region and the landscape properties that influence water and contaminant transport. However, the models might not have accounted for all sources and important landscape properties in all areas of the modeling domain due to limitations in data availability, the accuracy of the input data, or the strong correlation found between different sources. An assumption in SPARROW modeling is that watersheds in areas with relatively few calibration stations are represented in the model by other areas upstream of calibration stations. A disproportionate number of calibrations stations in the total nitrogen, total phosphorus, and suspended-sediment models were in the Texas Gulf water resource region (which has extensive areas of agricultural and large urban centers) and the Upper

Table 8. Median incremental yields of total nitrogen, total phosphorus, and suspended sediment for catchments in the Southwest region of the United States dominated by different land cover types.

[Median values are for incremental NHDPlus catchments that are made up of at least 90 percent of each land cover category. **Abbreviations**: $(kg/km^2)/yr$, kilogram per square kilometer per year; $(kg/km^2)/yr$, kilogram per square kilometer per year; $(Mt/km^2)/yr$, metric ton per square kilometer per year]

Generalized land cover group	Median incremental yield		
Dominant land cover	Total nitrogen $(kg/km^2)/yr$	Total phosphorus $(kg/km^2)/yr$	Suspended sediment $(Mt/km^2)/yr$
Forest land	24.6	3.70	43.4
Brushland	3.82	0.68	6.31
Agricultural land	214	49.9	179
Developed land	425	65.7	487

Colorado water resource region (which has extensive areas of forest land). This provided good representation for those water resource regions but generally poor coverage for the other water resource regions in the Southwest which are primarily brushland. Other areas that were poorly represented in the total nitrogen, total phosphorus, and suspended-sediment models included headwater watersheds, which have a profound influence on shaping downstream water quality (Alexander and others, 2007). This was because most of the water-quality data used to estimate the calibration loads for the models were obtained from state and local monitoring programs which, due to limited resources, tend to focus their efforts on relatively large streams. There's no universally accepted definition of headwater streams, but they are often considered to be those of the first and second order. Using that definition, headwater areas contribute 59 percent of the total nitrogen load, 64 percent of the total phosphorus load, and 79 percent of suspended load delivered to streams in the Southwest region. Only 5–10 percent of the calibration sites used in those models, however, were located on headwater streams. The increasing availability of stream hydrography at finer resolution underscores the potential usefulness of increased water-quality and streamflow monitoring on small streams to support a better understanding of water-quality conditions in headwater areas covered by existing regional models.

As is the case with any regression analysis, the range in SPARRROW predictions should generally reflect the range in calibration data upon which those predictions are based. One way to evaluate this for SPARROW models is to compare the measured loads at the calibration stations to all the predicted loads and then calculate the total area represented by the predicted loads that are outside the range of the loads in the calibration data. About one-half of the modeling domain drained to stream reaches where the predicted total nitrogen and total phosphorus loads were less than the smallest calibration loads and about 20 percent drained to stream reaches where the predicted suspended-sediment load was less than the smallest calibration load, providing additional evidence that headwater areas were under-represented in those models. In contrast, the calibration loads generally included the higher end of predicted loads. Less than one percent of the modeling domain drained to stream reaches where the predicted total nitrogen and suspended-sediment loads were greater than the largest calibration loads and about 11 percent drained to stream reaches where the predicted total phosphorus load was greater than the largest calibration load.

The results from the four Southwest region SPARROW models provide insights into the important landscape controls on streamflow and nutrient and suspended-sediment yields across the Southwest region. Mean annual precipitation varies greatly across the region, and this explains why it was a common feature across three of the four SPARROW models, whether expressed as part of a source term in the streamflow model or as part of a delivery term in the total nitrogen and total phosphorus models. Two other landscape properties, soil erodibility and soil clay content, were significant in the total phosphorus and suspended-sediment models, indicating that both processes play important roles in the delivery of these constituents from land to water. Additionally, the models estimated significant losses of total nitrogen and suspended sediment in free-flowing streams and significant losses of total nitrogen, total phosphorus, and suspended sediment in impoundments such as ponds, lakes, and reservoirs. There were other landscape properties, however, that were expected to be important but were not. One of these was catchment slope which, based on the results from other SPARROW suspended-sediment applications (Schwarz, 2008; Brakebill and others, 2010) and many empirical models of sediment erosion (for example, Wischmeier and Smith, 1978), was expected to have a positive effect on sediment delivery. Another landscape property that was not significant was the use of conservation practices as a control on nutrient and sediment runoff from farmland, which likely reflects the relatively small amount of land in the Southwest region used for agriculture (6.65 percent). SPARROW models developed for smaller areas within the Southwest region, however, might lead to different results. For example, conservation practices might be significant in a model that includes primarily agricultural watersheds.

The models developed for this study represented novel applications of SPARROW to the Southwest region. The streamflow model was calibrated using existing estimates of natural streamflow based on the difference between precipitation and evapotranspiration, but also accounted for locally important landscape factors that affect the movement of water through river basins as well as the extensive diversions found throughout the Southwest region for municipal water supply and irrigation. While previous nutrient and sediment SPARROW models have been developed for the entire continental United States, the SPARROW models developed for this study were the first to assess total nitrogen, total phosphorus, and suspended sediment specifically in the Southwest region and, as a result, were able to characterize the water-quality conditions more completely than the previous models. Therefore, the results from this study could help complement research and inform water-quality management activities in the region. The reach-scale estimates of nutrient and suspended-sediment conditions could be used as a screening tool for identifying potentially impaired waterbodies and help guide remediation efforts where impairment has been documented. The results from the suspended-sediment model could be used to evaluate reservoir sedimentation, which leads to reductions in storage capacity, by providing estimates of the amount of sediment retained by specific reservoirs on an annual basis. Another application could be the use of the input data and the model results (for example, streamflow, surface-water diversions for consumptive use, nutrient loads and concentrations) to help explain the spatial patterns in the harmful algal blooms that are an increasingly serious concern throughout the Southwest region. Finally, the results from this study could provide estimates of sediment and nutrient loadings to Texas Gulf estuaries, especially where such data are scarce or non-existent.

Summary

This report described the development of SPARROW models for the Southwest region of the U.S. for streamflow and three water-quality constituents – total nitrogen, total phosphorus, and suspended sediment. The streamflow model was used to characterize the complex hydrology that exists within the Southwest region and to provide the best available estimates of local water yield as input to the total nitrogen and total phosphorus models. The constituent models were then used to estimate local total nitrogen, total phosphorus, and suspended-sediment yields. The four SPARROW models were also used to estimate the water, total nitrogen, total phosphorus, and suspended-sediment yields for the 46 hydrologic subregions that make up the Southwest region and the relative contribution of different sources to those yields. In addition to providing estimates of local and watershed yields, the four SPARROW models provided insight into the watershed properties that control the delivery of water, nutrients, and sediment to streams and, ultimately, to downstream receiving waters. Inputs and outputs from the 2012 Southwest SPARROW models are available in a USGS data release (Miller and others, 2020).

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Appendix 1. Summary Of Wastewater Nutrient Discharge For Hydrologic Sub-Regions Within The Southwest Region Of The United States

Table 1.1. Summary of wastewater nutrient discharge for hydrologic sub-regions within the Southwest region of the United States.

[kg, kilogram; NPDES, National Pollutant Discharge Elimination System]

Region	Hydrologic subregion	Subregion name	Number of NPDES facilities that discharged wastewater	Total nitrogen discharged (kg)	Total phosphorus discharged (kg)
Texas Gulf	All	—	1,593	38,895,581	4,792,692
	SABI	Sabine	111	1,543,094	203,621
	NECH	Neches	76	1,856,172	143,377
	TRINI	Trinity	212	9,422,746	1,235,046
	GASJ	Galveston Bay-San Jacinto	684	13,654,827	1,496,264
	BRZH	Brazos headwaters	4	520,187	47,610
	MBRZ	Middle Brazos	72	767,766	107,873
	LBRZ	Lower Brazos	141	2,945,962	522,420
	UCOL	Upper Colorado	8	206,151	23,059
	LCSB	Lower Colorado-San Bernard Coastal	82	2,154,830	266,727
	CTXC	Central Texas Coastal	107	4,321,636	558,573
	NSTC	Nueces-Southwestern Texas Coastal	96	1,502,210	188,122
Rio Grande	All	—	92	2,353,175	228,552
	RIOH	Rio Grande headwaters	17	49,493	774
	RIOE	Rio Grande-Elephant Butte	24	632,167	74,579
	RIOM	Rio Grande-Mimbres	14	301,859	56,929
	RIOA	Rio Grande-Amistad	9	795,553	49,134
	RIOC	Rio Grande closed basins	2	4,217	1,559
	UPEC	Upper Pecos	7	54,863	12,207
	LPEC	Lower Pecos	3	1,392	60
	RIOF	Rio Grande-Falcon	11	503,570	31,071
	LRIO	Lower Rio Grande	5	10,060	2,238
Upper Colorado River	All	—	181	955,836	57,421
	COLH	Colorado headwaters	69	459,010	11,639
	GUNN	Gunnison	26	96,863	2,346
	UCOD	Upper Colorado-Dolores	10	13,006	2,532
	GDUG	Great Divide - Upper Green	13	94,267	16,031
	WHYA	White-Yampa	21	65,357	781
	LGRN	Lower Green	4	70,285	13,154
	UCDD	Upper Colorado-Dirty Devil	1	6,592	47
	SJUA	San Juan	37	150,457	10,892

Table 1.1. Summary of wastewater nutrient discharge for hydrologic sub-regions within the Southwest region of the United States.—Continued

[kg, kilogram; NPDES, National Pollutant Discharge Elimination System]

Region	Hydrologic subregion	Subregion name	Number of NPDES facilities that discharged wastewater	Total nitrogen discharged (kg)	Total phosphorus discharged (kg)
Lower Colorado River	All	—	61	4,545,453	990,272
	LCLM	Lower Colorado-Lake Mead	9	2,880,846	72,767
	LICO	Little Colorado	12	79,818	24,725
	LCOL	Lower Colorado	5	300,096	3,202
	UGIL	Upper Gila	1	459	99
	MGIL	Middle Gila	15	440,628	177,145
	SALT	Salt	13	793,254	673,713
	LGIL	Lower Gila	6	50,351	38,619
	SONO	Sonora	0	0	0
Great Basin	All	—	51	3,019,421	821,606
	BEAR	Bear	16	311,162	97,625
	GSLT	Great Salt Lake	29	2,613,573	711,618
	EDSL	Escalante Desert-Sevier Lake	3	10,415	2,595
	BRDH	Black Rock Desert-Humboldt	1	945	0
	CLAH	Central Lahontan	2	83,325	9,769
	CNDB	Central Nevada Desert Basins	0	0	0
Pacific Northwest	ORCB	Oregon Closed Basins	0	0	0
California	All	—	8	877,411	98,229
	NLAH	North Lahontan	1	9,519	2,499
	NMML	Northern Mojave-Mono Lake	0	0	0
	SMSS	Southern Mojave-Salton Sea	7	867,892	95,729
All hydrologic sub-regions		—	1,986	50,646,876	6,988,772

Appendix 2. Summary Of Water, Total Nitrogen, Total Phosphorus, And Suspended-Sediment Yields For Hydrologic Subregions Within The Southwest Region Of The United States

Table 2.1. Summary of water yields for hydrologic subregions within the Southwest region of the United States.

[**Precipitation minus actual evapotranspiration**: Mean annual difference between precipitation and evapotranspiration for water years 2000–14. **Wastewater discharge**: Mean discharge to surface water from municipal wastewater treatment facilities in 2012. **Spring discharge**: Mean spring discharge. **Inflows**: Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water]

Water resources region	Hydrologic subregion	Subregion name	Total water yield (mm/yr)	Contribution from individual sources (percent)			
				Precipitation minus actual evapotranspiration	Wastewater discharge	Spring discharge	Inflows
Texas Gulf	SABI	Sabine	381	99.5	0.54	0	0
	NECH	Neches	342	99.3	0.72	0	0
	TRINI	Trinity	223	92.8	7.21	0	0
	GASJ	Galveston Bay-San Jacinto	463	90.4	9.63	0	0
	BRZH	Brazos headwaters	10.2	89.1	10.9	0	0
	MBRZ	Middle Brazos	58	97.5	2.52	0	0
	LBRZ	Lower Brazos	135	96.9	2.66	0.48	0
	UCOL	Upper Colorado	9.1	96.8	3.20	0	0
	LCSB	Lower Colorado-San Bernard Coastal	61	94.2	3.26	2.6	0
	CTXC	Central Texas Coastal	117	82.0	5.69	12.3	0
	NSTC	Nueces-Southwestern Texas Coastal	30	93.4	5.70	0.9	0
Rio Grande	RIOH	Rio Grande headwaters	108.1	99.7	0.18	0	0.15
	RIOE	Rio Grande-Elephant Butte	19.0	83.8	7.02	0	9.19
	RIOM	Rio Grande-Mimbres	5.3	85.8	13.8	0	0
	RIOA	Rio Grande-Amistad	15.0	18.0	3.36	8.80	69.9
	RIOC	Rio Grande closed basins	5.34	99.6	0.37	0	0
	UPEC	Upper Pecos	11.3	98.2	1.12	0.7	0
	LPEC	Lower Pecos	7.00	84.7	0.03	15.3	0
	RIOF	Rio Grande-Falcon	20.9	11.1	1.81	2.79	84.3
	LRIO	Lower Rio Grande	17.9	5.77	0.32	0	93.9
Upper Colorado River	COLH	Colorado headwaters	146.7	98.9	1.08	0	0
	GUNN	Gunnison	105.6	99.7	0.32	0	0
	UCOD	Upper Colorado-Dolores	37.7	99.7	0.29	0	0
	GDUG	Great Divide - Upper Green	59.7	99.3	0.26	0.44	0
	WHYA	White-Yampa	80.9	99.8	0.20	0	0
	LGRN	Lower Green	60.3	93.3	0.27	6.43	0
	UCDD	Upper Colorado-Dirty Devil	14.03	80.4	0.00	19.6	0
	SJUA	San Juan	31.9	97.8	0.88	0	1.35
Lower Colorado River	LCLM	Lower Colorado-Lake Mead	15.5	76.7	13.3	10.0	0
	LICO	Little Colorado	8.95	82.2	2.25	15.6	0
	LCOL	Lower Colorado	36.6	11.6	0.79	0	87.6
	UGIL	Upper Gila	12.4	100.0	0	0	0
	MGIL	Middle Gila	7.8	65.0	14.0	0	21.0
	SALT	Salt	38.2	83.6	16.4	0	0
	LGIL	Lower Gila	7.1	59.7	7.14	0	33.2
	SONO	Sonora	6.63	60.6	0	0	39.4
Great Basin	BEAR	Bear	97	93.2	2.08	4.71	0
	GSLT	Great Salt Lake	28.1	86.2	10.5	3.33	0
	EDSL	Escalante Desert-Sevier Lake	27.3	96.8	0.12	3.05	0
	BRDH	Black Rock Desert-Humboldt	12.16	99.1	0	0.87	0
	CLAH	Central Lahontan	60.8	98.6	1.45	0.00	0
	CNDB	Central Nevada Desert Basins	6.67	94.3	0	5.75	0
Pacific Northwest	ORCB	Oregon Closed Basins	17.88	99.2	0	0.77	0
California	NLAH	North Lahontan	39.5	99.8	0.24	0	0
	NMML	Northern Mojave-Mono Lake	13.7	99.0	0	0.95	0
	SMSS	Southern Mojave-Salton Sea	41	11.8	2.33	0	85.8
All hydrologic sub-regions			40.1	87.8	3.54	1.79	6.86

Table 2.1. Summary of water yields for hydrologic subregions within the Southwest region of the United States.—Continued

[**Precipitation minus actual evapotranspiration**: Mean annual difference between precipitation and evapotranspiration for water years 2000–14. **Wastewater discharge**: Mean discharge to surface water from municipal wastewater treatment facilities in 2012. **Spring discharge**: Mean spring discharge. **Inflows**: Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water]

Water resources region	Hydrologic subregion	Subregion name	Total water yield (mm/yr)	Contribution from individual sources (percent)			
				Precipitation minus actual evapotranspiration	Wastewater discharge	Spring discharge	Inflows
Lower Colorado River	LCLM	Lower Colorado-Lake Mead	15.5	76.7	13.3	10.0	0
	LICO	Little Colorado	8.95	82.2	2.25	15.6	0
	LCOL	Lower Colorado	36.6	11.6	0.79	0	87.6
	UGIL	Upper Gila	12.4	100.0	0	0	0
	MGIL	Middle Gila	7.8	65.0	14.0	0	21.0
	SALT	Salt	38.2	83.6	16.4	0	0
	LGIL	Lower Gila	7.1	59.7	7.14	0	33.2
	SONO	Sonora	6.63	60.6	0	0	39.4
Great Basin	BEAR	Bear	97	93.2	2.08	4.71	0
	GSLT	Great Salt Lake	28.1	86.2	10.5	3.33	0
	EDSL	Escalante Desert-Sevier Lake	27.3	96.8	0.12	3.05	0
	BRDH	Black Rock Desert-Humboldt	12.16	99.1	0	0.87	0
	CLAH	Central Lahontan	60.8	98.6	1.45	0.00	0
	CNDB	Central Nevada Desert Basins	6.67	94.3	0	5.75	0
Pacific Northwest	ORCB	Oregon Closed Basins	17.88	99.2	0	0.77	0
California	NLAH	North Lahontan	39.5	99.8	0.24	0	0
	NMML	Northern Mojave-Mono Lake	13.7	99.0	0	0.95	0
	SMSS	Southern Mojave-Salton Sea	41	11.8	2.33	0	85.8
All hydrologic sub-regions			40.1	87.8	3.54	1.79	6.86

Table 2.2. Summary of total nitrogen yields for hydrologic subregions within the Southwest region of the United States.

[**Atmospheric deposition**: Mean wet and dry atmospheric deposition of oxidized and reduce nitrogen for water years 2010–12. **Developed land**: Area of developed land in 2011. **Commercial fertilizer**: Commercial fertilizer applied to cultivated crops and pasture in 2012. **Livestock manure**: Manure from livestock applied to cultivated crops and pasture land in 2012. **Wastewater discharge**: Discharge to surface water from municipal wastewater treatment facilities in 2012. **Inflows**: Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water. **Abbreviation**: (kg/km^2)/yr, kilogram per square kilometer per year]

Water resources region	Hydrologic subregion	Subregion name	Total nitrogen yield ([kg/km2)/yr])	Contribution from individual sources (percent)					
				Atmospheric deposition	Developed land	Commercial fertilizer	Livestock manure	Wastewater discharge	Inflows
Texas Gulf	SABI	Sabine	413	33.8	2.62	12.0	28.4	23.2	0
	NECH	Neches	405	33.3	2.64	10.8	25.5	27.8	0
	TRINI	Trinity	604	15.0	5.52	15.5	10.6	53.4	0
	GASJ	Galveston Bay-San Jacinto	1,616	10.1	9.06	5.6	4.17	71.1	0
	BRZH	Brazos headwaters	74.6	9.94	0.33	49.5	15.9	24.3	0
	MBRZ	Middle Brazos	134	22.3	1.66	35.7	18.2	22.1	0
	LBRZ	Lower Brazos	390	16.1	2.48	34.0	17.4	30.0	0
	UCOL	Upper Colorado	26.9	22.3	0.90	44.4	7.78	24.6	0
	LCSB	Lower Colorado-San Bernard Coastal	141	22.1	2.83	29.3	13.2	32.6	0
	CTXC	Central Texas Coastal	363	14.9	3.24	24.3	15.1	42.5	0
	NSTC	Nueces-Southwestern Texas Coastal	101	16.3	2.06	38.2	9.94	33.5	0
Rio Grande	RIOH	Rio Grande headwaters	74.0	48.2	0.11	43.9	1.60	5.7	0.53
	RIOE	Rio Grande-Elephant Butte	29.2	31.5	0.46	1.59	2.97	49.2	14.3
	RIOM	Rio Grande-Mimbres	22.6	17.2	1.24	11.6	7.63	62.1	0
	RIOA	Rio Grande-Amistad	34.7	6.82	0.28	0.46	1.31	23.2	67.9
	RIOC	Rio Grande closed basins	4.42	73.8	0.49	11.5	9.7	4.50	0
	UPEC	Upper Pecos	11.3	59.4	0.53	9.9	18.7	11.5	0
	LPEC	Lower Pecos	6.28	83.6	0.65	5.40	9.42	0.94	0
	RIOF	Rio Grande-Falcon	53.1	2.97	0.55	0.21	1.15	16.8	78.3
	LRIO	Lower Rio Grande	42.9	1.15	0.11	2.8	1.09	0.94	93.9
Upper Colorado River	COLH	Colorado headwaters	85.2	53.9	1.53	5.70	4.62	34.3	0
	GUNN	Gunnison	56.3	62.1	0.43	17.6	6.12	13.7	0
	UCOD	Upper Colorado-Dolores	23.3	76.5	0.24	13.6	4.89	4.73	0
	GDUG	Great Divide - Upper Green	21.9	74.4	0.29	4.58	7.53	13.2	0
	WHYA	White-Yampa	43.3	69.6	0.44	6.04	16.5	7.39	0
	LGRN	Lower Green	30.9	73.6	0.19	11.5	4.83	9.9	0
	UCDD	Upper Colorado-Dirty Devil	8.66	85.9	0.52	2.40	7.81	3.40	0
	SJUA	San Juan	25.0	51.6	0.41	22.0	5.88	17.0	3.21
Lower Colorado River	LCLM	Lower Colorado-Lake Mead	67.8	12.7	0.68	0.64	1.19	84.8	0
	LICO	Little Colorado	7.81	63.3	2.69	0.32	6.28	27.4	0
	LCOL	Lower Colorado	92.3	3.01	0.13	1.22	0.73	11.5	83.5
	UGIL	Upper Gila	11.5	79.5	0.39	8.11	11.8	0.15	0
	MGIL	Middle Gila	27.2	12.3	2.16	8.95	4.99	56.6	14.9
	SALT	Salt	56.3	32.5	1.61	1.14	1.38	63.4	0
	LGIL	Lower Gila	14.2	18.8	3.98	14.9	4.46	17.7	40.2
	SONO	Sonora	9.76	21.7	0	11.3	2.65	0	64.2
Great Basin	BEAR	Bear	113	37.2	1.15	20.4	18.6	22.6	0
	GSLT	Great Salt Lake	63.2	21.8	4.63	5.10	6.0	62.5	0
	EDSL	Escalante Desert-Sevier Lake	21.7	70.9	1.25	11.0	15.4	1.44	0
	BRDH	Black Rock Desert-Humboldt	6.91	64.5	0	14.9	19.6	0.83	0
	CLAH	Central Lahontan	23.7	62.1	9.52	4.90	6.16	17.3	0
	CNDB	Central Nevada Desert Basins	4.50	80.9	0	6.29	12.5	0	0
Pacific Northwest	ORCB	Oregon Closed Basins	6.35	72.5	0	8.29	19.2	0	0
California	NLAH	North Lahontan	17.9	63.8	3.18	8.93	17.1	6.98	0
	NMML	Northern Mojave-Mono Lake	12.1	70.9	5.01	19.4	4.68	0	0
	SMSS	Southern Mojave-Salton Sea	128	4.40	0	4.41	0.81	24.2	65.8
All hydrologic sub-regions			85.8	20.9	3.56	15.8	10.86	40.3	8.61

Table 2.3. Summary of total phosphorus yields for hydrologic subregions within the Southwest region of the United States.

[Perennial streams: Contribution from perennial stream channels. Geologic phosphorus: Contribution from geologic material represented by the incremental catchment area scaled by an estimate of the natural phosphorus content of local soil and rock. Developed land: Area of developed land in 2011. Commercial fertilizer: Commercial fertilizer applied to cultivated crops and pasture in 2012. Livestock manure: Manure from livestock applied to cultivated crops and pasture in 2012. Wastewater discharge: Discharge to surface water from municipal wastewater treatment facilities in 2012. Inflows: Mean annual streamflow imported from an adjoining river basin, entering from Mexico, or returned in irrigation water. Abbreviation: (kg/km2)/yr, kilogram per square kilometer per year]

Water resources region	Hydrologic subregion	Subregion name	Total phosphurus yield ([kg/km2]/yr)	Contribution from individual sources (percent)						
				Perennial streams	Geologic phosphorus	Developed land	Commercial fertilizer	Livestock manure	Wastewater discharge	Inflows
All hydrologic sub-regions			13.3	10.95	14.8	11.8	16.8	17.0	18.7	10.0
Texas Gulf	SABI	Sabine	99.8	6.47	12.7	15.1	15.5	47.5	2.76	0
	NECH	Neches	66.4	9.48	14.4	18.2	14.9	37.9	5.11	0
	TRINI	Trinity	98.6	3.66	10.9	15.1	22.0	23.4	24.9	0
	GASJ	Galveston Bay-San Jacinto	216	2.42	5.62	41.0	10.44	10.43	30.1	0
	BRZH	Brazos headwaters	6.44	2.89	17.0	1.22	48.9	15.0	15.0	0
	MBRZ	Middle Brazos	17.5	6.90	15.4	4.98	35.1	23.9	13.7	0
	LBRZ	Lower Brazos	58.3	4.48	10.11	7.68	38.7	30.6	8.4	0
	UCOL	Upper Colorado	1.93	4.03	36.9	3.38	27.2	6.58	21.9	0
	LCSB	Lower Colorado-San Bernard Coastal	19.3	7.85	11.9	5.23	38.6	19.3	17.1	0
	CTXC	Central Texas Coastal	45.2	6.06	6.97	5.31	36.2	22.6	22.9	0
	NSTC	Nueces-Southwestern Texas Coastal	9.7	9.24	13.2	7.01	36.7	8.31	25.6	0
Rio Grande	RIOH	Rio Grande headwaters	6.61	70.4	24.0	0.11	3.59	0.20	0.68	1.07
	RIOE	Rio Grande-Elephant Butte	4.36	29.2	26.52	0.97	0.51	1.19	24.4	17.2
	RIOM	Rio Grande-Mimbres	2.45	7.61	16.4	1.29	6.89	2.51	64.9	0
	RIOA	Rio Grande-Amistad	4.88	4.09	2.93	0.21	0.22	0.30	6.26	86.0
	RIOC	Rio Grande closed basins	1.60	2.41	81.2	1.09	8.15	5.14	1.98	0
	UPEC	Upper Pecos	2.38	27.0	48.0	1.56	4.56	11.7	7.10	0
	LPEC	Lower Pecos	0.68	30.1	61.60	1.16	3.35	3.58	0.24	0
	RIOF	Rio Grande-Falcon	8.17	2.34	2.70	0.79	0.08	0.47	4.23	89.4
	LRIO	Lower Rio Grande	7.91	2.69	2.7	0.30	1.77	0.52	0.67	91.4
Upper Colorado River	COLH	Colorado headwaters	13.3	54.0	37.63	1.34	1.75	1.29	3.96	0
	GUNN	Gunnison	11.3	61.0	33.6	0.47	2.70	1.41	0.87	0
	UCOD	Upper Colorado-Dolores	5.70	51.9	42.7	0.34	2.24	0.84	2.00	0
	GDUG	Great Divide - Upper Green	6.54	52.4	40.49	0.40	0.61	1.22	4.90	0
	WHYA	White-Yampa	8.16	42.2	51.85	0.50	1.58	3.49	0.34	0
	LGRN	Lower Green	5.18	64.0	24.6	0.87	1.66	2.48	6.34	0
	UCDD	Upper Colorado-Dirty Devil	3.00	61.8	36.74	0.35	0.44	0.66	0	0
	SJUA	San Juan	5.00	34.1	50.6	0.61	4.07	1.75	4.85	4.06

Table 2.3. Summary of total phosphorus yields for hydrologic subregions within the Southwest region of the United States.—Continued

Water resources region	Hydrologic subregion	Subregion name	Total phosphurus yield ([kg/km2]/yr)	Contribution from individual sources (percent)						
				Perennial streams	Geologic phosphorus	Developed land	Commercial fertilizer	Livestock manure	Wastewater discharge	Inflows
Lower Colorado River	LCLM	Lower Colorado-Lake Mead	2.40	31.1	30.49	1.71	0.67	1.24	34.8	0
	LICO	Little Colorado	1.74	25.7	48.50	0.68	0.08	0.84	24.2	0
	LCOL	Lower Colorado	15.2	3.21	3.17	0.14	1.03	0.18	0.76	91.5
	UGIL	Upper Gila	2.08	55.5	38.50	0.48	1.93	3.46	0.11	0
	MGIL	Middle Gila	5.69	3.66	9.27	1.79	6.55	1.81	63.7	13.2
	SALT	Salt	21.5	8.31	8.90	0.94	0.22	0.14	81.5	0
	LGIL	Lower Gila	3.20	4.49	10.6	3.80	7.8	0.94	40.0	32.3
	SONO	Sonora	1.61	1.34	23.9	0.11	3.69	0.54	0	70.4
Great Basin	BEAR	Bear	23.3	25.2	36.4	1.41	10.3	6.33	20.3	0
	GSLT	Great Salt Lake	9.81	10.73	18.67	3.96	2.95	1.76	61.9	0
	EDSL	Escalante Desert-Sevier Lake	3.47	44.9	44.3	1.45	3.94	4.72	0.66	0
	BRDH	Black Rock Desert-Humboldt	5.08	40.2	53.8	0.46	2.82	2.68	0.03	0
	CLAH	Central Lahontan	4.73	55.0	31.68	3.33	0.79	0.98	8.23	0
	CNDB	Central Nevada Desert Basins	1.47	27.7	68.33	0.44	0.72	2.81	0	0
Pacific Northwest	ORCB	Oregon Closed Basins	3.30	63.2	33.90	0.18	0.55	2.20	0	0
California	NLAH	North Lahontan	4.43	42.2	48.98	1.24	1.06	2.19	4.30	0
	NMML	Northern Mojave-Mono Lake	1.80	38.1	51.9	4.43	5.18	0.37	0	0
	SMSS	Southern Mojave-Salton Sea	18.6	1.43	3.93	0.28	2.05	0.35	10.8	81.2

Table 2.4. Summary of suspended sediment yields for hydrologic subregions within the Southwest region of the United States.

[**Alluvial sediments**: The area of alluvial sediments inclusive of all land cover groups. **Agricultural land, Developed land, Forest land, and Bushland**: The area of each individual land cover group for all types of surface geology except alluvial sediments. **Abbreviation**: $(t/km^2)/yr$, ton per square kilometer per year]

Water resources region	Hydrologic subregion	Subregion name	Suspended sediment yield ([t/km2)/yr)]	Contribution from individual sources (percent)					
				Perennial streams	Alluvial sediments	Agricultural land	Developed land	Forest land	Brushland
Texas Gulf	SABI	Sabine	758	2.40	2.36	8.95	8.08	76.3	1.89
	NECH	Neches	1,057	1.67	1.61	5.37	7.76	81.9	1.71
	TRINI	Trinity	571	1.78	1.23	15.8	13.1	64.6	3.50
	GASJ	Galveston Bay-San Jacinto	343	4.29	5.40	13.5	43.2	32.7	0.91
	BRZH	Brazos headwaters	62.8	0.83	6.60	55.0	15.8	3.49	18.3
	MBRZ	Middle Brazos	79.7	4.27	8.79	19.3	16.9	37.9	12.86
	LBRZ	Lower Brazos	195	3.78	2.76	27.5	15.3	46.5	4.10
	UCOL	Upper Colorado	22.5	0.98	2.37	34.3	24.4	2.51	35.4
	LCSB	Lower Colorado-San Bernard Coastal	67.4	6.33	4.88	22.4	13.6	46.0	6.77
	CTXC	Central Texas Coastal	127	6.08	5.37	39.4	15.7	29.2	4.27
	NSTC	Nueces-Southwestern Texas Coastal	34.8	7.24	7.07	34.8	26.5	8.04	16.35
Rio Grande	RIOH	Rio Grande headwaters	18.7	70.0	4.58	0.19	0.12	23.2	1.87
	RIOE	Rio Grande-Elephant Butte	79.4	4.52	5.58	0.26	1.18	77.3	11.14
	RIOM	Rio Grande-Mimbres	12.8	4.10	62.7	0.85	2.09	14.1	16.1
	RIOA	Rio Grande-Amistad	1.55	36.2	22.5	0.11	5.07	1.41	34.7
	RIOC	Rio Grande closed basins	155	0.07	21.4	1.06	3.32	15.3	58.9
	UPEC	Upper Pecos	74.9	2.42	18.8	0.54	2.64	32.5	43.1
	LPEC	Lower Pecos	12.4	4.68	34.5	0.26	3.68	1.68	55.2
	RIOF	Rio Grande-Falcon	3.28	16.4	11.9	6.66	30.3	1.83	32.9
	LRIO	Lower Rio Grande	3.23	18.5	5.01	37.8	17.7	7.38	13.7
Upper Colorado River	COLH	Colorado headwaters	91.1	22.3	2.44	8.06	5.95	55.0	6.22
	GUNN	Gunnison	106	18.2	1.82	5.58	2.26	67.3	4.75
	UCOD	Upper Colorado-Dolores	215	3.88	2.74	1.54	3.01	66.5	22.4
	GDUG	Great Divide - Upper Green	55.2	17.4	8.15	1.21	5.24	14.3	53.6
	WHYA	White-Yampa	60.2	16.1	2.04	1.98	1.55	60.5	17.9
	LGRN	Lower Green	86.9	10.7	11.5	11.4	8.5	20.4	37.4
	UCDD	Upper Colorado-Dirty Devil	162	3.22	1.78	0.35	1.26	51.6	41.8
	SJUA	San Juan	242	1.98	1.01	3.29	3.65	50.2	39.8
Lower Colorado River	LCLM	Lower Colorado-Lake Mead	27.9	7.50	16.2	0.27	1.83	58.6	15.5
	LICO	Little Colorado	368	0.34	0.45	0.01	0.86	90.4	7.97
	LCOL	Lower Colorado	14.6	9.4	43.6	1.77	3.40	31.9	9.89
	UGIL	Upper Gila	37.9	8.56	16.5	0.06	0.65	67.6	6.65
	MGIL	Middle Gila	19.6	2.99	61.3	0.56	1.84	23.3	9.99
	SALT	Salt	52.4	9.6	3.71	0.02	1.25	81.1	4.31
	LGIL	Lower Gila	8.85	4.56	66.5	4.03	8.08	9.58	7.25
	SONO	Sonora	7.80	0.78	69.5	0.03	0.26	17.2	12.25
Great Basin	BEAR	Bear	187	8.87	4.78	33.9	9.5	31.7	11.19
	GSLT	Great Salt Lake	102.6	2.89	3.14	12.42	9.1	27.1	45.4
	EDSL	Escalante Desert-Sevier Lake	65.0	6.75	19.2	7.45	4.42	28.2	33.9
	BRDH	Black Rock Desert-Humboldt	207	2.78	44.6	4.86	4.12	6.80	36.9
	CLAH	Central Lahontan	26.8	27.3	5.43	11.3	9.2	11.3	35.4
	CNDB	Central Nevada Desert Basins	75.4	1.52	22.2	2.00	0.63	49.1	24.6
Pacific Northwest	ORCB	Oregon Closed Basins	56.0	10.5	2.84	14.4	3.92	44.9	23.5
California	NLAH	North Lahontan	28.0	18.8	2.04	9.9	7.66	29.7	31.9
	NMML	Northern Mojave-Mono Lake	8.68	22.3	30.1	0.24	4.63	16.6	26.1
	SMSS	Southern Mojave-Salton Sea	10.9	6.88	75.1	0.04	2.22	4.39	11.38
All hydrologic sub-regions			107	3.81	8.39	9.24	7.80	53.1	17.7

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