Overview of Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells

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Section 1 of

Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001

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Overview of Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells

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Abstract

This study of the Transport of Anthropogenic and Natural Contaminants to public-supply wells (TANC study) is being conducted as part of the U.S. Geological Survey National Water Quality Assessment (NAWQA) Program and was designed to increase understanding of the most important factors to consider in ground-water vulnerability assessments. The seven TANC studies that began in 2001 used retrospective data and ground-water flow models to evaluate hydrogeologic variables that affect aquifer susceptibility and vulnerability at a regional scale. Ground-water flow characteristics, regional water budgets, pumping-well information, and water-quality data were compiled from existing data and used to develop conceptual models of ground-water conditions for each study area. Steady-state regional ground-water flow models were used to represent the conceptual models, and advective particle-tracking simulations were used to compute areas contributing recharge and traveltimes from recharge to selected public-supply wells. Retrospective data and modeling results were tabulated into a relational database for future analysis. Seven study areas were selected to evaluate a range of hydrogeologic settings and management practices across the Nation: the Salt Lake Valley, Utah; the Eagle Valley and Spanish Springs Valley, Nevada; the San Joaquin Valley, California; the Northern Tampa Bay region, Florida; the Pomperaug River Basin, Connecticut; the Great Miami River Basin, Ohio; and the Eastern High Plains, Nebraska. This Professional Paper Chapter presents the hydrogeologic settings and documents the ground-water flow models for each of the NAWQA TANC regional study areas that began work in 2001. Methods used to compile retrospective data, determine contributing areas of public-supply wells, and characterize oxidation-reduction (redox) conditions also are presented. This Professional Paper Chapter provides the foundation for future susceptibility and vulnerability analyses in the TANC study areas and comparisons among regional aquifer systems. The report is organized in sections. In addition to the introductory section (Section 1) are seven sections that present the hydrogeologic characterization and ground-water flow model documentation for each TANC regional study area (Sections 2 through 8). Abstracts in Sections 2 through 8 provide summaries and major findings for each regional study area.

Introduction

About one-third of the population of the United States obtains drinking water from public-supply systems that rely on ground water causing concern for the quality of ground water pumped by public-supply wells (Franke and others, 1998). The occurrence and concentration of anthropogenic and natural contaminants in public-supply wells is controlled by many factors intrinsic and extrinsic to a ground-water system. Aquifer and public-supply well susceptibility to contamination is determined by the intrinsic conditions of an aquifer such as depth to water, flow-system confinement, recharge rate, hydraulic conductivity, and porosity (Focazio and others, 2002). Factors extrinsic to the aquifer include land use and the presence and location of potential contaminant sources overlying or within the area contributing recharge to a public-supply well. Aquifer vulnerability is determined by considering both the intrinsic and extrinsic factors affecting water quality (Focazio and others, 2002). This study of the Transport of Anthropogenic and Natural Contaminants to supply wells (TANC) also considers public-supply well pumping rates and aquifer geochemical conditions when determining aquifer vulnerability.

The TANC study is part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program. The long-term goals of the NAWQA Program are to describe the status and trends in the quality of a large representative part of the Nation's surface- and ground-water resources and to provide a sound, scientific understanding of the major natural and human factors affecting the quality of those resources (Gilliom and others, 1995). The first cycle (Cycle I) of the NAWQA Program was implemented from 1991 to 2000, and a second investigative cycle (Cycle II) began in 2001. During Cycle II (2001 to 2011), 42 NAWQA study units will be revisited in three groups of 14 on a rotational schedule. Each group is intensively studied for 4 years, followed by 6 years of low-intensity assessment. The primary emphasis of Cycle II is to assess long-term trends in water quality and to improve understanding of the factors and processes governing water quality. The TANC study is one of several Cycle II NAWQA studies designed to aid understanding of our Nation's water quality.

Purpose and Scope

The TANC study was designed to increase understanding of anthropogenic and natural contaminants detected in public-supply wells in support of ground-water susceptibility and vulnerability assessments by examining answers to the question: "What are the primary anthropogenic and natural contaminant sources, aquifer processes, and well characteristics that control the transport and transformation of contaminants along flow paths to public-supply wells in representative water-supply aquifers?"

Seven TANC studies began in 2001 using retrospective data and ground-water flow models to evaluate hydrogeologic variables that affect aquifer susceptibility and vulnerability at a regional scale. Ground-water flow characteristics, regional water budgets, pumping-well information, and water-quality data were compiled from existing data and used to develop conceptual models of ground-water conditions for each study area. Steady-state regional ground-water flow models were used to represent the conceptual models, and advective particle-tracking simulations were used to compute areas contributing recharge and traveltimes from recharge to selected public-supply wells. Retrospective data, ground-water traveltimes from recharge to discharge areas, oxidation-reduction (redox) conditions along flow paths, and the presence of potential contaminant sources in areas contributing recharge to public-supply wells were tabulated into a relational database for future use in analyzing aquifer vulnerability. The 5-year period from 1997 to 2001 was selected for data compilation and modeling exercises in order to facilitate comparisons among study areas and to use large recently collected water-quality data sets.

The purpose of this report is to present the hydrogeologic settings, including regional redox and pH conditions, of the seven NAWQA TANC regional study areas that began work in 2001. The report also documents the ground-water flow models for each regional study area. This report provides the foundation for further susceptibility and vulnerability analyses in the TANC study areas, comparisons among regional aquifer systems, and future local-scale field and modeling investigations. The report is organized into sections. In addition to this introductory section (Section 1), there are seven sections that present the hydrogeologic characterization and ground-water flow model documentation for each TANC regional study area (Sections 2 through 8). Abstracts in Sections 2 through 8 provide summaries and major findings for each regional study area.

Study Area Locations

The U.S. Geological Survey has identified 62 principal aquifers in the United States (Miller, 1999). A principal aquifer is defined as a regionally extensive aquifer or aquifer system that has potential to be used as a source of potable water (U.S. Geological Survey, 2003; Maupin and Barber, 2005). An aquifer is a geologic formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant amounts of water to wells and springs. Aquifers are often combined into aquifer systems. The NAWQA Program has designated 19 of the Nation's 62 principal aquifers as the primary focus of Cycle II studies by considering the factors of aquifer areal extent, water use for drinking-water supply, lithology, and widespread geographic coverage of the United States (table 1.1). The 19 principal aquifers account for about 75 percent of the water used for domestic plus public drinking-water supply in the United States in 1990 (Lapham and others, 2005) and provide a good spatial coverage of aquifer systems across the country (fig 1.1).

Aquifers in different parts of the Nation differ in their susceptibility and vulnerability to contamination because of varying hydrogeologic settings and ground-water management practices. Of the NAWQA Cycle II study units that began investigations in 2001, 7 regional study areas located in 5 of the 19 principal aquifers were selected for TANC studies to evaluate a range of hydrogeologic conditions and management practices (fig. 1.2). Additional areas will be selected for TANC studies as NAWQA Cycle II proceeds through its rotational schedule. The NAWQA TANC 2001-start regional study areas and their associated principal aquifers are:

- Salt Lake Valley, Utah, in the Basin and Range basin-fill aquifers,
- Eagle Valley and Spanish Springs Valley, Nevada, in the Basin and Range basin-fill aquifers,
- San Joaquin Valley, California, in the Central Valley aquifer system,
- Northern Tampa Bay, Florida, in the Floridan aquifer system,
- Pomperaug River Basin, Connecticut, in the glacial aquifer system,
- Great Miami River Basin, Ohio, in the glacial aquifer system, and
- Eastern High Plains, Nebraska, in the High Plains aquifer.

A hydrogeologic description of each TANC 2001-start regional study area and its associated principal aquifer follows with additional details of each study provided in subsequent sections of this report.

Table 1.1. The 19 principal aquifers selected as the primary focus of ground-water studies during Cycle II of the National Water-Quality Assessment Program.

[km^2, square kilometers; Mm^3/d, millions of cubic meters per day; NAWQA, National Water-Quality Assessment Program]

Principal aquifer or aquifers	Primary lithologies of the principal aquifer	Approximate area of principal aquifer (km^2)	Number of NAWQA Cycle II study units over-lying principal aquifer	Principal aquifer rank by 2000 drinking-water use[1]	Estimated with-drawals for public supply[3] (Mm^3/d)
Glacial aquifer system	Sand and gravel	2,470,655	18	1	7.38
Mississippi Embayment—Texas Coastal Uplands aquifer system	Semiconsolidated sandstone	511,191	7	8	2.74
Cambrian-Ordovician aquifer system	Sandstone	459,722	5	10	2.23
High Plains aquifer	Sand and gravel	457,594	4	14	1.47
Basin and Range basin-fill and carbonate aquifers	Sand and gravel, carbonates	423,513	4	4	4.09
Floridan aquifer system and overlying Surficial aquifer system[2]	Carbonate	292,088	5	3	5.89
Coastal Lowlands aquifer system	Semiconsolidated sandstone	255,975	4	5	3.82
Piedmont and Blue Ridge aquifers	Carbonate and crystalline	227,449	8	24	0.42
Edwards-Trinity aquifer system	Sandstone and carbonate	194,439	2	12	1.56
New England crystalline-rock aquifers	Crystalline	183,158	4	31	0.28
North Atlantic Coastal Plain aquifer system (NACPAS)[3]	Semiconsolidated sandstone	114,542	4	7	3.00
Columbia Plateau basin-fill and basaltic-rock aquifers	Sand and gravel, basalt	112,811	1	18	0.84
Central Valley aquifer system	Sand and gravel	52,633	2	6	3.18
California Coastal basins aquifers	Sand and gravel	26,367	1	2	6.0
Denver Basin aquifer system	Sandstone	17,595	1	49	0.10
Hawaiian volcanic-rock aquifers	Basalt	16,691	1	16	0.92
Biscayne aquifer	Carbonate	9,259	1	9	2.64
Snake River basin-fill and basaltic-rock aquifers	Sand and gravel, basalt	5,060	1	23	0.57

[1]Rank 1 is largest water use; use was estimated for 62 principal aquifers.

[2]Includes that part of the Coastal Plain surficial aquifer that overlies the Floridan.

[3]From Maupin and Barber, 2005

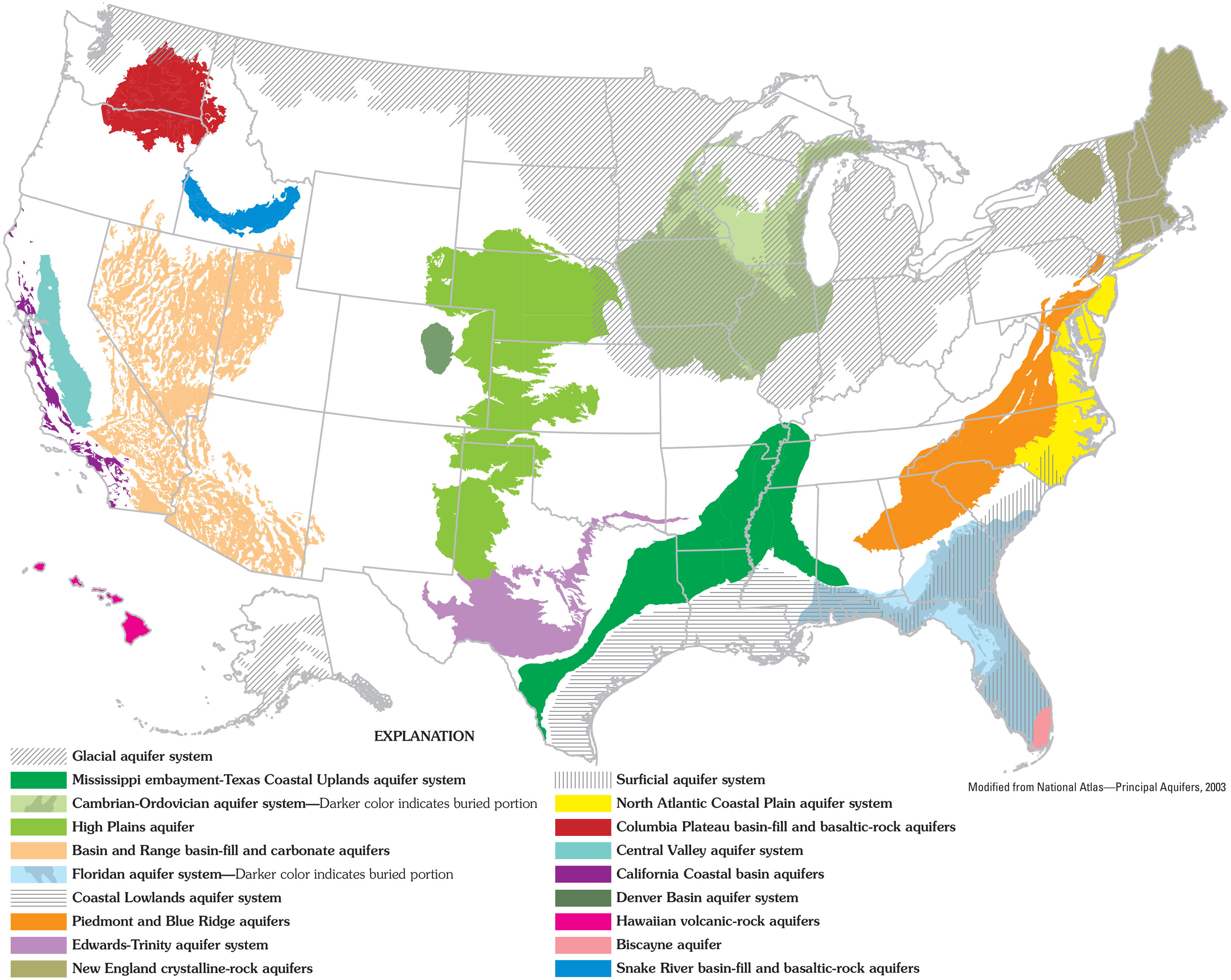

Figure 1.1. The 19 principal aquifers selected as the primary focus of ground-water studies during Cycle II of the National Water-Quality Assessment program.

Basin and Range Basin-Fill Aquifers

The Basin and Range basin-fill aquifers are a primary source of water in the arid West extending through about 423,513 square kilometers (km^2) of the Southwestern United States and underlying most of Nevada and parts of eastern California, southern Oregon and Idaho, western Utah, southern Arizona, and southwestern New Mexico (fig. 1.2). The Basin and Range basin-fill aquifers are thick deposits of alluvial materials in valleys bounded by bedrock mountain ranges. Basin fill primarily consists of unconsolidated to moderately consolidated, poorly- to well-sorted beds of gravel, sand, silt, and clay deposited on alluvial fans, pediments, flood plains, and playas. Basin-fill thickness is not well known in some basins but ranges from about 305 to 1,525 m in many basins and may exceed 3,050 m in a few deep basins in Utah and south-central Arizona (Robson and Banta, 1995).

Recharge to the Basin and Range basin-fill aquifers primarily is derived from stream runoff (mountain-front recharge) and subsurface flow (mountain-block recharge) from mountains surrounding the basins (Robson and Banta, 1995). The generally arid climate of the area causes almost all precipitation in the basins and most of the precipitation in the mountains to be lost to evapotranspiration; only about 5 percent of precipitation recharges the basin-fill aquifers (Robson and Banta, 1995). In extensively developed parts of the aquifers, agricultural and urban irrigation return flow percolates into the basin fill and ultimately recharges the aquifers. Discharge from the aquifers is by evapotranspiration, discharge to streams and springs, underflow, interbasin flow, and withdrawal by wells (Robson and Banta, 1995; Planert and Williams, 1995). Basin-fill aquifers generally are not connected to other basins although underflow and interbasin flow can be significant components of recharge or discharge in some basins where the surrounding bedrock is composed of cavernous carbonate rocks (Robson and Banta, 1995; Planert and Williams, 1995). Ground-water withdrawal from wells is the largest component of discharge from Basin and Range basin-fill aquifers and supplies water for agricultural irrigation and public water supply (Robson and Banta, 1995). Evapotranspiration is the largest natural component of ground-water discharge and can decrease when the water table is lowered by ground-water withdrawal (Robson and Banta, 1995). Although agricultural irrigation is still a principal ground-water use in the area, population increases since the 1960s have decreased the percentage of ground water used for irrigation and increased the percentage of ground water used for public water supply (Robson and Banta, 1995).

Ground water in the basin-fill aquifers generally is of suitable chemical quality for most uses; most ground water has a dissolved-solids concentration of less than 1,000 milligrams per liter (mg/L). However, the dissolved-solids concentration of water in parts of some basins can be as large as 300,000 mg/L (Robson and Banta, 1995). Water that has small dissolved-solids concentration generally is present near the margins of the basins, where recharge from the nearby mountains enters the aquifers; and water with larger dissolved-solids concentrations is present in topographically low parts of some basins, where ground water is discharged by evaporation and transpiration (Robson and Banta, 1995). In basins that have no discharge by underflow or streamflow, salts can accumulate over long periods of time in the fine-grained sediments near the center of the basin or can form extensive surface deposits of salt, such as the salt flats of the Great Salt Lake Desert in western Utah (Robson and Banta, 1995).

The Salt Lake Valley and Eagle Valley and Spanish Springs Valley regional study areas, which are within the Basin and Range basin-fill aquifers, are characterized by the occurrence of ground water in deep sediment-filled graben basins between mountain ranges. The Salt Lake Valley regional study area encompasses the Great Salt Lake Valley west of the Wasatch Range where ground water is used extensively for water supply in and around Salt Lake City, Utah. The basin-fill aquifer of the Salt Lake Valley study area is unconfined on the valley margins and transitions to confined conditions near the center of the valley where an overlying confining layer is present. Section 2 of this report presents the hydrogeologic setting, model setup, and modeling results for the Salt Lake Valley regional study area.

The Eagle Valley and Spanish Springs Valley regional study includes two alluvial basins—Eagle Valley near Carson City, Nevada, in the Carson River basin, and Spanish Springs Valley north of Sparks, Nevada, in the Truckee River basin. Rapid urban development in both the Eagle Valley and the Spanish Springs Valley regional study areas has resulted in reliance on ground water for water supply. Differing population stresses and rates of ground-water movement make the two study areas unique. The Eagle Valley is more urbanized and receives more recharge from precipitation than the Spanish Springs Valley. Section 3 of this report presents the hydrogeologic setting, model setup, and modeling results for the Eagle Valley and Spanish Springs regional study areas.

Central Valley Aquifer System

The Central Valley aquifer system of California (fig. 1.2) contains the largest basin-fill aquifer system in the Western United States. The Central Valley is one of the most important agricultural areas in the World, having more than 28,000 km^2 of agricultural land under irrigation in 1995 (Planert and Williams, 1995). During 1985, crop irrigation accounted for 96 percent of the surface water and 89 percent of the ground water withdrawn in the Central Valley (Planert and Williams, 1995).

The Central Valley is in a structural trough about 644 km long and from 32 to 113 km wide and extends over more than 52,633 km^2 (Planert and Williams, 1995). The trough is filled by marine and continental sediments up to 10 km thick (Gronberg and others, 1998), which form an important aquifer system. The Central Valley is bounded on the west by the Coast Ranges and on the east by the Cascade Range and the Sierra Nevada. The valley floor, which consists primarily of alluvial

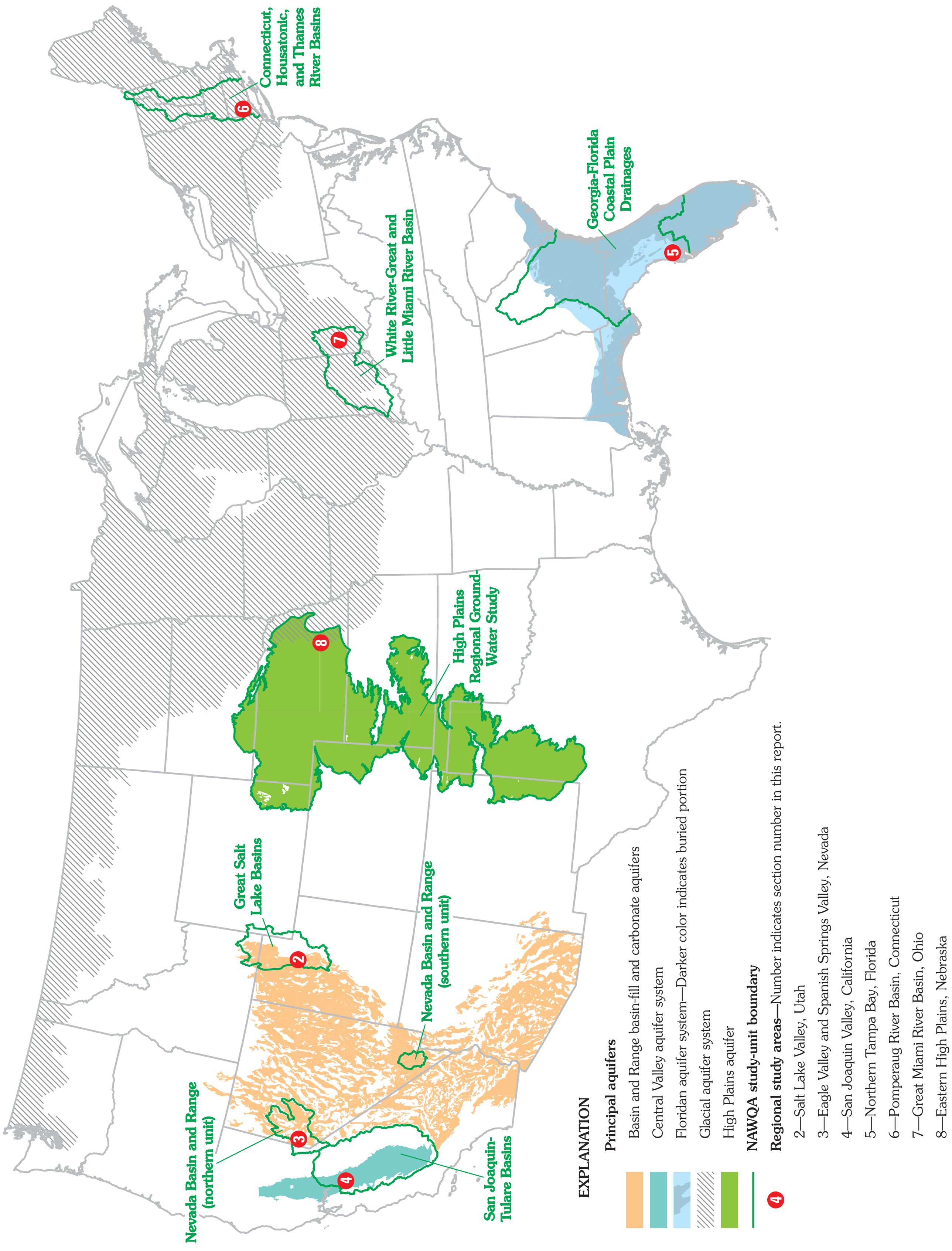

Figure 1.2. Locations of principal aquifers, National Water-Quality Assessment program study-unit boundaries, and 2001-start regional study areas for the transport of anthropogenic and natural contaminants.

and flood-plain deposits of the major rivers, is relatively flat to gently rolling and is generally below an altitude of 152 m. The Sacramento River drains the northern end of the Central Valley, and the San Joaquin River drains much of the middle one-third. The two rivers join in the Sacramento-San Joaquin Delta and empty into the upper end of San Francisco Bay. The southern end of the valley is occupied by the Tulare Basin, in which drainage is internal and the inflowing water is removed by evapotranspiration (Gronberg and others, 1998).

The climate of the Central Valley is Mediterranean and Steppe, characterized by hot summers and mild winters with about 85 percent of the precipitation falling from November to April (Planert and Williams, 1995). Annual precipitation decreases from north to south, with an average of about 58.4 cm in the northern part of the Sacramento Valley to about 15.2 cm in the southern part of the San Joaquin Valley (Planert and Williams, 1995). Runoff from the Coast Ranges is principally on the western slopes to the Pacific Ocean.

Under natural conditions, ground water in the Central Valley aquifer system flowed from areas of higher altitude at the valley margins toward rivers and marshes near the valley axis (Davis and others, 1959). The aquifer was recharged primarily by streams emanating from the Cascade Range and the Sierra Nevada (average of 30.5 cm/yr) (Planert and Williams, 1995). Ground water that was not evaporated or transpired by plants discharged either into the Sacramento and the San Joaquin Rivers or into the Tulare Basin, from which it was eventually removed by evaporation or transpiration. By the early 1960s, intensive ground-water development for agricultural irrigation had substantially lowered water levels and altered ground-water flow patterns in the Central Valley aquifer system (Planert and Williams, 1995). The most striking effect of development on water levels was in the San Joaquin Valley, where water-level declines in the confined part of the aquifer system were locally more than 122 m (Planert and Williams, 1995). Large withdrawals from deep wells in the San Joaquin Valley diverted ground-water flow toward the wells and away from the San Joaquin River and reversed vertical hydraulic gradients over much of the San Joaquin Valley to the point that water in the upper unconfined aquifer leaked downward into the lower confined aquifer (Planert and Williams, 1995). Well construction also affected vertical flow in the valley as many deep wells were perforated across confining units, allowing unrestricted vertical flow through the well bores. Ground-water withdrawals have decreased since the late 1960s as additional surface water was imported to the valley (Planert and Williams, 1995).

Water quality in the Central Valley aquifer system is affected by natural geologic and hydrologic factors as well as agricultural land use. The thickness of aquifers saturated with freshwater (water with less than 1,000 mg/L dissolved solids) varies greatly within the basin, but in general, freshwater is contained in continental fluvial deposits, and dissolved-solids concentrations increase with depth (Gronberg and others, 1998). Selenium, nitrate, and pesticide concentrations are elevated in ground water of some areas of the Central Valley as the result of agricultural irrigation. The pesticide dibromochloropropane (DBCP) is particularly problematic and is present in ground water in every county in the San Joaquin Valley (Planert and Williams, 1995).

The San Joaquin Valley regional study area is located in the northeastern San Joaquin Valley and centered around the city of Modesto, California, which relies heavily on ground water for public water supply. The study area is about 2,700 km^2 in area, bounded on the west by the San Joaquin River, on the north by the Stanislaus River, on the south by the Merced River, and on the east by the Sierra Nevada foothills. The San Joaquin Valley occupies the southern two-thirds of the Central Valley principal aquifer system. Unconfined ground water is present in the Pleistocene sediments of the San Joaquin Valley above a thick confining unit known as the Corcoran Clay member of the Tulare Formation. Confined ground water occurs primarily in Pleistocene and Tertiary sediments below the Corcoran Clay. Section 4 of this report presents the hydrogeologic setting, model setup, and modeling results for the San Joaquin Valley regional study area.

Floridan Aquifer System

The Floridan aquifer system, one of the most productive aquifers in the World, underlies an area of about 292,088 km^2 in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida (Miller, 1990). The Floridan aquifer system provides water for several large cities, including Savannah and Brunswick in Georgia and Jacksonville, Gainsville, Tallahassee, Orlando, Tampa, and St. Petersburg in Florida. An average of about 15,230,000 m^3/d of freshwater was withdrawn from the Floridan aquifer system for all purposes during the year 2000 (Marella and Berndt, 2005).

A thick sequence of carbonate rocks (limestone and dolomite) of Tertiary age constitutes the Floridan aquifer system (Miller, 1990). In most places, the system can be divided into the Upper and Lower Floridan aquifers, separated by a less permeable confining unit (Miller, 1986). Because it is a prolific aquifer with acceptable water quality, the Upper Floridan is the primary water supply for the area, and its geology and hydraulic properties have been extensively studied. The Upper Floridan is highly permeable in most places and includes the Suwannee and Ocala Limestones and the upper part of the Avon Park Formation (Miller, 1986). Where the Tampa Limestone is highly permeable, it also is included in the Upper Floridan; however, aquifer-system boundaries do not necessarily conform to formational boundaries (Miller, 1990). In most areas, the limestones are highly fractured and dissolved to form secondary porosity and karst features. Sinkholes, springs, and conduits are numerous in the Floridan aquifer in northern and central Florida. The Floridan aquifer system generally thickens seaward from a thin edge near its northern limit to about 914 m in thickness in southern Florida (Miller, 1986).

Prior to extensive ground-water development in the 1960s, ground water generally moved coastward from the outcrop area of the aquifer in Georgia and South Carolina and outward in all directions from a potentiometric high in central Florida. Although recharge to the aquifer takes place throughout more than one-half of its area, recharge tends to be concentrated in outcrop areas and at potentiometric highs. Recharge rates range from less than 2.54 cm/yr to more than 51 cm/yr depending on local geologic and hydrologic conditions (Miller, 1990). Before development, nearly 90 percent of the discharge from the Floridan aquifer system was to springs and streams supplying base flow to the Suwannee, Flint, Sante Fe, Withlacoochee, Hillsborough, and other rivers, which are important water supply and recreational resources (Bush and Johnson, 1988). The Floridan aquifer also discharged to offshore springs both on the Gulf of Mexico and Atlantic Ocean sides of the northern part of peninsular Florida (Bush and Johnson, 1988).

Following development of the Upper Floridan aquifer, deep cones of depression developed near some major pumping centers, regional water-level declines were noted in some areas, and predevelopment potentiometric gradients were reversed in some coastal areas, creating the potential for encroachment of saltwater from the Gulf of Mexico (Miller, 1990). However, the major characteristics of the predevelopment flow system have not been greatly altered, and the dominant form of discharge remains springflow and discharge to streams (Miller, 1990).

Water quality and dissolved-solids concentrations of water in the Floridan aquifer system are related to (1) the ground-water flow system and (2) the proximity to saltwater. Water in the Floridan aquifer system is predominantly calcium-bicarbonate type water with dissolved-solids concentrations ranging from 10 to 30,000 mg/L and averaging 250 mg/L (Katz, 1992). In places where the aquifer system is unconfined or thinly confined, large volumes of water move quickly in and out of the aquifer system, and dissolved-solids concentrations are generally less than 250 mg/L (Katz, 1992). In areas where the aquifer system is confined, water travels along longer flow paths and has greater dissolved-solids concentrations. Near the east and west coasts of Florida, and locally in coastal areas of South Carolina and Georgia, large dissolved-solids concentrations result from mixing of fresh ground water with deeper saltwater that migrates into the aquifer from the ocean (Miller, 1990).

The Northern Tampa Bay regional study area is located in west-central peninsular Florida in the Tampa Bay metropolitan area. The study area overlies the karst Floridan aquifer system of the Southeastern United States. This study area was chosen because of the extensive water use from the Floridan aquifer system, because the aquifer is shallow, susceptible, and vulnerable to contamination, and because it represents a range of hydrogeologic and land-use conditions found throughout areas overlying the Floridan aquifer system. The Tampa Bay metropolitan area relies heavily on the Floridan aquifer system for drinking water, and the Floridan aquifer system is the primary source of water for domestic, irrigation, and industrial supplies. The study area includes public water-supply systems for the cities of Tampa, St. Petersburg, and Clearwater, Florida, and numerous smaller cities. Section 5 of this report compares the study area characteristics to those of the Floridan principal aquifer system and presents the hydrogeologic setting, model setup, and modeling results for the Northern Tampa Bay regional study area.

Glacial Aquifer System

The glacial aquifer system is present in 21 States from Maine to Washington, and covers more than 27 percent or approximately 2.5 billion km^2 of the continental United States (fig. 1.2) (U.S. Geological Survey, 2003). The glacial sand and gravel aquifers were ranked first in withdrawals for domestic plus public drinking-water supply among the approximately 62 principal aquifers in the United States.

The glacial aquifer system is generally composed of unconsolidated sand, gravel, and clay commonly deposited as individual valley-fill deposits of outwash and ice-contact materials in bedrock valleys when large continental glaciers covered parts of Canada and the northern United States between approximately 1.6 million and 10,000 years ago (Olcott, 1995). The glacial sand and gravel deposits range from a few meters to more than 300 m in thickness and are highly heterogeneous across the North-Central and Northeastern United States. The glacial sand and gravel aquifers are generally unconfined and in hydraulic connection with valley streams and are the most productive aquifers throughout the glaciated area of the country. The glacial aquifer system in the Northeastern United States is located in humid climatic regions with precipitation ranging from 91 to 127 cm/yr (Randall, 1996), and ground-water recharge is primarily from local precipitation and stream runoff from surrounding bedrock uplands. The bedrock surrounding glacial aquifers is usually less permeable than the valley-fill sediments, and ground-water underflow from bedrock uplands is minimal (Randall, 2001). Ground-water discharge in the glacial aquifers is generally to streams and wells with ground-water pumping accounting for about 15 percent of ground-water discharge (Morrissey, 1983).

Ground-water quality in the glacial aquifers is generally characterized as calcium-bicarbonate type water with dissolved-solids concentrations less than 150 mg/L and pH values in the range of 6 to 8 (Rogers, 1989). However, water quality varies regionally, depending on ground-water flow conditions, valley-fill sediment size, and sediment source area (Randall, 2001). Source area of glacial deposits determines the mineral composition of valley-fill deposits, and rock/water interaction and changing redox conditions in an aquifer can mobilize many constituents that affect natural water quality (Warner and Arnold, 2006). For example, high iron concentrations are detected in some parts of glacial aquifers where geochemical reducing conditions cause dissolution of iron oxides present in sediment. The glacial aquifer system also is vulnerable to anthropogenic contaminants such as nitrates and pesticides in agricultural areas because of the unconfined ground-water flow conditions and short ground-water flow paths.

The Pomperaug River Basin and Great Miami River Basin regional study areas are both within the glacial aquifer system. The Pomperaug River Basin study area is located in west-central Connecticut and represents glacial aquifers in the Northeastern United States. Characteristics of the aquifer system selected for this study are similar to many valley-fill-aquifer systems in the Eastern Hills and Valley Fills hydrophysiographic region (Randall, 2001), which encompasses much of the most populated parts of New England, northern New Jersey, and eastern New York. Public water supply in the Pomperaug River Basin is obtained from ground water in the glacial valley-fill aquifer. Section 6 of this report presents the hydrogeologic setting, model setup, and modeling results for the Pomperaug River Basin regional study area.

The Great Miami River Basin regional study area is in the east-central portion of the White River-Great and Little Miami River Basin NAWQA study unit and is centered on the city of Dayton, Ohio. Ground water in the study area occurs in the valley-fill glacial aquifer underlying the Great Miami River, and the study area represents the glacial aquifer system in the North-Central United States. The glacial aquifer in the study area is heavily used by industry and municipalities, and pumping often causes induced infiltration from nearby rivers or artificial recharge lagoons. Section 7 of this report presents the hydrogeologic setting, model setup, and modeling results for the Great Miami River Basin regional study area.

High Plains Aquifer

The High Plains aquifer underlies 457,594 km^2 in parts of eight States (fig. 1.2) and is primarily composed of Tertiary sand and gravel deposits of the Ogallala Formation (Gutentag and others, 1984). Ground water also occurs in Quaternary sand and gravel deposits overlying the Ogallala Formation in some areas. Approximately 27 percent of the irrigated land in the United States is in the High Plains, and about 30 percent of the ground water used for irrigation in the United States is pumped from the High Plains aquifer (Dennehy, 2000). The High Plains aquifer also provides drinking water to 82 percent of the 2.3 million people (1990 census) who live within the aquifer boundary.

The Ogallala Formation, which underlies about 80 percent of the High Plains, is the principal geologic unit forming the aquifer. The Ogallala Formation is a heterogeneous sequence of gravel, sand, silt, and clay deposited by braided streams flowing eastward from the ancestral Rocky Mountains during the Tertiary period. Younger unconsolidated alluvial deposits of Quaternary age in hydraulic connection with the Tertiary deposits make up the High Plains aquifer in eastern and central Nebraska and Kansas. These Quaternary alluvial deposits are derived from erosion and redeposition of sediments from the Ogallala Formation (Gutentag and others, 1984). The Quaternary alluvial deposits directly overlie the Ogallala Formation in many areas of the High Plains.

Regionally, the High Plains aquifer is considered an unconfined aquifer, but confined conditions can exist locally (Gutentag and others, 1984). The average saturated thickness of the aquifer is about 61 m with a maximum of about 366 m (Gutentag and others, 1984; McGuire and others, 2003). Pumping from more than 130,000 wells (Sharon Qi, U.S. Geological Survey, oral commun., 2004) is the largest component of ground-water discharge. Ground water generally flows from west to east and discharges naturally to streams and springs and by evapotranspiration in areas where the water table is near land surface. Irrigation return flows, precipitation, and seepage from canals and reservoirs are the principal sources of recharge to the aquifer (Luckey and others, 1986; Dennehy and others, 2002). Substantial pumping of the High Plains aquifer for irrigation since the 1940s has resulted in water-level declines of nearly 46 m in some parts of the aquifer (McGuire and others, 2003).

Ground-water quality in the High Plains aquifer is characterized as calcium- bicarbonate type water with dissolved-solids concentrations generally less than 500 mg/L (Dennehy and others, 2002). Ground water is generally oxidized with dissolved-oxygen concentrations greater than 5.4 mg/L and pH ranges from 7 to 8 (Dennehy and others, 2002). Naturally occurring constituents in the ground-water system, which are derived from the water interaction with the sedimentary materials and are considered contaminants, include salinity, iron, manganese, fluoride, radon, uranium, and arsenic (Dennehy and others, 2002). Anthropogenic contaminants are the results of agricultural practices and include nitrate, pesticides, salinity, and carbon tetrachloride (Dennehy and others, 2002).

The Eastern High Plains regional study area is near York, Nebraska, in the eastern part of the High Plains aquifer. Ground water in the Eastern High Plains study area is present in Quaternary sand and gravel deposits, is used extensively for public water supply by the city of York, Nebraska, and is vulnerable to contamination because of the shallow depth to water and high permeability. Section 8 of this report presents the hydrogeologic setting, model setup, and modeling results for the Eastern High Plains regional study area.

Methods

The TANC regional studies consisted of implementing the following tasks:

- Compilation of retrospective water-quality, well-construction, water-use, and geologic data.
- Collection of ground-water samples from public-supply wells in each study area in association with the NAWQA Source Water-Quality Assessment (SWQA) project.
- Development of a steady-state regional ground-water flow model to represent conditions for 1997–2001.
- Use of the regional ground-water flow model and advective particle tracking to compute the extent of the

steady-state contributing recharge area and the zone of contribution for as many as 15 public-supply wells within each quartile of pumping for each modeled study area.

- Mapping of regional redox and pH conditions using the retrospective and newly collected SWQA water-quality data.
- Development of a TANC database to store retrospective data and modeling results.

The following sections present details of each task.

Retrospective Data Compilation

Existing water-quality, well-construction, water-use, and geologic data were compiled for each study area from the U.S. Geological Survey National Water Information System (NWIS), the U.S. Environmental Protection Agency STORET database, and State and local agencies. Data compilation focused on information for public-supply wells, but information from monitoring and domestic wells was included where available. Parameters within each data set were cross-checked and stored in a consistent manner to allow the data to be jointly evaluated. To support understanding of recent water-quality and water-use conditions, the period 1997–2001 was selected as the focus for the water-quality and water-use data compilation. If more than one water-quality analysis was available for a well, the most recent and complete analysis for the period 1997–2001 was saved in the database developed for the TANC study (discussed in “Database Development” section). In some instances, a well was not sampled for all water-quality parameters on any given date, and for these cases, the complete analysis stored in the database is a composite of the most recent analysis for each parameter.

Source Water-Quality Assessment Sample Collection

NAWQA Source Water-Quality Assessments (SWQA) consisted of sampling public-supply wells. In 2003 and 2004, SWQA studies were implemented in 10 NAWQA study units including the 7 TANC regional study areas discussed in this report. Between 8 and 31 public-supply wells were sampled in each study area, and samples were analyzed for a suite of natural and anthropogenic constituents including major ions (Fishman, M.J., and Friedman, 1989), nutrients (Fishman, 1993), trace elements (Faires, 1993; Garbarino and others, 2006), volatile-organic compounds (Connor and others, 1998; Rose and Sandstrom, 2003), pesticides (Zaugg and others, 1995; Furlong and others, 2001; Sandstrom and others, 2001), and waste-water compounds (Zaugg and others, 2002). Results from the SWQA sampling are stored in the U.S. Geological Survey NWIS database (*http://waterdata.usgs.gov/nwis,* accessed January 31, 2007) and the NAWQA Data Warehouse (*http://infotrek.er.usgs.gov/travers/f?p=NAWQA:HOME:9108424999420775073*, accessed January 31, 2007).

Ground-Water Flow Simulation

As a process-based tool for understanding ground-water vulnerability, a steady-state ground-water flow model was developed or updated from existing models for each TANC regional study area. Ground-water flow was simulated using the U.S. Geological Survey’s modular finite-difference ground-water flow simulation code MODFLOW-2000 (Harbaugh and others, 2000; Hill and others, 2000). Models were calibrated following the guidelines of Hill (1998) using water-budget estimates and water-level data for the period 1997–2001 to facilitate comparisons of modeling results among study areas. Steady-state regional models and the particle-tracking program MODPATH (Pollock, 1994) were used to delineate areas contributing recharge and to compute advective traveltime through the aquifers for as many as 143 public-supply wells within each study area. For study areas with more than 60 public-supply wells, at least 15 public-supply wells were selected for particle tracking from each quartile percentage of pumping. Model conceptualization, boundary conditions, calibration, and particle-tracking simulations for each regional study area are presented in Sections 2 through 7 of this report.

MODPATH uses the cell-by-cell flow values calculated by MODFLOW to calculate the ground-water flow velocity distribution throughout the ground-water system, which is then used to determine flow paths of water particles moving through the aquifer (Pollock, 1994). Traveltimes along flow paths are computed by MODPATH using the magnitude of the cell-by-cell flows, porosity of the aquifer, and the model cell dimensions. MODPATH calculates advective ground-water flow only; the effects of mechanical dispersion and chemical reaction on ground-water transport are not included in the analysis.

Particle-tracking simulations can outline the aquifer area contributing recharge to a pumping well and the aquifer volume composing the zone of contribution to a pumping well (fig. 1.3). The “area contributing recharge” is defined as the surface area of the ground-water system that delineates the location of water entering the ground-water system that eventually flows to the well and discharges. This area must provide an amount of recharge that balances the amount of water being discharged from the well (Franke and others, 1998). Thus, lower areal recharge rates result in larger contributing areas (Franke and others, 1998). The “zone of contribution” is the three-dimensional volumetric part of the aquifer through which ground water flows to the discharging well from the area contributing recharge. If the zone of contribution intercepts a surface-water body, the area contributing recharge is reduced and its size is a function of areal recharge rate and surface-water leakage (Franke and others, 1998). Depending on the screen placement of the well and local ground-water

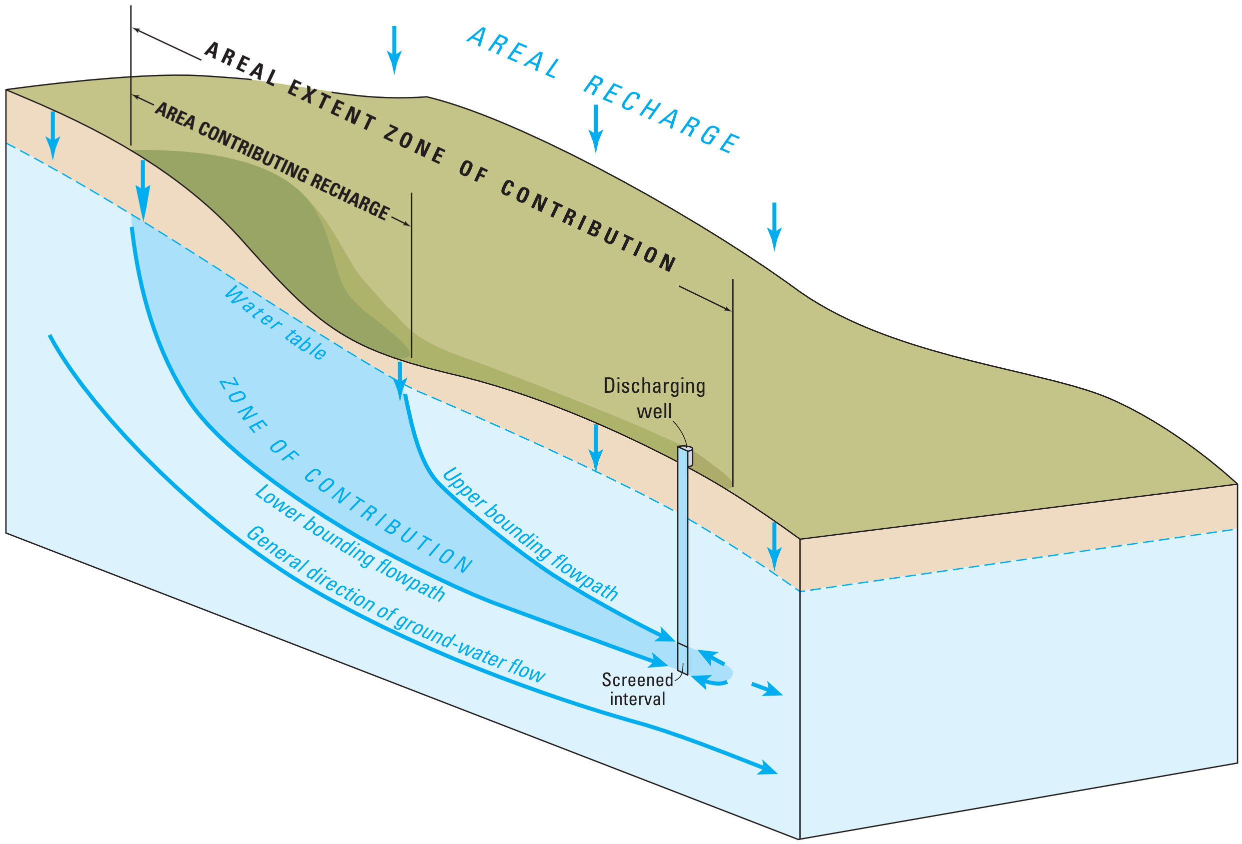

Figure 1.3. Area contributing recharge and zone of contribution for a single discharging well in a simplified hypothetical ground-water system.

flow conditions, the area contributing recharge to a well does not necessarily have to include the location of the well. The vertical projection of the zone of contribution to the land surface is termed the "areal extent of the zone of contribution" (USGS Office of Ground Water Technical Memorandum No. 2003.02, *http://water.usgs.gov/admin/memo/GW/gw03.02.html*, accessed June 15, 2004). Zones of contribution and their areal extents will always include the location of the well.

Because of the regional scale of the models used in this study, special consideration was given to the treatment of weak sinks in the determination of contributing areas. A weak sink is a model cell (representing a well, for example) with an insufficient discharge rate to capture all ground-water flow entering the cell; thus, some of the flow leaves the cell across one or more cell faces. Particle flow paths calculated for a weak-sink cell cannot be uniquely defined because it is impossible to know whether a specific water particle discharges to the weak sink or passes through the cell (Spitz, 2001).

Weak sinks cause problems with associating a given amount of water with each particle. MODPATH offers three options for dealing with weak sinks. Particles can be stopped when they reach a weak sink, allowed to pass through weak sinks, or stopped if the percentage of flow entering the model cell that is captured by the weak sink exceeds a user-supplied threshold (Pollock, 1994). Table 1.2 shows the effects of the first two options. Effects of the third option would be some combination of the other two options.

The approach of grid refinement described by Spitz (2001) was used in TANC particle-tracking simulations to better represent particle movement through weak sinks (see discussions on weak sinks in preceding paragraphs and table 1.2). The grid-refinement approach creates a MODFLOW model of the weak-sink cell (fine model) so the cell containing the well becomes a strong sink. The boundaries of this fine model are set to a constant flux equal to the flow across each face as simulated in the original (coarse) model. The FORTRAN programs described by Spitz (2001) were altered to allow particles to be transferred from the coarse model to the fine model (to allow for forward particle tracking) and to allow the fine model to represent multiple layers from the coarse model (for the case where a well screen spans several model layers).

A forward particle-tracking approach was used in the MODPATH simulations together with a grid-refinement program (Spitz, 2001) to delineate areas contributing recharge to public-supply wells (see discussions on weak sinks and grid-refinement approach). Particles were started on model-boundary cell faces for cells representing sources of water, forward tracked along path lines, and then were stopped when they reached a weak-sink cell. A fine model was constructed for each weak sink cell, particles were transferred from the coarse model to the fine model and tracked through the model, and then the particles that did not terminate in the fine model were transferred back to the coarse model. The remaining particles then were forward tracked again in the coarse model. This process was repeated until all particles reached a strong sink either in the coarse model or one of the fine models. MODPATH simulations of areas contributing recharge were initially run by starting particles on every boundary cell face of the model with a positive flux of water and tracking particles as previously described. For the final calculation of areas contributing recharge, the particle density for each well was adjusted so that between 100 and 1,500 particles were used to represent the contributing area.

Contributing area results were used to create GIS datasets, which were subsequently used to determine a variety of attributes for each contributing area. The starting locations of particles on a given model-cell face were evenly distributed so a flow could be assigned to each particle equal to the total flow associated with the face divided by the number of particles started on the face. A traveltime also was associated with each particle. For particles associated with recharge from irrigation and(or) precipitation, properties of the landscape (data on land use, census, soils, and potential contaminant sources) were assigned to the particles. Path-line information was combined with descriptions of redox conditions, pH, and geology to determine the environments “experienced” by each particle on the way to the well. To determine average statistics for the entire contributing area, the properties for each particle were weighted by the percentage of the total flow to the well that they represented. A full list of the attributes calculated for the contributing areas is presented in Appendix 1.

Oxidation-Reduction and pH Classification and Mapping

The oxidation-reduction (redox) state of ground water is an important geochemical control on the solubility and mobility of anthropogenic contaminants and naturally occurring trace elements. In aquifers where redox chemistry controls chemical reactions in the system, it is sometimes possible to define redox zones where a dominant redox couple controls the redox potential of the system (Domenico and Schwartz, 1990). Numerous studies have deduced redox conditions in ground water on the basis of concentrations of electron acceptors, intermediate products, and accumulations of final products from terminal electron-accepting processes. However, the lack of an electron acceptor or final product accumulation does not always define the distribution of redox processes and is an admitted limitation of inferring redox state from redox indicator species. For example, a decrease in sulfate concentration and an increase in sulfide concentration would indicate a sulfate-reducing redox zone. However, a decrease in sulfate concentration may not be observed during sulfate reduction if there is a continuous source of sulfate to a system such as gypsum dissolution (Plummer and others, 1990). Similarly, an increase in sulfide concentration may not be observed if metal sulfides are precipitated during sulfate reduction. The measurement of hydrogen concentrations in ground water can be used in conjunction with patterns of electron-acceptor consumption and final-product accumulation to more accurately identify the distribution of terminal electron-accepting processes in ground-water systems (Chapelle and others, 1995).

The TANC regional studies inferred aquifer redox conditions by using concentrations of redox-indicator species from the retrospective water-quality data. A redox-classification system was developed as discussed below, and a “redox environment consistent with redox indicator species” was assigned to each well location based on concentrations of dissolved oxygen, nitrate, manganese, iron, and sulfate (table 1.3). The

Table 1.2. Effects of weak sinks on the determination of contributing areas.

	Water particles stop at weak sink	Water particles pass through weak sink
Forward tracking	First weak sinks encountered can have too many particles, resulting in areas contributing recharge that are too large. Sinks (weak or strong) farther along the flow path may intercept too few particles, resulting in areas contributing recharge that are too small.	No particles associated with weak sink cells. Too many particles reach strong sinks, resulting in areas contributing recharge that are too large. Particles passing through weak sinks effectively lose flow.
Backward tracking	Difficulty in assigning starting particles for weak sinks. Particles that pass back through weak sinks are effectively gaining flow; the resulting area contributing recharge will be too large.	

TANC redox classification system used five general categories to assign redox conditions to individual wells in the TANC regional study areas:

- Conditions consistent with oxygen reduction
- Conditions consistent with nitrate reduction
- Conditions consistent with manganese reduction
- Conditions consistent with iron reduction with high sulfate
- Conditions consistent with iron reduction with low sulfate

Concentration data for these redox-indicator species were commonly available in the retrospective data, and concentration significance levels were used to infer redox conditions for each well location. Hydrogen data were generally not available in the regional retrospective data set. Concentration significance levels for the redox-indicator species followed those presented by Chapelle and others (1995) for dissolved oxygen and nitrate, the Geological Survey of Sweden (*http://www.internat.environ.se/index.php3?main=/documents/legal/assess/assedoc/gndwdoc/aqui.htm*, accessed June 15, 2004) for manganese and iron, and Chapelle and others (2002) for sulfate. The sulfate significance level (4 mg/L) was chosen because Chapelle and others (2002) suggested the threshold sulfate concentration for sulfate reduction may be on the order of 4 mg/L. Thus, once iron-reducing conditions have been achieved and sulfate concentrations drop below 4 mg/L, geochemical conditions likely have progressed well into, if not beyond, sulfate reduction. Such highly-reducing conditions may or may not correspond to methanogenic conditions, but likely do represent a low energy state that may have significance in geochemical investigations.

For this redox classification system, the assumption is made that recharge water contains dissolved oxygen and nitrate at concentrations greater than the significance levels discussed above. Furthermore, the assumption is made that oxidized forms of manganese and iron are available in the aquifer matrix so that manganese and iron are available for reduction. No assumptions are made about initial sulfate concentrations. In this classification system, oxygen-, nitrate-, and manganese-reducing conditions do not depend on sulfate concentrations. This allowance arises from the expectation that sulfate concentrations in recharge water commonly may be either greater than or less than the significance level for sulfate. However, the assumption is made that by the time redox conditions progress to iron-reducing conditions, sulfate will have become available from either recharge area sources or from various aquifer sources (e.g. Hem, 1985). This assumption facilitates the creation of high-sulfate and low-sulfate iron-reducing conditions.

Examples of how the redox classification system was applied follow. If dissolved-oxygen and nitrate concentrations were greater than their respective significance levels, and manganese and iron concentrations were less than or equal to their respective significance levels, a redox classification was assigned consistent with oxygen reduction. If dissolved-oxygen, manganese, and iron concentrations were less than or equal to their respective significance levels, and nitrate concentration was greater than its respective significance level, a redox classification was assigned consistent with nitrate reduction. For the case of dissolved-oxygen, nitrate, and iron concentrations less than or equal to their respective significance levels, and manganese concentration greater than its respective significance level, a redox classification was assigned consistent with manganese reduction. With dissolved-oxygen and nitrate concentrations less than or equal to their respective significance levels, and manganese, iron, and sulfate concentrations greater than their respective significance levels, a redox classification was assigned consistent with iron reduction, high sulfate. Similar water, but with sulfate concentrations less than or equal to its significance level, would be assigned a redox classification consistent with iron reduction, low sulfate. If

Table 1.3. Oxidation-reduction classification scheme.

[DO, dissolved oxygen; NO_3, nitrate; Mn, manganese; Fe, iron; SO_4, sulfate; mg/L, milligrams per liter; mg N/L, milligrams nitrogen per liter: µg/L, micrograms per liter; >, greater than; ≤, less than or equal to; —, not applicable]

Redox category assigned—consistent with indicator species concentrations	Redox indicator species significance level				
	DO 0.5 mg/L	NO_3 0.5 mg N/L	Mn 50 µg/L	Fe 100 µg/L	SO_4 4 mg/L
Oxygen reduction	>	>	≤	≤	—
Nitrate reduction	≤	>	≤	≤	—
Manganese reduction	≤	≤	>	≤	—
Iron reduction with high sulfate	≤	≤	>	>	>
Iron reduction with low sulfate	≤	≤	>	>	≤

more than one redox category was assigned to a sample, the sample was categorized as having a “mixed” redox state.

Redox conditions were mapped at a regional scale using the redox categories assigned to each well, and the maps were discretized using the MODFLOW model grids to calculate traveltime through various redox environments. A wide range of available redox data and redox conditions was observed among TANC study areas, and the redox classification was reduced to two categories in the final particle-tracking analysis: 1) conditions consistent with oxygen or nitrate reduction, and 2) conditions consistent with manganese or iron reduction. The redox classification using retrospective data proved effective for delineating regional redox patterns in all study areas except the Northern Tampa Bay. Redox zones were not mapped for the Northern Tampa Bay regional study area because complex ground-water flow patterns in this karst aquifer resulted in no discernable redox pattern.

The pH of ground water can be another important geochemical control on the mobility of naturally occurring trace elements and anthropogenic contaminants. For example, the adsorption of trace elements onto iron oxides is often a pH-dependent reaction. For the TANC regional study areas, ground-water pH values were grouped into two categories: pH values less than 8 (circumneutral), and pH greater than 8 (high pH). A pH of 8 was chosen, in part, on the basis of the zero point of charge for iron oxide being roughly 8 (Stumm and Morgan, 1981).

Database Development

To conduct a more process-oriented national assessment of the susceptibility and vulnerability of aquifers and public-supply wells than has been previously possible and to complement earlier work such as the U.S. Environmental Protection Agency’s review of contaminant occurrence in public-water systems (U.S. Environmental Protection Agency, 1999), TANC data and results were organized using relational-database software. Information in the TANC database includes retrospective water-quality data, well-construction data, water-use data, geologic data, SWQA water-quality data, ground-water flow model and particle-tracking results, potential contaminant sources within the area contributing recharge of selected public-supply wells, and geochemical classifications of redox and pH. Many of the data-field definitions in the TANC database follow those in the U.S. Geological Survey NWIS database. However, several additional data tables and fields were added to accommodate modeling results, which cannot be stored in NWIS. The TANC database structure is such that additional tables can be added as data collection and analyses proceed.

The database currently (2006) consists of 10 data tables generally linked by a combination of NAWQA TANC Study Unit code and U.S. Geological Survey Site Identification (ID) number, which forms a unique identification number assigned to each well location. Appendix 1 contains data dictionaries for the TANC data tables. The TANC_STUDIES table contains summary information about each TANC study area such as its start date, overall location, area, and general aquifer characteristics. The SITES table contains information specific to each sampling location such as U.S. Geological Survey Site ID, local station name, location, altitude, and site use, and the WELL_INFO table contains well-completion details. The RESULTS_RGNL table contains water-quality analysis results for the regional study areas, and the PARAMETERS table contains parameter-code definitions for the RESULTS_RGNL table. The PUMPING_RGNL table stores information about all pumping centers simulated in each of the TANC regional ground-water flow models. Four tables contain ground-water particle-tracking results and geochemical interpretations. The ANCILLARY table includes the geochemical interpretations of redox conditions as previously discussed in the “Redox and pH Classification and Mapping” section. The CAREASUM_RGNL table contains contributing area and traveltime information for each well calculated from the regional ground-water flow models, as previously discussed in the “Ground-Water Flow Simulation” section, and the CAREARDXPH_RGNL table contains tabulations of ground-water traveltime through redox and pH zones. The CAREASRCE_RGNL table contains a tabulation of the land use, population density, and potential contaminant sources overlying contributing areas.

At the completion of initial data compilation (2003), nearly 196,000 water-quality records from 2,242 sampling locations were included in the TANC database; 129 of these locations had new water-quality data collected as part of the NAWQA SWQA project. Contributing areas were calculated for 405 public-supply wells, and water-quality data were stored in the TANC database for 321 of the 405 public-supply wells with calculated contributing areas.

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