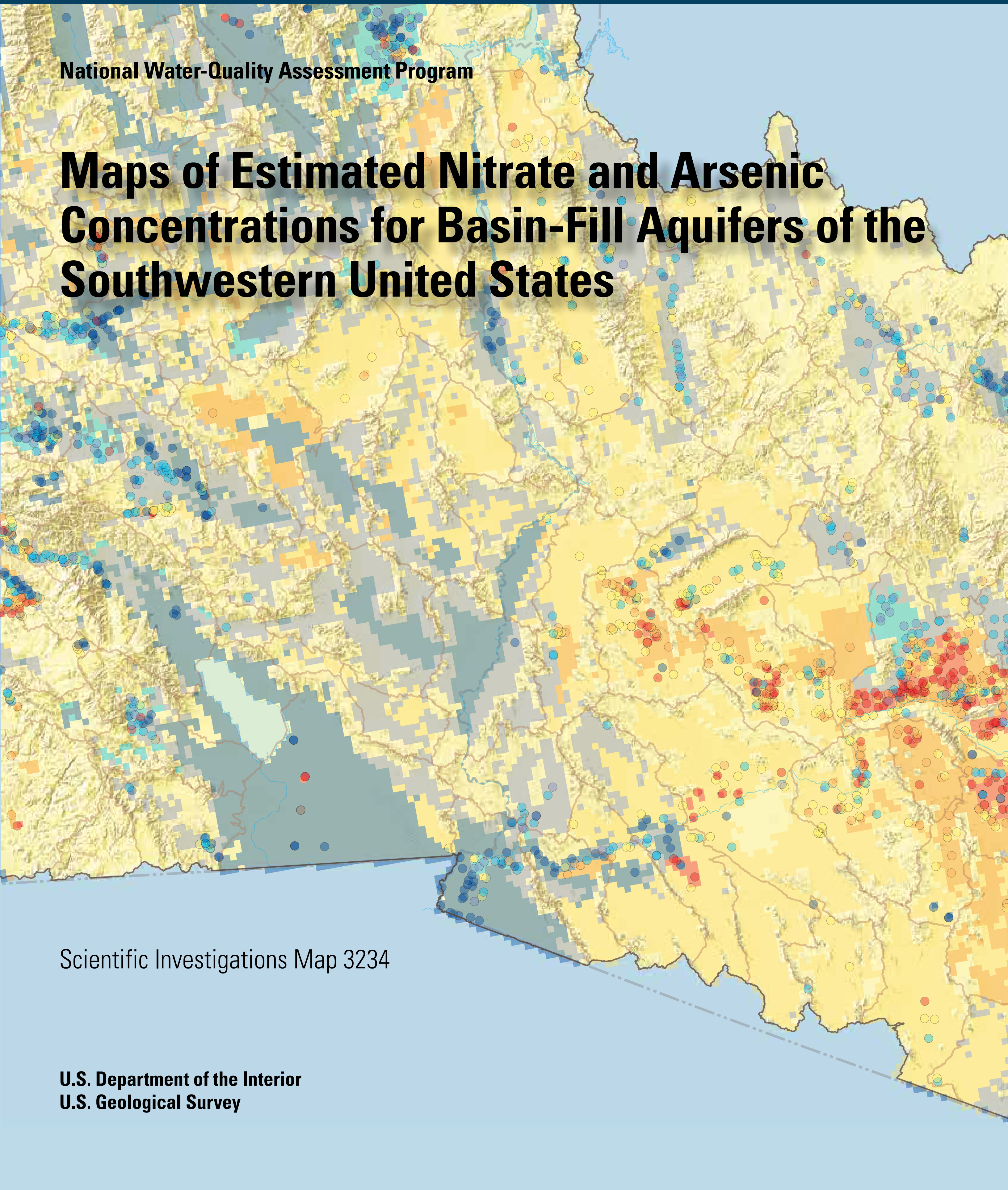

National Water-Quality Assessment Program

Maps of Estimated Nitrate and Arsenic Concentrations for Basin-Fill Aquifers of the Southwestern United States

Scientific Investigations Map 3234

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

Cover art: Observed and predicted nitrate concentrations in basin-fill aquifers of the Southwest Principal Aquifers study area.

Maps of Estimated Nitrate and Arsenic Concentrations for Basin-Fill Aquifers of the Southwestern United States

By Kimberly R. Beisner, David W. Anning, Angela P. Paul, Tim S. McKinney, Jena M. Huntington, Laura M. Bexfield, and Susan A. Thiros

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Abstract

Human-health concerns and economic considerations associated with meeting drinking-water standards motivated a study of the vulnerability of basin-fill aquifers to nitrate contamination and arsenic enrichment in the southwestern United States. Statistical models were developed by using the random forest classifier algorithm to predict concentrations of nitrate and arsenic across a model grid representing about 190,600 square miles of basin-fill aquifers in parts of Arizona, California, Colorado, Nevada, New Mexico, and Utah. The statistical models, referred to as classifiers, reflect natural and human-related factors that affect aquifer vulnerability to contamination and relate nitrate and arsenic concentrations to explanatory variables representing local- and basin-scale measures of source and aquifer susceptibility conditions. Geochemical variables were not used in concentration predictions because they were not available for the entire study area. The models were calibrated to assess model accuracy on the basis of measured values.

Only 2 percent of the area underlain by basin-fill aquifers in the study area was predicted to equal or exceed the U.S. Environmental Protection Agency drinking-water standard for nitrate as N (10 milligrams per liter), whereas 43 percent of the area was predicted to equal or exceed the standard for arsenic (10 micrograms per liter). Areas predicted to equal or exceed the drinking-water standard for nitrate include basins in central Arizona near Phoenix; the San Joaquin Valley, the Santa Ana Inland, and San Jacinto Basins of California; and the San Luis Valley of Colorado. Much of the area predicted to equal or exceed the drinking-water standard for arsenic is within a belt of basins along the western portion of the Basin and Range Physiographic Province that includes almost all of Nevada and parts of California and Arizona. Predicted nitrate and arsenic concentrations are substantially lower than the drinking-water standards in much of the study area—about 93 percent of the area underlain by basin-fill aquifers was less than one-half the standard for nitrate as N (5.0 milligrams per liter), and 50 percent was less than one-half the standard for arsenic (5.0 micrograms per liter). The predicted concentrations and the improved understanding of the susceptibility and vulnerability of southwestern basin-fill aquifers to nitrate contamination and arsenic enrichment can be used by water managers as a qualitative tool to assess and protect the quality of groundwater resources in the Southwest.

Introduction

The National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) is performing a regional analysis of water quality in the principal aquifer systems across the United States (Lapham and others, 2005). The Southwest Principal Aquifers (SWPA) study is developing a better understanding of the susceptibility and vulnerability of basin-fill aquifers in the Southwest to groundwater contamination by synthesizing baseline knowledge of groundwater-quality conditions in 16 basins previously studied by the NAWQA Program (fig. 1).

About 46.6 million people live in the SWPA study area (Oak Ridge National Laboratory, 2005), mostly in urban areas, but also in rural agricultural communities that cultivate about 14.4 million acres of cropland (U.S. Geological Survey, 2003). Other rural areas contain small communities with mining, retirement, or tourism/recreational-based economies. Because of the generally limited availability of surface-water supplies in the arid to semiarid climate, cultural and economic activities in the region are dependent on high-quality groundwater supplies. In the year 2000, about 33.7 million acre-feet (acre-ft) of surface water was diverted from streams, and about 23.0 million acre-ft of groundwater was withdrawn from basin-fill aquifers in the SWPA study area (U.S. Geological Survey, 2004). Irrigation and public-supply groundwater withdrawals from basin-fill aquifers in the study area were about 18.0 million acre-ft and 4.1 million acre-ft, respectively, and together account for about one quarter of the total withdrawals from all aquifers in the United States (Maupin and Barber, 2005).

Basin-fill aquifers underlie about half (190,600 square miles (mi^2)) of the 409,000 mi^2 SWPA study area (fig. 1) and are the primary groundwater supply for most cities and agricultural communities. In several areas, these aquifers provide base flow to streams that support important aquatic and riparian habitats. Basin-fill aquifers primarily consist of sand and gravel deposits that partly fill faulted basins and are bounded by consolidated rock mountains.

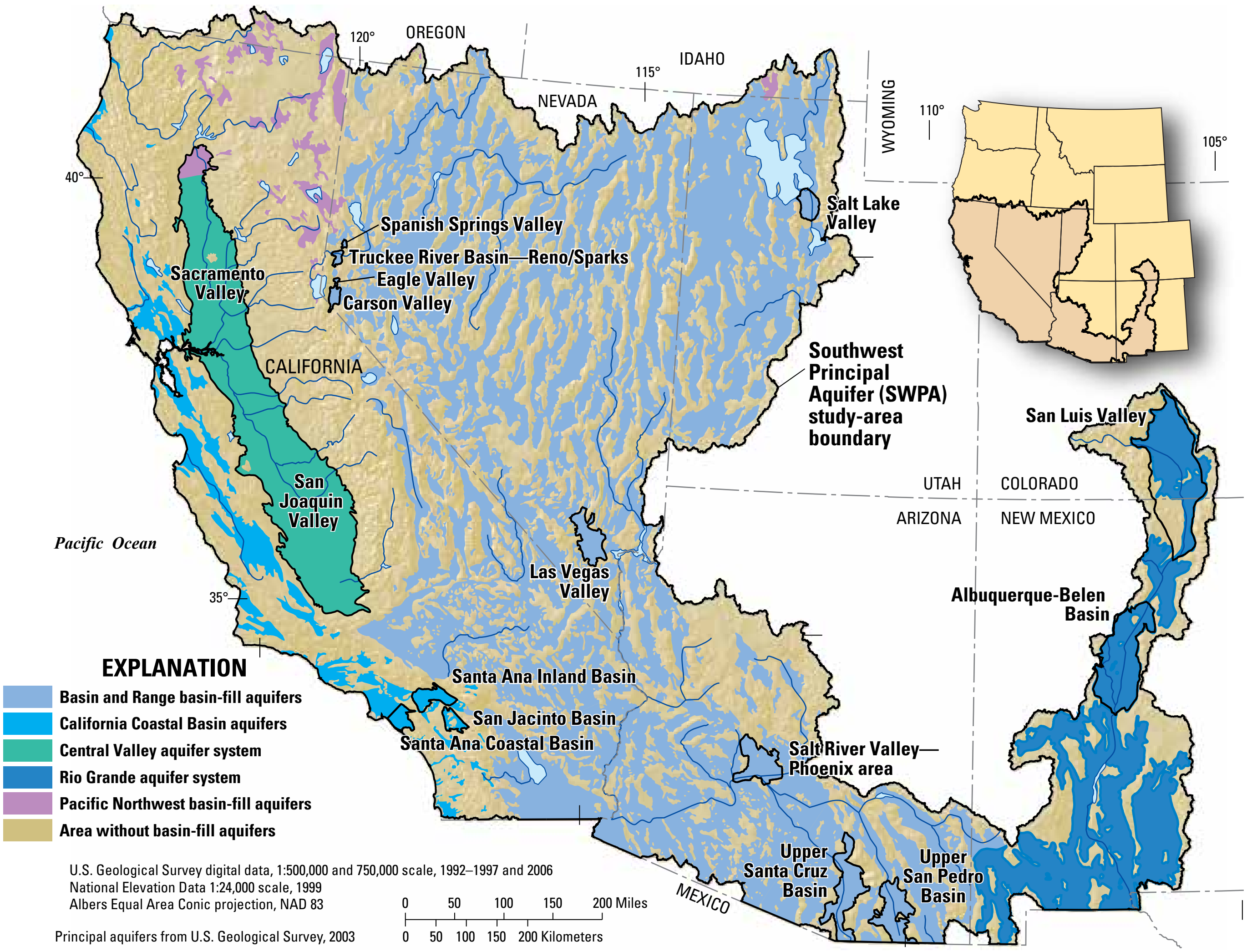

Figure 1. The principal aquifers and locations of basins previously studied by the National Water-Quality Assessment Program in the Southwest Principal Aquifers study area.

Similarities in the hydrogeology, land- and water-use practices, and water-quality issues allow for regional analysis of the vulnerability of basin-fill aquifers to contamination in the SWPA study area. Published studies have summarized current knowledge about the water quality of groundwater systems of basin-fill aquifers in the 16 basins previously studied by NAWQA (Thiros and others, 2010) and developed conceptual models of the primary natural and human-related factors commonly affecting groundwater quality in basin-fill aquifers on a regional scale (Bexfield and others, 2011).

Nitrate and arsenic concentrations are known to be elevated in many areas of the west; however, the contributing factors are distinct for each constituent. The motivation for study of nitrate and arsenic concentrations in basin-fill aquifers in the SWPA study area arose from concerns about human-health issues and economic costs associated with the protection and treatment of drinking water with respect to these constituents, as well as the potential for contaminant concentrations to increase over time and degrade the quality of groundwater in the aquifers as development progresses.

The U.S. Environmental Protection Agency (USEPA) regulates nitrate in drinking water because of the potential for elevated nitrate to restrict oxygen transport in the blood of infants in a condition known as acquired methemoglobinemia or blue-baby syndrome (U.S. Environmental Protection Agency, 2012). Recent concern also has arisen over transformation of nitrate within the human body into *N*-nitroso compounds, which are known carcinogens (Ward and others, 2005). The current nitrate as N standard of 10 milligrams per liter (mg/L) is the maximum allowable concentration of nitrate in drinking water delivered to the consumer by a public-supply system.

Arsenic has been recognized as a toxic element for centuries and is a human-health concern because elevated concentrations can contribute to a wide variety of adverse health effects, including skin damage and circulatory problems. In addition, arsenic in drinking water can lead to several types of cancers, including bladder, lung, skin, and possibly kidney and liver (National Research Council, 2001). On the basis of a review of available scientific research on health effects of arsenic, long-term consumption of drinking water in excess of 5 micrograms per liter (µg/L) has been linked with an increased human-health risk (National Research Council, 2001). In light of the risk level, the USEPA lowered the drinking-water standard for arsenic from 50 µg/L to 10 µg/L, effective in 2006, as a compromise between the risk to individuals and the expense to water suppliers (U.S. Environmental Protection Agency, 2012).

This report summarizes statistical models developed by Anning and others (2012) that relate concentrations of nitrate and arsenic in basin-fill aquifers of the SWPA study area to selected natural and human-related factors representing contaminant sources and aquifer susceptibility conditions. Statistical models allow the understanding of nitrate and arsenic concentrations to be expanded from discrete observations to broader spatial predictions. Specifically, this report presents the spatial and statistical distribution of nitrate (plate 1) and arsenic (plate 2) concentrations in basin-fill aquifers across the SWPA study area as determined by using predictions from statistical models.

Approach and Methods

Statistical models used in this investigation were constructed by using the random forest classifier algorithm (Breiman, 2001) and are hereafter called 'classifiers.' In short, the classifiers "learn" the relations between known nitrate and arsenic concentrations and known environmental conditions associated with the aquifer. These relations take the form of complex decision trees and are used with known spatially-distributed environmental-condition data to predict concentrations in areas where observed concentration data are unavailable.

The concentration data used for training the classifiers were from 6,234 well samples stored in the USGS National Water Information System (NWIS; U.S. Geological Survey, 2010). These data were partitioned into six concentration groups for nitrate and seven concentration groups for arsenic. The break points between concentration classes were 0.50, 1.0, 2.0, 5.0, and 10 mg/L for nitrate and 1.0, 2.0, 3.0, 5.0, 10, and 25 µg/L for arsenic. The environmental conditions represented in the classifiers were from several existing geospatial datasets and included factors such as nitrogen loading rates, geologic characteristics, soil conditions, land use, water use, and other hydrologic conditions. Anning and others (2012) developed exploratory models with geochemical conditions that were found not to greatly improve the accuracy of the predictions. The environmental factors considered in the statistical model are related to geochemical conditions and likely account for much of the variability without the need for direct use of geochemical data. Additionally, geochemical data were not available for the entire study area.

Classifier and Predicted Concentration Results

The random forest classifiers provided a context to evaluate the spatial distribution of nitrate and arsenic within the upper 200 ft of basin-fill aquifers in the study area and to assess the vulnerability of aquifers throughout the SWPA study area to nitrate contamination and arsenic enrichment. Predicted nitrate and arsenic concentrations are discussed in this report for the upper 200 ft of the aquifer primarily because regression analysis on observed data showed that, at the regional scale, systematic concentration variations with depth were not found in the aquifers.

The classifiers were successfully trained to relations between observed nitrate and arsenic concentrations and important factors affecting them. This enabled the extrapolation of predicted nitrate and arsenic concentrations from areas where concentrations were measured into areas where data were unavailable. The nitrate and arsenic classifiers were found to be generally consistent with, and provided additional information and detail for, the conceptual models for natural and human-related factors affecting these constituents as described in Bexfield and others (2011).

Classifier Goodness-of-Fit and Prediction Uncertainty

The classifiers for nitrate and for arsenic performed well for assessing the vulnerability of basin-fill aquifers in the SWPA study area to contamination by these constituents. The classifiers generally produced unbiased predictions, and misclassification errors for each classifier were generally low, given the spatial variability within individual model grid cells. For each explanatory variable, the range of values in the study area was well represented by nitrate and arsenic observations, and there were no environmental conditions poorly represented by the dataset used to train the classifiers. In addition, analysis of the misclassification errors indicated that there were no environmental conditions where the classifier tended to overpredict or underpredict concentrations. Analysis of the misclassifications indicated that the models were unbiased spatially and unbiased across the distribution of values for the explanatory variables.

The ability of the model to predict concentrations across the study area within plus or minus one concentration class was 72 percent for nitrate and 70 percent for arsenic. Misclassification errors were generally symmetric about the correct (true) class; 29 percent of nitrate and 34 percent of arsenic observations were misclassified into lower concentration classes than the true class, and 29 percent of nitrate and 31 percent of arsenic observations were misclassified into higher concentration classes (fig. 2).

Nitrate

While the training observations indicate nitrate concentrations were equal to or exceeded 10 mg/L in 11 percent of the groundwater samples, use of the prediction classifier to extrapolate concentrations across the SWPA study area (plate 1) revealed that only about 2 percent of the study area underlain by basin-fill aquifers is likely to exceed this concentration, and 93 percent of the area could have groundwater with less than 5.0 mg/L of nitrate as N (fig. 3). These differences in the distribution of observed and predicted nitrate concentrations are expected and result from the fact that the prediction dataset represents the full extent of basin-fill aquifers in the SWPA study area, whereas the training dataset represents a subset of those aquifers where observations were available. Generally, samples of groundwater were collected from areas where groundwater resources have been developed. The measured and predicted concentration datasets have somewhat different but overlapping distributions of source and aquifer-susceptibility variables that affect nitrate in groundwater.

Relative background concentrations of nitrate in groundwater in undeveloped land-use settings were determined to be less than 2.0 mg/L for most biotic communities overlaying basin-fill aquifers, except for the Semidesert Grassland, Mojave Desertscrub, Sonoran Desertscrub-Arizona Uplands, and Sonoran Desertscrub-Lower Colorado River Valley communities generally located in southern Arizona. In these four biotic communities, concentrations were estimated to be less than 5.0 mg/L but greater than 2.0 mg/L. Nitrate concentrations greater than these relative background concentrations are largely found in areas with agricultural or urban land development.

Concentrations of nitrate in the basin-fill aquifers were predicted to exceed relative background concentrations in about 34 percent of areas having more than 5-percent agricultural or urban land. Exceedance of relative background concentrations increased with the amount of agricultural or urban development. Nitrate concentrations in basin-fill aquifers underlying land where greater than half the area has been developed for agricultural or urban uses are predicted to equal or exceed 10

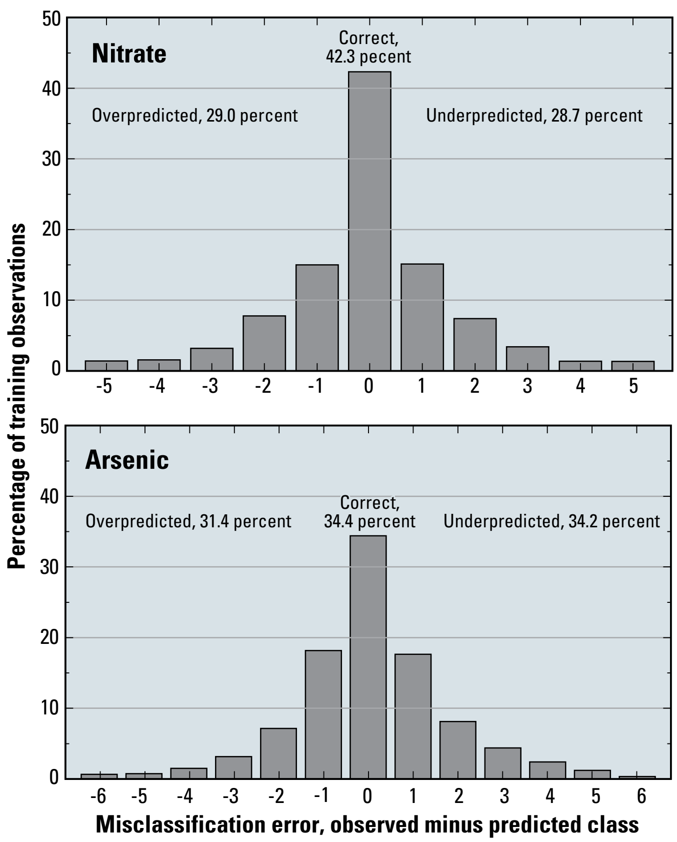

Figure 2. Statistical distribution of misclassification errors for the random forest prediction classifiers of basin-fill aquifers of the Southwest Principal Aquifers study area for nitrate and arsenic concentrations.

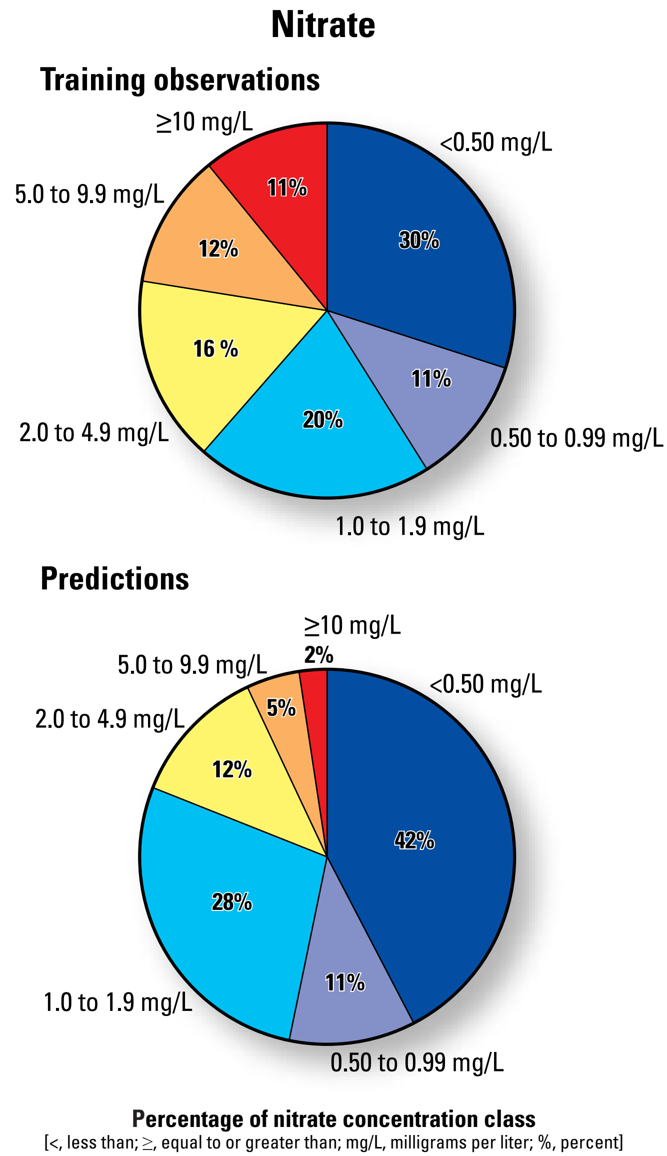

Figure 3. Percentage of nitrate concentration class for training observations and predictions.

mg/L in 15 percent of that area, which increases to 48 percent for areas entirely used for agricultural or urban related activities. Predicted concentrations generally decreased along groundwater-flow paths from the basin margin to the basin lowlands. Nearly all wetland areas in the basin lowlands have concentrations less than 0.50 mg/L, regardless of the amount of land development. These low concentrations could result from denitrification, a microbially facilitated process where nitrate is converted to nitrogen gas, although other explanations are possible (Anning and others, 2012).

A further understanding of conditions that render the basin-fill aquifers in the SWPA study area vulnerable to nitrate contamination was gained from an analysis of the correlations between the predicted concentrations and the explanatory variables (table 1), as well as correlations between observed nitrate and other constituent concentrations in the training dataset, which are described in detail in Anning and others (2012). These univariate correlations indicated that areas are more likely to have higher concentrations and, therefore, are generally more vulnerable to nitrate contamination, where one or more of the following conditions is found:

- Land is used for agricultural or urban purposes, especially where fertilizers are used or where there are livestock.

Table 1. Relation between predicted nitrate and arsenic concentrations and explanatory variables representing conditions for basin-fill aquifers in the Southwest Principal Aquifers study area.

[Positive values of Kendall’s tau indicate that higher concentrations are associated with greater values of the explanatory variable and lower concentrations are associated with lesser values of the explanatory variable. Negative values of Kendall’s tau indicate that the opposite relation exists between concentration and the explanatory variable. Small p-values (<0.001) indicate the Kendall’s tau correlation between the nitrate or arsenic concentration and a given explanatory variable is statistically significant. **Abbreviations:** —, constituent not tested in classifier; <, less than]

Variable group	Explanatory variable	Represented area	Kendall’s tau test on predicted nitrate concentration		Kendall’s tau test on predicted arsenic concentration	
			tau	p-value	tau	p-value
Source variables						
Nitrogen loading	Atmospheric deposition	Grid cell	–0.06	<0.001	—	—
	Farm fertilizer	Grid cell	0.06	<0.001	—	—
	Non-farm fertilizer	Grid cell	0.05	<0.001	—	—
	Confined manure	Grid cell	0.06	<0.001	—	—
	Unconfined manure	Grid cell	0.03	<0.001	—	—
	Total nitrogen	Grid cell	0.01	<0.001	—	—
Land use	Septic/sewer ratio	Grid cell	–0.02	<0.001	–0.07	<0.001
	Local population	Grid cell	0.09	<0.001	–0.16	<0.001
	Local population density	Grid cell	0.09	<0.001	–0.16	<0.001
	Basin population	Basin average	0.08	<0.001	–0.18	<0.001
	Basin population density	Basin average	0.10	<0.001	–0.20	<0.001
	Local urban land	Grid cell	0.08	<0.001	–0.15	<0.001
	Local agricultural land	Grid cell	0.04	<0.001	–0.11	<0.001
	Basin urban land	Basin average	0.08	<0.001	–0.21	<0.001
	Basin agricultural land	Basin average	0.02	<0.001	–0.20	<0.001
	Basin rangeland	Basin average	0.00	0.551	0.29	<0.001
	Basin other land cover	Basin average	–0.11	<0.001	–0.26	<0.001
Geologic sources	Carbonate rocks	Contributing area	-0.15	<0.001	–0.07	<0.001
	Crystalline rocks	Contributing area	0.18	<0.001	0.04	<0.001
	Clastic sedimentary rocks	Contributing area	–0.10	<0.001	–0.16	<0.001
	Mafic volcanic rocks	Contributing area	0.08	<0.001	0.16	<0.001
	Felsic and silicic volcanic rocks	Contributing area	–0.11	<0.001	0.04	<0.001
	Intermediate composition volcanic rocks	Contributing area	0.05	<0.001	0.11	<0.001
	Undifferentiated volcanic rocks	Contributing area	0.00	0.855	–0.07	<0.001
	Distance to carbonate rocks	Grid cell	0.11	<0.001	0.07	<0.001
	Distance to crystalline rocks	Grid cell	–0.11	<0.001	–0.02	<0.001
	Distantce to clastic sedimentary rocks	Grid cell	0.03	<0.001	0.14	<0.001
	Distance to mafic volcanic rocks	Grid cell	–0.10	<0.001	–0.19	<0.001
	Distance to felsic and silicic volcanic rocks	Grid cell	0.07	<0.001	–0.06	<0.001
	Distance to intermediate composition volcanic rocks	Grid cell	–0.02	<0.001	–0.12	<0.001
	Distance to undifferentiated volcanic rocks	Grid cell	0.01	0.006	0.03	<0.001
	Soil and rock equivalent uranium-238	Grid cell	—	—	0.14	<0.001

Table 1. Relation between predicted nitrate and arsenic concentrations and explanatory variables representing conditions for basin-fill aquifers in the Southwest Principal Aquifers study area.—Continued

[Positive values of Kendall's tau indicate that higher concentrations are associated with greater values of the explanatory variable and lower concentrations are associated with lesser values of the explanatory variable. Negative values of Kendall's tau indicate that the opposite relation exists between concentration and the explanatory variable. Small p-values (<0.001) indicate the Kendall's tau correlation between the nitrate or arsenic concentration and a given explanatory variable is statistically significant. **Abbreviations:** —, constituent not tested in classifier; <, less than]

Variable group	Explanatory variable	Represented area	Kendall's tau test on predicted nitrate concentration		Kendall's tau test on predicted arsenic concentration	
			tau	p-value	tau	p-value
Aquifer susceptibility variables						
Flow path	Land-surface slope	Grid cell	0.05	<0.001	–0.12	<0.001
	Land-surface elevation	Grid cell	–0.17	<0.001	–0.10	<0.001
	Land-surface elevation percentile	Grid cell	0.15	<0.001	–0.16	<0.001
	Basin elevation	Basin average	–0.20	<0.001	–0.07	<0.001
	Distance to basin margin	Grid cell	–0.02	<0.001	0.08	<0.001
Soil properties	Seasonally high water depth	Grid cell	0.25	<0.001	–0.03	<0.001
	Hydric	Grid cell	–0.22	<0.001	0.04	<0.001
	Hydrologic group A[1]	Grid cell	–0.13	<0.001	0.14	<0.001
	Hydrologic group B[2]	Grid cell	0.20	<0.001	–0.04	<0.001
	Hydrologic group C[3]	Grid cell	–0.01	<0.001	–0.11	<0.001
	Hydrologic group D[4]	Grid cell	–0.20	<0.001	0.00	0.806
	Permeability	Grid cell	–0.07	<0.001	0.16	<0.001
	Organic material	Grid cell	0.00	0.695	–0.15	<0.001
	Clay	Grid cell	–0.02	<0.001	–0.07	<0.001
	Silt	Grid cell	–0.13	<0.001	–0.09	<0.001
	Sand	Grid cell	0.12	<0.001	0.09	<0.001
Water use and hydroclimatic	Water-resources development index	Basin average	0.04	<0.001	–0.20	<0.001
	Groundwater use, irrigated agriculture	Grid cell	0.05	<0.001	–0.11	<0.001
	Surface-water use, irrigated agriculture	Grid cell	0.04	<0.001	–0.11	<0.001
	Groundwater use, public water supply	Grid cell	0.03	<0.001	–0.06	<0.001
	Surface-water use, public water supply	Grid cell	0.03	<0.001	–0.05	<0.001
	Recharge, contributing area	Contributing area	0.00	0.938	–0.37	<0.001
	Recharge, basin	Basin average	0.02	<0.001	–0.37	<0.001
	Potential evapotranspiration	Grid cell	0.23	<0.001	0.13	<0.001
	Mean air temperature	Grid cell	0.23	<0.001	0.13	<0.001

[1] Hydrologic Group A—Sand, loamy sand, or sandy loam types of soils. Low runoff potential and high infiltration rates even when thoroughly wetted. Consists chiefly of deep, well to excessively drained sands or gravels and has a high rate of water transmission.

[2] Hydrologic Group B—Silt loam or loam types of soils. Moderate infiltration rate when thoroughly wetted and consists chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

[3] Hydrologic Group C—Sandy clay loam type of soil. Low infiltration rates when thoroughly wetted and consists chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine structure.

[4] Hydrologic Group D—Clay loam, silty clay loam, sandy clay, silty clay, or clay types of soils. Highest runoff potential and very low infiltration rates when thoroughly wetted. Consists chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material.

- Nitrogen is fixed by natural vegetation, such as legumes in the Sonoran Desert.
- Soils are present that have textures favorable to water infiltration, lack hydric conditions, or lack organic material.
- High water-use from groundwater or surface-water supplies for agricultural purposes or public-water supply.
- Natural recharge is low in the drainage area contributing flow to the groundwater basin.
- Mean air temperatures and potential evapotranspiration are high.
- Bedrock surrounding the basin-fill aquifer has an abundance of crystalline, mafic volcanic, and intermediate composition volcanic rock, which likely produces geochemical conditions favorable to nitrate persistence.

Arsenic

While the training observations indicated arsenic concentrations equal or exceed 10 µg/L in 25 percent of the groundwater samples, use of the prediction classifier to extrapolate concentrations across the SWPA study area (plate 2) revealed 43 percent of the area underlain by basin-fill aquifers is likely to exceed this concentration, whereas 50 percent of the area could have concentrations less than 5.0 µg/L (fig. 4). Such differences in the distributions of observed and predicted arsenic concentrations are expected and result from the fact that the prediction dataset represents the full extent of basin-fill aquifers in the SWPA study area, whereas the training dataset represents a subset of those aquifers where observations were available, and each dataset has somewhat different but overlapping distributions of source and aquifer-susceptibility variables that affect arsenic in groundwater.

The largest area where arsenic concentrations in groundwater were predicted to be equal to or greater than the drinking-water standard of 10 µg/L was in the Basin and Range basin-fill aquifers (fig. 1, plate 2). Spatially, the Basin and Range basin-fill aquifers compose about 73 percent of the regional study area, and much of the area is undeveloped or used as open rangeland. Distribution patterns with depth obtained from the random forest classifiers support the conceptual-model findings indicating that arsenic concentrations can exceed 10 µg/L at various depths within aquifers throughout the SWPA study area (Bexfield and others, 2011).

Within a given basin, predicted concentrations generally increased along groundwater-flow paths from the upper basin margins to the basin lowlands, with greater concentrations associated with basin-fill sediments derived from surrounding mountains predominately composed of volcanic or crystalline bedrock. Basins surrounded by carbonate rocks generally contained groundwater with lower predicted concentrations of arsenic. Although areas developed for agricultural or urban use had lower observed and predicted arsenic concentrations compared to minimally developed areas, this is thought to be largely an artifact of the hydrogeologic nature of the developed areas. Generally, the more developed areas have higher rates of natural recharge because of the availability of water resources and possibly greater flushing rates of solutes out of the basin either to rivers or the ocean. In contrast, basins with lower rates of natural recharge, and likely correspondingly lower flushing rates of solutes, tend to be less developed and generally located in areas with relatively high potential evapotranspiration rates.

A further understanding of conditions that render the basin-fill aquifers in the SWPA study area vulnerable to arsenic enrichment was gained from an analysis of the correlations between the predicted concentrations and the explanatory variables (table 1), as well as correlations between observed arsenic and other constituent concentrations in the training dataset, which are described in detail in Anning and others (2012). These univariate correlations indicated that higher arsenic concentrations are more likely to be found in areas where the following conditions exist:

- Basins are surrounded by mafic volcanic bedrock, felsic/silicic volcanic bedrock, or crystalline bedrock.
- Long groundwater-flow paths.
- There is a general lack of groundwater flushing as indicated by low rates of natural recharge, high potential evapotranspiration rates, and minimal or altogether absent groundwater flow out of the basin.
- Geochemical conditions favor the release of arsenic from aquifer substrates to surrounding groundwater.

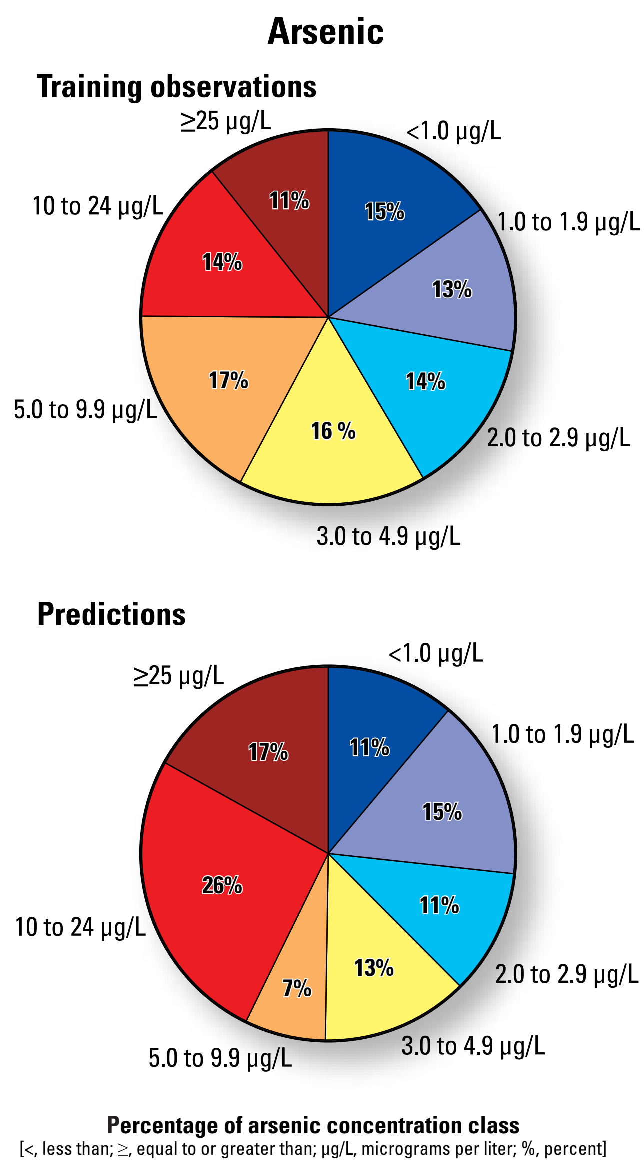

Figure 4. Percentage of arsenic concentration class for training observations and predictions.

Relevance and Implications

Areas predicted to exceed the nitrate drinking-water standard are generally developed, especially for irrigated agriculture, but are also located in more urbanized locations such as Phoenix, Arizona, and Modesto and suburbs east of Los Angeles, California. While population densities are generally much lower in agricultural areas than in urban areas, high nitrate concentrations underlying agricultural landscapes could be problematic with respect to public supply for large populations if those lands are eventually converted to urban uses. For the areas affected by high nitrate concentrations in agricultural land-use settings, fertilizer and livestock manure are significant sources and are typically mitigated with best management practices. Large tracks of land in the Sonoran Desert with nitrate concentrations between 2.0 and 5.0 mg/L, however, appear to be affected by natural nitrogen fixation by legumes and present a more challenging condition for nitrogen management.

Arsenic in groundwater is derived primarily from natural sources, namely the basin-fill sediments and the parent bedrock from which the sediments were derived. Whereas most of the area predicted to have arsenic concentrations equal to or greater than the current drinking-water standard of 10 µg/L is sparsely populated, major population centers are not necessarily unaffected. Areas within or adjacent to the metropolitan areas of Albuquerque, Bakersfield, Phoenix, Reno, Sacramento, Salt Lake City, and Stockton have measured and predicted arsenic concentrations above the drinking-water standard, which could affect future groundwater development as these cities grow.

As population centers in the west continue to grow, areas that are currently undeveloped are sought for alternative public-water supplies. Currently available groundwater data are generally focused on areas where wells already exist for groundwater development. The statistical model and associated reconnaissance scale maps of predictions (plates 1 and 2) for nitrate and arsenic concentrations are representative of the entire basin-fill groundwater resource available in the Southwest. The maps are based on statistical models that do not include geochemical data, and can help inform future management strategies as well as identify the need for additional locally relevant information in areas of interest.

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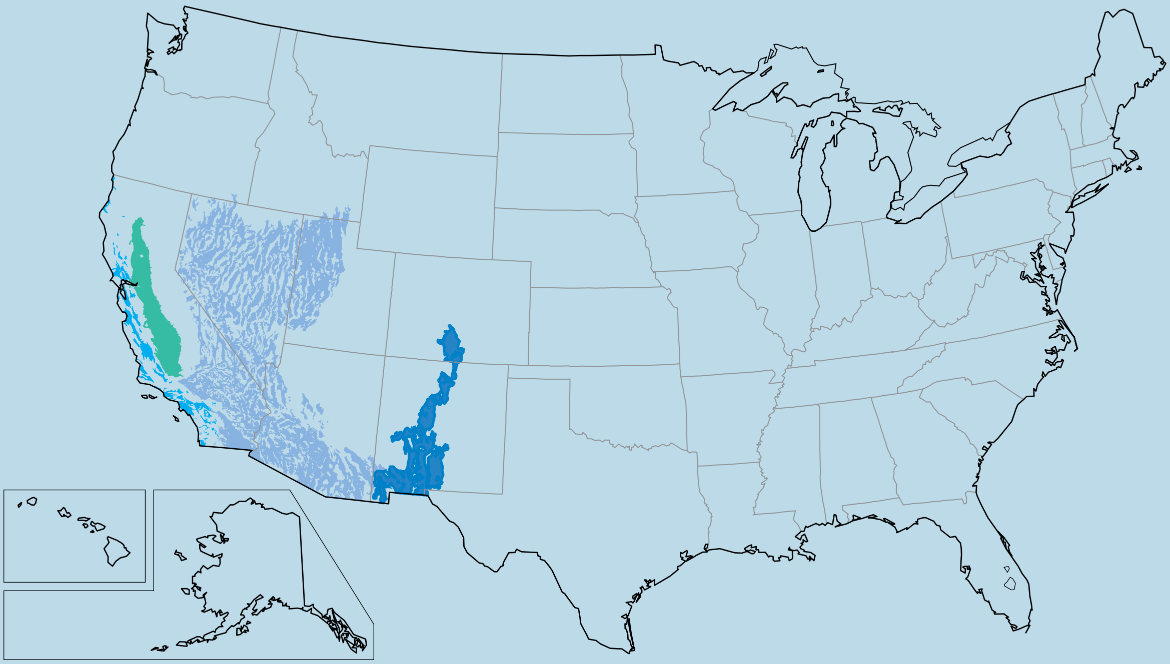

Southwest Principal Aquifers—Includes (from left to right) California Coastal Basin aquifers, Central Valley aquifer system, Basin and Range basin-fill aquifers, and Rio Grande aquifer system

Beisner and others—**Maps of Estimated Nitrate and Arsenic Concentrations for Basin-Fill Aquifers of the Southwestern United States**—Scientific Investigations Map 3234

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