Section 1.—Conceptual Understanding and Groundwater Quality of Selected Basin-Fill Aquifers in the Southwestern United States—Background and Study Approach

By Susan A. Thiros, Laura M. Bexfield, David W. Anning, Jena M. Huntington, and Tim S. McKinney

in

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Introduction

The National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) has been conducting a regional analysis of water quality in the principal aquifer systems in the southwestern United States (hereinafter, "Southwest") since 2005. The Southwest Principal Aquifers (SWPA) study within the NAWQA Program is building a better understanding of the factors that affect water quality in basin-fill aquifers in the region by synthesizing the baseline knowledge of groundwater-quality conditions in basin-fill aquifers previously studied by the Program. Resulting improvements in the understanding of the sources, movement, and fate of contaminants are assisting in the development of tools that water managers can use to help assess aquifer susceptibility and vulnerability to contamination. Regional assessments are being done across the country that focus on water-quality issues of concern at the principal-aquifer scale (Lapham and others, 2005).

The ease with which water enters and moves through an aquifer is described as its intrinsic susceptibility (Focazio and others, 2002). Aquifer susceptibility is dependent on the aquifer properties and other characteristics such as recharge rate, the presence or absence of an overlying confining unit, vertical hydraulic gradient, groundwater travel time, thickness and characteristics of the unsaturated zone, and pumping. The vulnerability of groundwater to contamination is the probability for contaminants to reach a specified part of an aquifer after being introduced, usually at the land surface. Vulnerability to contamination is dependent on the properties of the groundwater system (susceptibility), the existence of contaminant sources, and the contaminant's chemical characteristics.

Purpose and Scope

This report documents and provides a review of the conceptual models and water-quality conditions for basin-fill aquifers in 15 case-study basins in the SWPA study area. Specifically, each basin summary describes the following:

1. A conceptual model of the groundwater-flow system in the basin, how it has been modified by development, and groundwater quality conditions that are based on published reports of NAWQA studies and other investigations.

2. Effects of components of the groundwater-flow system and other natural and human-related factors on groundwater quality in the basin-fill aquifers, with a focus on factors that contribute to the susceptibility of the aquifer and the vulnerability of the groundwater to contamination.

The information presented and citations listed in this report serve as a resource for those interested in the groundwater-flow systems in the NAWQA case-study basins. The basin summaries also serve as a foundation for subsequent development of regional-scale conceptual models and statistical models of the primary factors affecting water quality of basin-fill aquifers in the Southwest.

Background on the Southwest Principal Aquifers Study

Basin-fill aquifers occur in about 200,000 mi^2 of the 410,000 mi^2 SWPA study area and are the primary source of groundwater supply for cities and agricultural communities. In several areas, these aquifers provide baseflow to streams that support important aquatic and riparian habitats. When aggregated across the study area, the basin-fill aquifers comprise four of the principal aquifers or aquifer systems of the United States: (1) the Basin and Range basin-fill aquifers in California, Nevada, Utah, and Arizona; (2) the Rio Grande aquifer system in New Mexico and Colorado; (3) the California Coastal Basin aquifers; and (4) the Central Valley aquifer system in California (fig. 1; U.S. Geological Survey, 2003a).

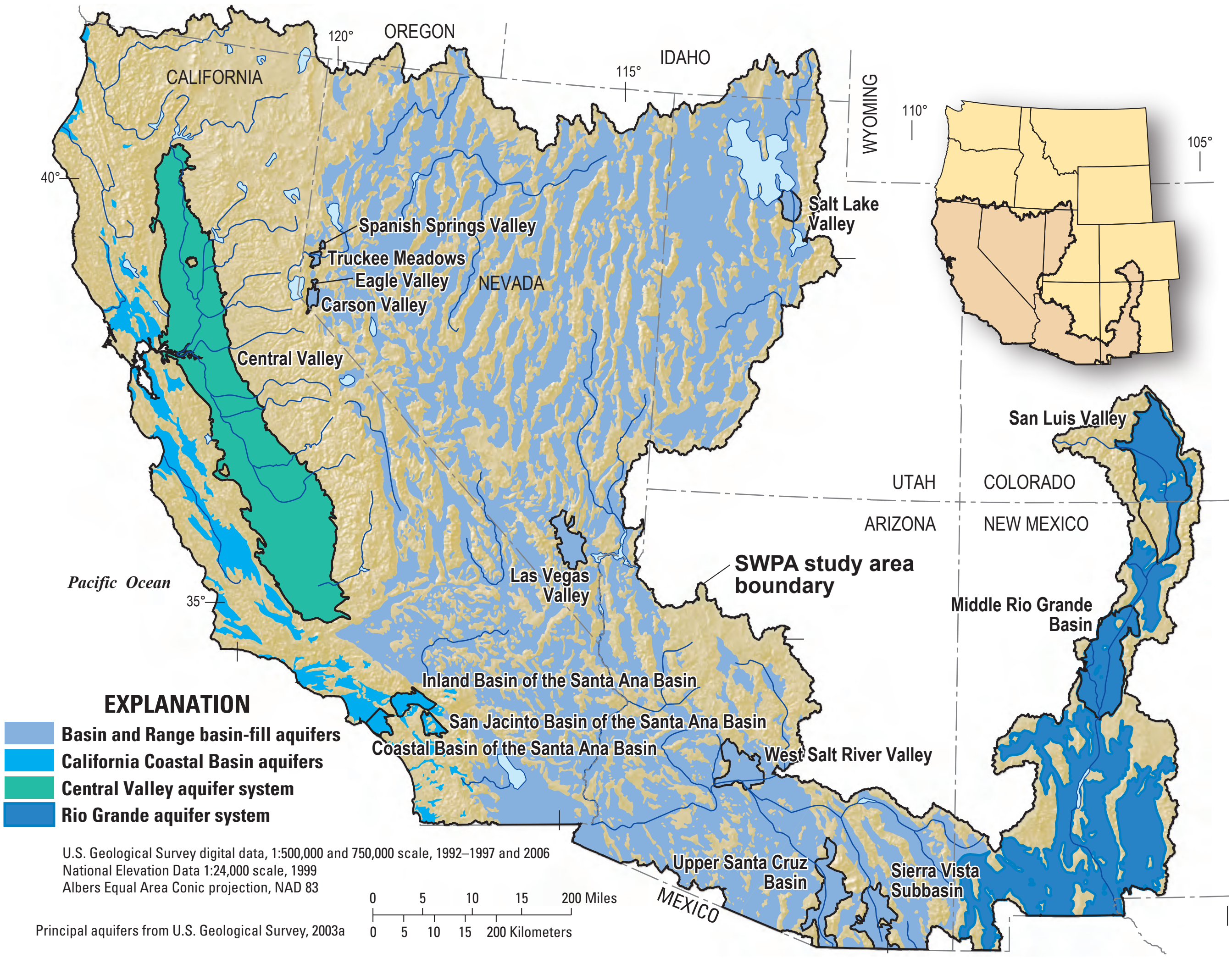

Figure 1. Principal aquifers and locations of 15 basins previously studied by the National Water-Quality Assessment Program in the Southwest Principal Aquifers (SWPA) study area.

About 46.6 million people live in the SWPA study area (Oak Ridge National Laboratory, 2005), mostly in urban metropolitan areas; a smaller percentage live in rural agricultural communities that tend about 14.4 million acres of cropland (U.S. Geological Survey, 2003b). Other rural areas have small communities with mining, retirement, and(or) tourism- and recreational-based economies. Because of the generally limited availability of surface-water supplies in parts of the Southwest, cultural and economic activities in the region are particularly dependent on good-quality groundwater supplies. In the year 2000, about 33.7 million acre-ft of surface water was diverted from streams and about 23.0 million acre-ft of groundwater was withdrawn from aquifers in the SWPA study area, mostly for agricultural uses (U.S. Geological Survey, 2004). Withdrawals from basin-fill aquifers in the study area for irrigation and public supply in the year 2000 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, table 1). Although irrigation and public supply are the primary uses of groundwater in the study area, water use varies locally by basin, and withdrawals for industrial, mining, and electric power generation are also significant in some areas.

Basin-Fill Aquifers

Basin-fill aquifers in the Southwest consist primarily of sand and gravel deposits that partly fill structurally formed depressions that are commonly bounded by mountains (fig. 2). In some areas, silt and clay layers interbedded with the more-permeable sand and gravel deposits form confining units that impede the vertical movement of groundwater. Most basins contain thousands of feet of deposits, and the sediments become more compacted and less permeable with depth and in the topographically lower parts of basins. Many basins are drained by a stream that flows through a gap in the surrounding consolidated rock or they coalesce with a topographically lower basin, although some are closed basins from which groundwater and surface water are removed naturally only by evapotranspiration.

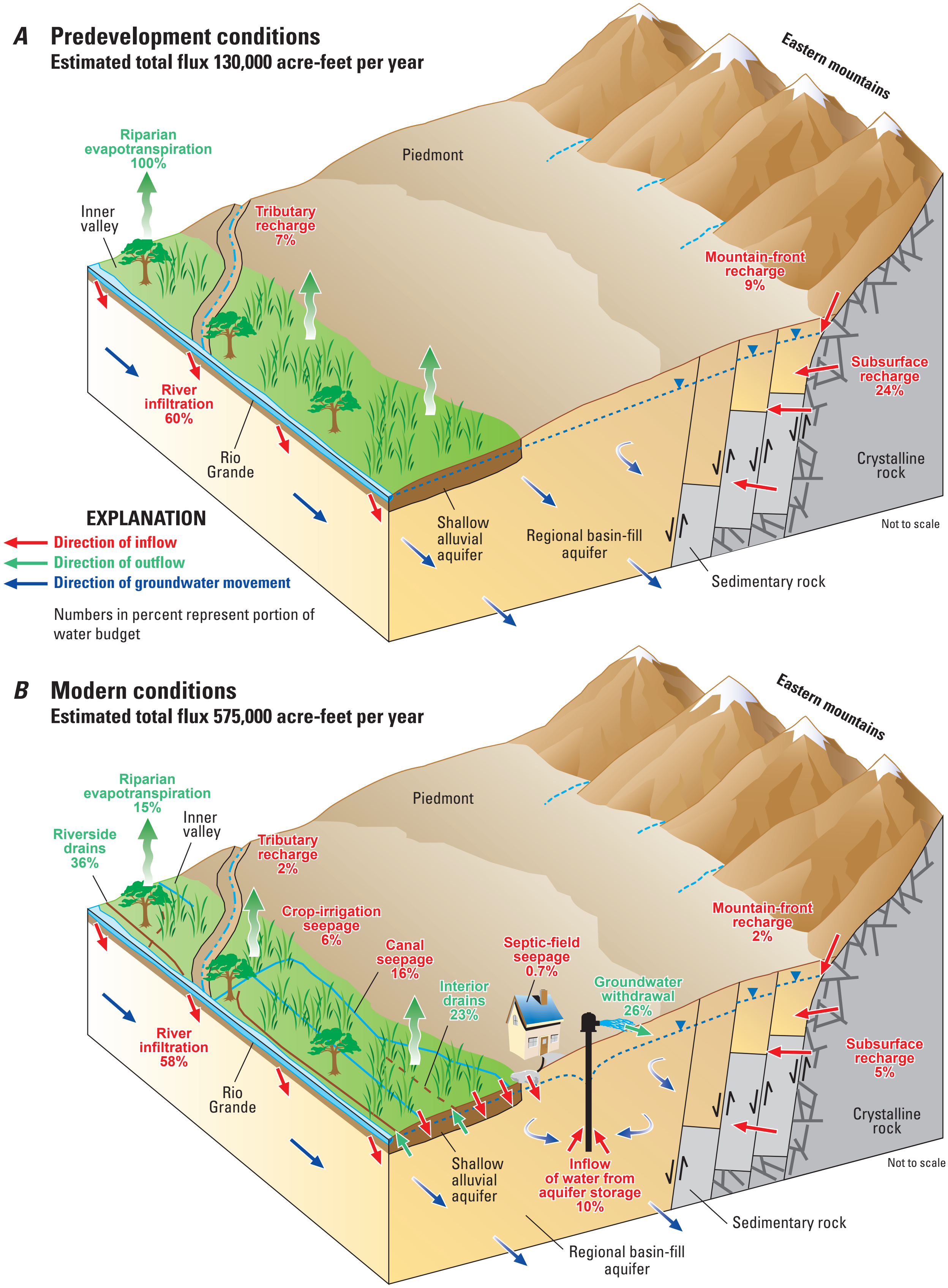

Figure 2. Generalized diagram for the Middle Rio Grande Basin, New Mexico, showing components of the groundwater system under (*A*) predevelopment and (*B*) modern conditions.

Generally, high-energy streams form alluvial fans of coarse-grained deposits along the mountain fronts, where a thick unsaturated zone is underlain by an unconfined aquifer. Steep alluvial fans transition to a relatively flat valley floor, where lacustrine and fluvial depositional environments commonly have created layers of fine-grained sediment interbedded with more permeable layers of sand and gravel. In groundwater discharge areas in the topographically lowest parts of some basins, this depositional sequence results in confined and artesian conditions as the upward flow of water is impeded by fine-grained layers of sediment. Somewhat continuous clay layers typically occur within about 100 ft of the land surface in many basins, forming the base of a shallow aquifer system that can be perched or that can contribute to or receive water from the underlying confined aquifer.

The primary source of natural recharge to the deeper parts of most Southwest basin-fill aquifers is precipitation on the surrounding mountains. Mountain runoff seeps into the coarse-grained stream-channel and alluvial-fan deposits near the basin margins. Precipitation also can infiltrate the consolidated rock of the mountains where the rock is fractured or weathered and move into the basin-fill deposits as subsurface inflow. Low precipitation rates combined with high evaporation rates in the Southwest result in a relatively small contribution of groundwater recharge from precipitation that falls on the basin floor (generally less than 5 percent of annual precipitation). Mountain-front recharge to the basin-fill aquifer includes both the runoff and subsurface inflow components.

Before human development of water resources began in the alluvial basins, sources of discharge from the groundwater systems typically were evapotranspiration, springs, and seepage to streams flowing through the basin. Constrictions in the surrounding bedrock and faulting restrict groundwater flow out of many of the basins. Playa lakes or wet playas were present in the topographically low areas of basins with no through-flowing drainage. Artesian areas existed in several basins where groundwater flowed to the land surface through layers of less permeable material. The cities of Las Vegas (Nevada), Tucson (Arizona), and San Bernardino (California) owe their locations to the availability of groundwater that historically discharged to streams or springs throughout the year.

Changes to the Basin-Fill Aquifers

Some basin groundwater systems in the Southwest have changed considerably with water development. Imported surface water and the redistribution of water from various sources to areas that previously did not receive recharge have resulted in increased flow velocities, greater saturated thicknesses, and changes in flow directions for some basins. New sources of recharge include seepage of excess irrigation water applied to crops and lawns; seepage from canals, leaking water-distribution and sewer pipes, and septic systems; infiltration of stormwater runoff from retention basins, recharge basins and wells used to receive runoff (dry wells); and seepage of treated wastewater through streambeds or irrigated fields as a means of disposal, artificial recharge, or as excess irrigation water. As an example of the effects of water development on an aquifer, the change in groundwater recharge and discharge in the Middle Rio Grande Basin from predevelopment to modern conditions is shown in figure 2.

Withdrawal from wells has become the primary path of groundwater discharge from many of the basins at the expense of discharge to streams and evapotranspiration. Water-level declines and changes in flow directions and magnitudes occur where groundwater withdrawals are large. The recharge and discharge quantities associated with water development have resulted in the acceleration of flow through parts of many basin-fill groundwater systems, especially from the land surface to the shallower parts of the aquifer. Groundwater withdrawals from relatively deep wells that are typically used for public supply also have resulted in enhanced movement of groundwater from shallower to deeper parts of basin-fill aquifers. Water development and urbanization, therefore, typically result in aquifers that are more susceptible to water-quality degradation by human activities occurring at the land surface and more vulnerable to contamination where contaminant sources are present. Changes in flow directions, geochemical conditions, or vertical mixing in a groundwater system that has small rates of flow, long residence times, and slow rates of contaminant degradation can make treatment of contaminated groundwater difficult. Contamination can affect whether the groundwater resource can feasibly be used as a drinking-water supply for many years. Therefore, it is imperative to understand the natural and human-related factors associated with the susceptibility and vulnerability of these aquifers to contamination, allowing water managers to plan for their optimal protection and utilization.

Regional Analysis

Similarities in the hydrogeology, land- and water-use practices, and water-quality issues within the SWPA study area allow for regional analysis. Regional analysis begins by determining the primary factors that affect water quality—and the associated susceptibility and vulnerability of basin-fill aquifers to contamination—on the basis of data and information from a subset of information-rich basin-fill aquifers in the study area. Conceptual and mathematical models formed for these basins can then be used to provide insight on areas that are hydrologically similar, but that are lacking groundwater-quality data and interpretive studies, or on areas where water development has not progressed as far as in the modeled basins. Regional analysis, therefore, is a cost-effective means of providing water managers of multiple basins with information that could be used to determine the likely level of susceptibility and vulnerability of their aquifers to contamination.

During its first data-collection and analysis phase from 1991 to 2001, NAWQA Program scientists sampled wells and established baseline water-quality conditions for basin-fill aquifers in 15 basins across the study area (fig. 1 and table 1). Groundwater quality also was evaluated for its relation to natural and human-related factors on the basis of a wide suite of constituents, including major ions, nutrients, trace elements, pesticides, and volatile organic compounds (VOCs). These studies resulted in the identification and detailed understanding of local conditions and factors affecting groundwater quality in each basin. The SWPA study described here develops a regional understanding by synthesizing information from the 15 case-study basins into a common set of important natural and human-related factors found to affect water quality in basin-fill aquifers across the Southwest. The synthesis consists of the following major components:

1. Summary of current knowledge about the groundwater systems, and the status of, changes in, and influential factors affecting groundwater quality of basin-fill aquifers in the 15 basins previously studied by NAWQA (this report).
2. Development of a conceptual model of the primary natural and human factors commonly affecting groundwater quality, thereby building a regional understanding of the susceptibility and vulnerability of basin-fill aquifers to contaminants.
3. Development of statistical models that relate the concentration or occurrence of specific chemical constituents in groundwater to natural and human-related factors linked to the susceptibility and vulnerability of basin-fill aquifers to contamination.

Regional-scale models and other decision-support tools that integrate aquifer characteristics, land use, and water-quality monitoring data will help water managers to evaluate water-quality conditions in unmonitored areas, to broadly assess the sustainability of water resources for future supply, and to help develop cost-effective groundwater monitoring programs.

Table 1. Alluvial basins in the southwestern United States described in this report.

Section	Case-study alluvial basin	Principal aquifer system
2	Salt Lake Valley, Utah	Basin and Range basin-fill aquifers
3	Truckee Meadows, Nevada	Basin and Range basin-fill aquifers
4	Eagle Valley, Nevada	Basin and Range basin-fill aquifers
4	Carson Valley, Nevada	Basin and Range basin-fill aquifers
5	Spanish Springs Valley, Nevada	Basin and Range basin-fill aquifers
6	Las Vegas Valley, Nevada	Basin and Range basin-fill aquifers
7	West Salt River Valley, Arizona	Basin and Range basin-fill aquifers
8	Upper Santa Cruz Basin, Arizona	Basin and Range basin-fill aquifers
9	Sierra Vista Subbasin of the Upper San Pedro Basin, Arizona	Basin and Range basin-fill aquifers
10	San Luis Valley, Colorado and New Mexico	Rio Grande aquifer aystem
11	Middle Rio Grande Basin, New Mexico	Rio Grande aquifer aystem
12	San Jacinto Basin of the Santa Ana Basin, California	California Coastal Basin aquifers
12	Inland Basin of the Santa Ana Basin, California	California Coastal Basin aquifers
12	Coastal Basin of the Santa Ana Basin, California	California Coastal Basin aquifers
13	Central Valley, California	Central Valley aquifer system

Previous Regional Investigations of Basin-Fill Aquifers in the Southwest

Previous NAWQA SWPA reports have described groundwater quality in the Southwest from a regional perspective. Anning and others (2007) studied the spatial distribution of dissolved solids in basin-fill aquifers and streams in the Southwest, along with sources of dissolved solids and the factors that affect observed concentrations. The effects of agricultural and urban land use on the quality of shallow groundwater was evaluated by Paul and others (2007) using data collected by the NAWQA Program for the SWPA study area from 1993 to 2004. Other USGS studies of large areas in the Southwest include those of the Regional Aquifer-System Analysis (RASA) and the Regional Groundwater Availability programs. In many of these studies, computer models were used to develop estimates of water availability at the time of the study and into the future. The National Ground Water Atlas, which was compiled using RASA findings (Miller, 1999), includes maps and information on the principal aquifer systems described in this report.

Publications that describe components of the groundwater budgets for several basin-fill aquifers in the Southwest include those by Hogan and others (2004), Anning and Konieczki (2005), Paschke (2007), Stonestrom and others (2007), and Reilly and others (2008). Hogan and others (2004) and Stonestrom and others (2007) focus particularly on arid and semiarid recharge mechanisms and quantities. Anning and Konieczki (2005) focus on classification of basins based on hydrogeologic characteristics, whereas Reilly and others (2008) focus on groundwater availability. Paschke (2007) includes discussion of regional groundwater budgets, general groundwater quality characteristics, and areas that groundwater-flow models simulated as contributing recharge to public-supply wells in four basins within the SWPA study area.

Study Approach

For each of the NAWQA case-study basins, information needed to understand the basin's groundwater system and its water-quality characteristics was compiled and presented in an individual section on the basin in this report (table 1). A spatial dataset of natural and human-related factors that may affect groundwater quality in the basin-fill aquifers of the Southwest was developed for the SWPA study (McKinney and Anning, 2009) and was used as the basis for describing the case-study basins. This dataset includes physical characteristics of the region such as geology, elevation, and precipitation, as well as human-related factors, such as population, land use, and water use.

Each section contains a basin overview and a description of the water-development history, hydrogeology, conceptual understanding of the groundwater system under both predevelopment and modern conditions, and the effects of natural and human-related factors on groundwater quality in the basin. The information was gathered from existing publications and summarized to provide a complete conceptual model for use in the next phase of the SWPA study, which is to synthesize the compiled information for the individual basins to provide a regional perspective on how water quality in Southwest basin-fill aquifers is affected by various natural and human-related factors. Some of the basins have more information available on the groundwater system and water quality than others, resulting in longer and more detailed sections.

The conceptual models presented in this report are formed from the results of previous studies, some of which included the construction of a numerical groundwater-flow model. Recharge to and discharge from the case-study basin-fill aquifers were separated into budget components that were generally consistent across the basins, such as recharge from precipitation on the basin and along the mountain front; subsurface inflow from bedrock and other basins; seepage from excess applied irrigation, canals, and artificial recharge facilities; and discharge from evapotranspiration, springs, wells, seepage to streams, and subsurface outflow from the basin. Estimates for groundwater recharge and discharge components under predevelopment and modern conditions are based, whenever possible, on flow-model simulations that utilize some measured data, such as water levels and engineered recharge amounts, and a calibration process to determine unmeasured components, such as subsurface inflow and outflow. For basins without available flow models, groundwater budgets have been compiled from information gleaned from other reports or were estimated for this study. The estimated budgets do not represent a rigorous analysis of individual budget components, and some estimates may be less certain than others. The groundwater budgets presented in this report are intended only to provide a basis for comparing the overall magnitude of recharge and discharge between predevelopment and modern conditions in a basin and to allow for comparisons across the case-study basins.

Concentrations of selected constituents and compounds in groundwater from the case-study basins were compared with drinking-water standards established by the U.S. Environmental Protection Agency (2009). Primary drinking-water standards limit the concentration levels of specific contaminants that can adversely affect public health. Examples of primary drinking-water standards are 10 milligrams per liter (mg/L) for nitrate (measured as nitrogen), 0.010 mg/L for arsenic, and 0.003 mg/L for the pesticide atrazine. These standards are the maximum contaminant levels (MCL) that are legally allowed in public water systems to protect drinking-water quality. Secondary drinking-water standards are non-enforceable guidelines for contaminants that may cause changes in cosmetic or aesthetic effects such as taste, odor, or color. Examples of secondary drinking-water standards are 500 mg/L for total dissolved solids and 250 mg/L for sulfate.

A variety of environmental tracers were used in many of the case-study basins to help determine the susceptibility of groundwater to the effects of human activities at the land surface. Most commonly, these tracers were used to estimate groundwater "age," which is defined as the time since the water being sampled reached the water table. The presence of at least a fraction of groundwater less than about 50 years old typically indicates parts of an aquifer that are susceptible to water-quality effects from human activities at the land surface. The quality of older groundwater that does not contain a discernable fraction of water that recharged within the past 50 years typically is considered not to have been affected by human activities, but rather by natural factors. One environmental tracer, tritium, which occurs naturally in precipitation, is a radioactive isotope of hydrogen with a half life of 12.4 years. Large amounts of tritium were introduced into the atmosphere by nuclear testing beginning in the early 1950s (atmospheric testing was banned in 1963). The presence of tritium in groundwater above a threshold concentration is used as an indicator that at least a component of the water was recharged since the early 1950s, and therefore, is "young."

The presence of chlorofluorocarbons (CFCs) in groundwater also is used as an indicator of young water and as a tool for estimating specific groundwater ages. CFCs are man-made organic compounds that are used in industrial processes and in the home. After their introduction in the 1930s, atmospheric concentrations increased nearly exponentially until the 1990s (Plummer and Busenberg, 2000). Three specific CFCs—CFC-11, CFC-12, and CFC-113—have long residence times and uniform concentrations in the atmosphere, making them valuable groundwater tracers once incorporated into the hydrologic cycle (Solomon and others, 1998; Cook and Herczeg, 2000). In populous areas, CFC contamination from leaking sewage systems and other sources besides the atmosphere is a good indicator of aquifer susceptibility to human activities, even though a specific age cannot be estimated for groundwater that has been contaminated with urban sources of CFCs.

Carbon-14 is a naturally occurring radioactive isotope of carbon that can be useful to estimate the age of "old" groundwater, or water that recharged an aquifer between about 1,000 and 40,000 years ago (Coplen, 1993). Most carbon-14 present in water that recharges an aquifer results from contact with carbon dioxide in the soil zone and(or) atmosphere. Knowledge of groundwater flow paths and the geochemical processes likely to affect carbon-14 along flow paths is necessary to properly adjust the carbon-14 measured in a groundwater sample prior to estimating an age through half-life calculations. Other factors, such as the addition of carbon-14 to the atmosphere through thermonuclear testing, also must be taken into account to arrive at an appropriate age estimate. Detailed discussions of the use of carbon-14 in estimating groundwater age can be found in Kalin (2000) and Kazemi and others (2006).

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