Ground Water Protection Council Annual Forum 2006, Sept. 30 – Oct. 4, 2006, Miami Beach, FL

Knowledge of Where and How Contamination-Susceptible Water Enters Public-Supply Wells Can Be Used To Improve Monitoring Strategies and Protection Plans

M.K. Landon, S.M. Eberts, B.C. Jurgens, B.G. Katz, K.R. Burow, C.A. Crandall, C.J. Brown, and J.J. Starn

Biographical Sketch of Authors

Matthew Landon has been a hydrologist with the U.S. Geological Survey since 1990. He has conducted studies of ground-water hydrology and ground-water quality in Minnesota, Nebraska, and California. He is currently working on studies of transport of anthropogenic and natural contaminants to public supply wells for the National Water-Quality Assessment Program and the California Ground Water Ambient Monitoring and Assessment program.

Sandra Eberts is a Professional Hydrogeologist certified and registered by the American Institute of Hydrology. She has been with the U.S. Geological Survey for over twenty years and is currently team leader of the USGS National Water-Quality Assessment Program Transport of Anthropogenic and Natural Contaminants to Supply Wells (TANC) topical study. Prior to her work on the TANC study, Sandra spent 8 years as a USGS technical liaison to the U.S. Air Force for clean-up of ground-water contamination at weapons manufacturing facilities nationwide.

Bryant Jurgens has been a hydrologist with the U.S. Geological Survey since 2002. His interests include aquifer geochemistry, tracers of ground-water age, and processes that affect the transport and fate of trace elements in ground-water systems.

Karen Burow is a Hydrologist with the US Geological Survey in Sacramento, where she has served as the Ground-Water Specialist for the San Joaquin-Tulare Basins Study Unit of the National Water-Quality Assessment Program since 1992, specializing in local-scale ground-water flow and transport modeling with an emphasis on geologic characterization. She has also authored several publications on the occurrence, distribution and trends in nitrate and pesticides in ground water at both regional and local scales.

Brian G. Katz, PhD, is a research hydrologist with the U.S. Geological Survey in Tallahassee, Florida. During his career with the USGS, he has conducted numerous geochemical studies of processes that control the composition of natural and contaminated waters. His current research involves the use of isotopic and other chemical tracers to quantify hydrochemical interactions between ground water and surface water, determine sources and chronology of contamination in karst aquifers, and assess flow-system dynamics in complex aquifer systems.

Christy A. Crandall is a hydrologist with the U.S. Geological Survey's National Water Quality Assessment Program with training and experience in hydrology and water quality. Since 2002, she has served as project manager and ground-water modeler for the Transport of Anthropogenic and Natural Contaminants to Supply Wells study in Tampa, Florida from its planning phase into full implementation. Christy moved to the U.S. Geological Survey in 1993 from the National Park Service and has worked in a variety of water programs over the last 20 years.

Craig Brown is a hydrologist with the U.S. Geological Survey. His research interests include aquifer geochemistry, geochemical modeling, and processes associated with the transport of natural contaminants and other trace elements.

Jeff Starn has been a hydrologist with the Federal government for over twenty years. He has worked overseas with the Peace Corps, with the USEPA in Region IV, and with the USGS in the Kentucky and Connecticut Water

Science Centers. His current interests include probabilistic ground-water modeling and using combined watershed and ground-water models to help better understand hydrologic processes in glacial/crystalline rock aquifer systems.

Abstract
A USGS investigation into the transport of contaminants to public-supply wells (PSWs) in four distinctly different aquifers demonstrates how differences in the chemistry of water produced by PSWs and nearby monitoring wells can reveal where and how contamination-susceptible water enters PSWs. This knowledge can be translated into improved monitoring strategies and protection plans.

Samples were collected from multiple depths during pumping in selected PSWs. The chemistry of these depth-dependent samples, along with composite samples from the PSWs, was compared to that of adjacent nested monitoring wells. Four examples are given here:

- In the Central Valley aquifer system, comparisons revealed that concentrations of uranium above the drinking water standard are a result of cross contamination between the shallow and deeper parts of the aquifer as a result of downward well-bore flow in the PSW during periods of low or no pumping. Improved water quality at this well probably could be achieved by changes in the PSW's pumping schedules. Similar consideration of the influence of vertical hydraulic head gradients that exist because of regional pumping and reapplication of irrigation water may be useful for improving monitoring and protection strategies throughout this setting.
- In the High Plains aquifer, comparisons revealed that wells and boreholes open to multiple aquifer layers create short-circuit pathways vertically across a confining unit and are responsible for anthropogenic and natural compounds entering the PSW. Strategies for improved protection of PSWs in this setting include locating and altering the open interval of or destroying such multi-layer wells.
- In the Floridan aquifer system, comparisons revealed that the PSW produces water that is more similar to water in the overlying surficial aquifer system than to water from the Upper Floridan aquifer itself due to short-circuiting that results from the co-occurrence of sinkholes and high pumping stresses. As a result, monitoring and protection efforts could largely focus on the surficial aquifer system and the most transmissive zones within the Upper Floridan aquifer in areas where breaches in the confining unit and high pumping stress co-occur.
- In a glacial aquifer, potential sources and pathways throughout the contributing area were consistent with observations near the PSW; the aquifer contains young ground water and is affected by point-source contaminants. Protection plans that focus on determining the distribution and density of point sources of ground-water contamination would substantially contribute to the understanding of the vulnerability of PSWs in this setting.

Although the mechanisms for transport of contaminants to the PSWs vary among these diverse hydrogeologic settings, effective protection strategies require an understanding of the dominant pathways of water contributed to the wells.

Introduction

About one-third of the U.S. population obtains drinking water from public-supply wells (PSWs). The occurrence of contaminants in these wells is highly variable (U.S. Environmental Protection Agency, 1999). To safeguard public health, a better understanding is needed of how these wells can become contaminated. Understanding PSW contamination also is an economic issue because remediating contaminated ground water or replacing supply wells is expensive and difficult.

In 2001, the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program began an intensive study to assess the vulnerability of PSWs to contamination from a variety of compounds (Eberts and others, 2005). The Transport of Anthropogenic and Natural Contaminants to Supply Wells (TANC) study is focusing on the transport and chemical breakdown of selected naturally occurring and anthropogenic contaminants from urban and agricultural sources within that part of the ground-water system contributing water to PSWs. Because subsurface processes and management practices differ among aquifers and public-water systems, PSWs in different parts of the Nation are not equally vulnerable to contamination, even where similar contaminant sources exist. This study is identifying and comparing these important differences, as well as similarities, in a complementary set of aquifer systems, land use settings, and public-water systems, on the basis of data that were collected and analyzed using consistent methods.

Depth-dependent flow and chemistry profiles in pumping supply wells have recently been shown to be an informative technique for understanding sources and pathways for contaminants to supply wells (Izbicki and others, 1999, 2005a, 2005b; Izbicki, 2004; Danskin and Church, 2005). Each TANC study area conducted flow measurements and collected water samples, where possible, at multiple depths from inside a pumping PSW to ascertain where contaminants in the surrounding aquifer enter the PSW screen. In this investigation, "depth-dependent" data from the PSWs were then compared to data from nearby nested monitoring wells screened at different vertical depths in the aquifer system. These comparisons provided additional insight into how contaminants reached the PSWs. This paper briefly describes the results of depth-dependent and monitoring-well sampling in TANC study areas in four different hydrogeologic settings. More importantly, it describes an approach that can be used to gain knowledge of where and how contamination-susceptible water enters PSWs and how such knowledge can be converted into improved monitoring strategies and protection plans, adding another tool to the water managers vulnerability toolbox.

Description of study areas

Investigations were conducted within the contributing area of a single PSW in four study areas in selected aquifers of the United States (USGS, 2003) during 2003-2006 (fig. 1). These local-scale investigations (less than 100 square kilometers) took place in: Modesto, California in the Central Valley aquifer system; York, Nebraska in the High Plains aquifer; Tampa, Florida in the Floridan aquifer system; and in a glacial aquifer in the Pomperaug River Basin, Connecticut. Regional-scale investigations (up to thousands of square kilometers) also were conducted at these locations, as well as in four additional study areas during 2001-2003 (Eberts and others, 2005). Additional local- and regional-scale investigations are currently being conducted in TANC study areas in San Antonio, Texas in the Edwards-Trinity aquifer system, and in Albuquerque, New Mexico in the Rio Grande aquifer system. This paper will focus on local-scale investigations conducted in the Central Valley, High Plains, Floridan, and glacial aquifer study areas. Conceptual illustrations of the aquifer systems in the four study areas are shown in figure 2. The study areas are briefly described below.

The TANC study area in the Central Valley aquifer system is located in Modesto, California, which typifies cities in the San Joaquin Valley having high growth rates resulting in gradual urbanization of adjacent farmlands. Although more than 90 percent of the 1995 water demands for the region were for irrigation, approximately half of the demand for municipal and industrial supply is met by ground water withdrawals. The aquifer sediments in the study area are comprised of a series of overlapping, stacked alluvial fan sequences deposited by streams during Pleistocene glacial cycles (Burow and others, 2004). In the TANC study area, the aquifer is unconfined, although water-bearing layers of sand and gravel become semi-confined with depth owing to numerous, overlapping, discontinuous clay lenses. Percolating irrigation water is the primary form of ground-water recharge, and irrigation pumpage is the primary form of ground-water discharge. As a result, ground water is driven vertically downward within the regional and local flow systems, and water moving laterally may be pumped and reapplied at the surface multiple times (fig. 2a).

The TANC study area in the High Plains aquifer is located in east-central Nebraska around the City of York. The aquifer serves as an important source of water for agricultural irrigation and drinking-water supply throughout the region. Although ground-water withdrawals for public supply are small in comparison with withdrawals for irrigation, ground water is the source of drinking water for 100 percent of the people in the area. The aquifer is composed locally of layered Quaternary alluvial deposits with unconfined and confined sands as the primary water-bearing units. Many irrigation and some commercial and older supply wells are screened in both the unconfined and confined layers. Irrigation withdrawals from the confined layer result in large downward hydraulic head gradients, creating conditions where water from the unconfined layer can move downward to confined layers through wellbores that cross the confining unit (fig. 2b).

The TANC study area in the Floridan aquifer system is located in west-central peninsular Florida in the central Tampa Bay region. The Tampa metropolitan area, as well as a significant portion of the southeastern U.S., relies heavily upon the Upper Floridan aquifer as a source of drinking water. The Upper Floridan aquifer is overlain by another aquifer, the surficial aquifer system. The Upper Floridan aquifer and the surficial aquifer system are separated by a clay-rich intermediate confining unit. A number of localized surface or buried depressions called sinkholes disrupt this layered geologic framework. Breaches in this clay unit result from localized subsidence activity that occurs when the underlying limestone dissolves, causing the collapse of overlying clay layers. Many of these breaches in the intermediate confining unit serve as preferential flow paths to the underlying Upper Floridan aquifer (fig. 2c). The Upper Floridan aquifer consists of limestone and dolomite, which contains many solution-enlarged fractures that commonly yield large supplies of water to wells. Precipitation provides the majority of recharge to the Upper Floridan aquifer.

The TANC study area in Connecticut is located near the eastern edge of the region typified by sand and gravel aquifers of glacial origin. The study area is in the Pomperaug River Basin where most water for public supply is obtained from wells completed in glacial aquifer deposits, which are mostly less than 30 meters thick. Characteristics of the selected aquifer system are similar to many glacial aquifer systems in the region that encompasses much of the populated parts of New England, northern New Jersey, and eastern New York. The primary inflow to the aquifer system is direct recharge from precipitation, and the primary outflow is discharge to streams (fig. 2d). Upland surface and shallow subsurface runoff also is an important source of water to this glacial aquifer system. Inflow from underlying Mesozoic bedrock of relatively low permeability is a minor source of water. High recharge rates, high permeability, and relatively thin sand units result in relatively rapid ground-water travel times through the aquifer--nearly all ground-water in the local-scale study area has a residence time less than 25 years.

Methods

The differences between the aquifers studied provide an opportunity to compare, across a range of settings, where and how contamination-susceptible water enters PSWs. In all four study areas, a network of short-screened monitoring wells was installed throughout the area contributing recharge to the selected PSW, including one well nest located adjacent to the supply well itself. Areas contributing recharge to the PSWs were estimated using ground-water flow models (Kauffman, 2006). Criteria used to select the PSWs for investigation included representative and well-understood hydrogeologic, land use, and operational conditions and the presence of detectable anthropogenic and natural compounds of concern. Samples were collected and analyzed for a broad suite of analytes, including water temperature, specific conductance, pH, dissolved oxygen, major and trace elements, nutrients, volatile organic chemicals (VOCs), pesticides, age-dating tracers, radium isotopes and radon, arsenic species, and isotopes of oxygen, hydrogen, nitrogen, sulfur, carbon, and uranium.

Because of the wide range of pumping rates, screen lengths, well diameters, and hydrogeologic characteristics of the PSWs studied, approaches for collecting depth-dependent flow and chemistry data in the PSWs had to be customized to the different study areas. In the Central Valley and High Plains study areas, the tracer pulse method of Izbicki and others (1999) was used to collect flow profiles through the PSW. This technique uses a narrow diameter hose (1.25 centimeter (cm) outside diameter) that can be used in wells with limited access, which differs from typical geophysical or flowmeter methods of obtaining downhole information that require 7.5 cm or more of clearance down the well. The dye-injector hose was lowered into the well casing during pumping and fluorescent dye was injected at regular depth intervals. The fluorescence of water was measured in the discharge at the wellhead, and the time of travel between the injection and arrival of the fluorescent dye at the wellhead was recorded. The differences in time-of-travel between each measurement interval were used to calculate the velocity of the water at different screen intervals.

Samples were collected from 5 depths in each of these two PSWs under typical pumping conditions; sample depths were selected to bracket screen intervals having large flow contributions. Although the tracer pulse apparatus can be used to collect samples, a submersible pump was used to collect the samples from the different depths. In the Central Valley study area, some samples were collected with a 5-cm diameter submersible pump and some were collected using a small-diameter positive displacement pump developed for depth-dependent sampling by Izbicki and others (2004). In the High Plains study area, samples were collected using a 2-cm diameter bladder pump. Water samples also were collected from the PSW wellhead under normal pumping conditions in all study areas during the period when depth-dependent sampling was done.

In the Floridan study area, the PSW is an uncased borehole in karstic limestone of variable diameter. Consequently, the tracer pulse method could not be used for flow profiling because it requires that the diameter of the hole be constant and known. Instead, geophysical approaches were used to characterize flow in the borehole, which required that the supply well turbine pump be temporarily removed. Geophysical measurements were made in the PSW borehole to obtain detailed information on well diameter, aquifer properties, rock lithology and solution features, dominant flow zones, permeability, and water quality (J.H. Williams, USGS, oral commun., 2004). Logs included caliper, gamma, spontaneous potential, fluid resistivity, temperature, flowmeter, and optical televiewer. On the basis of geophysical measurements made in the wellbore, three depths were targeted for sample collection under both pumping and non-pumping conditions. Water samples were collected from these three intervals using a Grundfos submersible pump (pumping rate approx. 3.8 liters/minute (L/min)) under two conditions, one with a large-capacity submersible pump lowered to 38 meters (m) (set the same place as regular pump intake) and a pumping rate of 1,320 L/min (compared to approximately 2,650 L/min for the turbine pump), the other with no pumping (ambient conditions).

Depth-dependent samples could not be collected in the PSW in the glacial aquifer study area in Connecticut because of well access limitations and a short well screen (4.6 m long), making it difficult to resolve vertical differences in chemistry within the PSW. Samples from the monitoring well nest installed adjacent to the PSW were used to understand vertical changes in chemistry near the PSW. This nest of wells includes three wells with 0.6 to 1.0-m-long screens, one completed near the water table about 4 m below land surface, one completed just above the top of the PSW screen and one completed near the center of the PSW screen. Geophysical logging and field parameter profiling in a borehole that was located adjacent to, and spanned the length of, the PSW's screened interval also was conducted. Measurements included profiles of temperature, specific conductance, dissolved oxygen, and flow using an electromagnetic (EM) flowmeter under pumping and ambient conditions.

Results

Central Valley Study Area

The PSW selected for study in the Central Valley aquifer system was drilled in 1961 to a depth of approximately 115 m. It is screened from 27.7 m to 111.2 m below land surface (bls) with an open bottom (fig. 3), and was pumped at a rate of approximately 5,700 L/min (1,500 gallons/minute (gpm)) at the time of the depth-dependent measurements; this pumping rate is within the range of normal operating conditions for this well. On the basis of monitoring-well data and the long screened interval, the water discharged from the well is a mixture of water from three depth zones: shallow-intermediate, deep-intermediate, and deep zones within the aquifer system. The age of the water varies widely, from less than 50 years in the shallow-intermediate aquifer zone to thousands of years in the deep aquifer zone.

Two velocity profiles of the PSW were done to quantify the proportion of water contributed to the well from each of these zones. Flow from the shallow-intermediate zone is less than 20 percent of the total, with the deep-intermediate zone comprising about 55 percent, followed by 25 percent of flow from the deep zone below 80 m. Because the pump intake is located at approximately 47 m bls, water entering the well above this depth flows downward, while water entering the well below the pump intake flows upward.

Although the majority of water discharged from the well is primarily from the deep-intermediate and deep zones (roughly 80 percent), the chemistry of water from the shallow-intermediate zone had a substantial impact on the overall water quality under some circumstances. The water chemistry from the shallow-intermediate PSW depth sample was consistent with the type, number, and concentration of organic and inorganic compounds found in the adjacent monitoring wells screened in the shallow-intermediate zone. The shallow-intermediate sample had the highest specific conductance and the highest alkalinity, nitrate, sulfate, arsenic, and uranium concentrations of the PSW depth-dependent samples, as well as the highest concentrations and number of detections of VOCs (4) and pesticides (3). Concentrations of constituents in depth-dependent samples generally decreased with increasing depth, although the deepest sample had higher concentrations and numbers of detections of organic compounds and higher concentrations of inorganic constituents than the deep-intermediate depth samples. The occurrence of organic compounds in this deep zone sample was similar to that detected in the shallow-intermediate zone.

Because the concentrations and numbers of detections of organic and inorganic constituents in the PSW deep zone samples were higher than those observed in deep aquifer zone monitoring wells, it is hypothesized that the long-screened interval of the PSW acts as a conduit for flow from the shallow-intermediate aquifer zone to the deep aquifer zone during periods of low or no pumping at the PSW, resulting in the water chemistry in the deep aquifer zone surrounding the well to be periodically influenced by the water chemistry of the shallow-intermediate zone (Burow and others, 2005). Data from a continuous recorder of hydraulic head and specific conductance installed in the adjacent deep monitoring well supports this hypothesis. The monitoring well FPA-4 is located less than 40 m away from the PSW and is screened between 104.5 and 106.1 m bls. During summer months (peak pumping) the specific conductance and hydraulic head in FPA-4 was at a minimum, whereas hydraulic head and specific conductance increased dramatically during winter months when pumping from the

PSW was at a minimum. Concentrations of organic and inorganic constituents were greater in the deep monitoring well following periods of little or no pumping of the PSW than following periods of extensive pumping of the PSW. This result is consistent with leakage of shallow water having relatively higher concentrations of these constituents downward in the PSW during periods of low or no pumping, leading to the temporary storage of water from the shallow-intermediate zone in the deep aquifer zone surrounding the PSW.

Seasonal sampling data in the PSW indicates that the water chemistry in the shallow-intermediate zone has historically had a profound impact on water-quality samples taken from the PSW as well (Burow and others, 2005). Nitrate concentrations in samples collected from the PSW since 1966 have been significantly higher in samples collected during the winter season (October through May) than nitrate concentrations in samples collected during the summer. Similar effects are seen in uranium concentrations from samples since 1989; median uranium concentrations from winter samples have been higher than the median of summer samples. When pumping is increased during summer to meet increased demand, the stored water is evacuated from the deep aquifer zone surrounding the PSW. For the remainder of the summer, water from the shallow-intermediate zone is diluted by inflow of unaffected waters from the deeper zones and the overall concentration in the PSW decreases. Comparison of vertical chemistry profiles in the PSW and adjacent monitoring wells was a key step in discerning the mechanism producing periodically high uranium concentrations in the PSW.

High Plains Study Area

The PSW selected for study in the High Plains aquifer was installed in 1977. The geology at the PSW, characteristic of that throughout the study area, is strongly layered, with a shallow unconfined sand-and-gravel layer separated from an upper confined fine sand that is the principal unit providing drinking water for public supply (fig. 4). The intervening silty clay till confining unit is found throughout the study area. The selected PSW is screened only in the upper confined layer, has an 18-m-long screen, and pumps at about 1,900 L/min (500 gpm). The pump intake is located above the well screen so that all water within the screened interval flows vertically upward during pumping, and samples collected at discrete depths represent a composite of all of the water entering the well below the sampling point.

Samples collected from the PSW wellhead, which integrates water from the entire screened interval within the upper confined sand layer, contained concentrations of the VOCs tetrachloroethylene (PCE) and trichloroethylene (TCE), and uranium that were below drinking-water standards but of concern as indicators of contamination. The velocity profile for this PSW indicates that only 25 percent of the flow in the well comes from the bottom half of the screened interval (fig. 4). Depth-dependent sampling indicated that most contaminants enter the PSW in the bottom half of the screened interval, where only about 25 percent of the total inflow to the well originates. For most constituents, concentrations in the depth-dependent samples were greatest at a depth near the mid-point of the screened interval. Figure 4 shows concentrations of PCE as an example, but similar profiles were observed for many other tracers and constituents, including uranium, major ions, TCE, oxygen ($\delta^{18}O$) and hydrogen (δD) isotopes, radium isotopes, and radon. Above the middle of the screened interval, concentrations decreased as they were diluted by inflow of waters having lower concentrations.

The chemistry of the depth-dependent and wellhead samples from the PSW can be explained as mixing of contamination-susceptible waters from the unconfined sand-and-gravel layer with mostly contaminant-free waters from the upper confined sand layer. Results from depth-dependent sampling showed a clear contrast between water entering the bottom half of the screened interval and many other confined water samples, including monitoring wells in the upper confined layer adjacent to the PSW, and most confined-layer monitoring wells further upgradient.

Chemical and isotopic data revealed that samples from unconfined and confined layers of the aquifer are chemically distinct (Landon and others, 2006). However, a small number of confined-layer monitoring-well samples have chemical compositions intermediate between unconfined and confined water samples, and show evidence of mixing of unconfined and confined waters. The depth-dependent samples similarly have intermediate compositions between some unconfined water samples and confined waters. Mixing calculations indicate that up to 50 percent of the depth-dependent sample from the middle of the screened interval was water from the unconfined sand-and-gravel layer (fig. 4). The unconfined mixing fraction decreased to about 10 percent at the wellhead, at which inflow had been integrated from the entire screened interval. Samples in some confined-layer monitoring wells upgradient of the PSW represented mixtures of up to 85 percent unconfined-layer waters. However, most of the confined-layer monitoring wells contained little or no unconfined-layer water.

Results suggest that preferential flow paths that permit water from the unconfined sand-and-gravel layer to recharge directly to the confined sand layer exist in several places within the contributing area of the PSW. The evidence of mixing in some monitoring wells completed in the confined sand layer, along with the PSW wellhead and depth-dependent sample results, suggests the presence of unconfined-layer waters in the confined sand layer is not likely a result of cross-wellbore flow in the supply well itself. If leakage down the PSW wellbore, which is screened only in the confined layer, was the mixing mechanism, unconfined water would be expected to be present in greatest abundance near the top of the screened interval, and unconfined waters would not be expected to be present in other confined-layer monitoring wells.

The existence of irrigation, commercial, and older PSWs that are screened in both the unconfined and confined layers likely permit water leakage from the unconfined to confined layer. Large vertical downward hydraulic-head gradients are present between the unconfined and confined layers that result from confined-layer withdrawals, particularly summer irrigation. The measured chemical, isotopic, and age-distribution data from this study substantiate that conduits exist that allow movement of water and contaminants from the unconfined layer to the confined layer. Results of a numerical ground-water-flow and solute-transport model are consistent with an interpretation that the vulnerability of the PSW to contamination is dependent upon preferential pathways and transient seasonal vertical-head gradients in the aquifer system (Clark and others, 2006). The simulations indicate that about 25 percent of the water flow through the confining layer separating the unconfined and confined layers moves through boreholes rather than as leakage through the confining layer itself. Although unidentified natural discontinuities also could permit preferential flow through the 5 to 15-m-thick apparently continuous confining unit, such discontinuities were not detected in test holes drilled in this or previous studies. Sampling results from depth-dependent work in the supply well and monitoring wells, in combination with simulation results, and physical data, led to the conceptual model of the system shown in figure 2b, which shows multilayer wells as conduits for movement of contamination-susceptible water to depths where PSWs are screened.

Floridan Study Area

The PSW selected for study in the Floridan study area has an open borehole completion in the Upper Floridan aquifer from 36-53 m bls, and is pumped at a rate of about 2,500 L/min (660 gpm). It produces water, in part, from a high yielding cavernous zone described by Stewart and others (1973); caliper and televiewer logs collected for this study revealed large solutional openings in the Upper Floridan aquifer limestone at depths of 49-53 m in the PSW. Geophysical logs were used to identify three zones of high ground-water inflow to the well (38, 43, and 49 m bls), and water samples were collected during pumping and non-pumping conditions at these depths to evaluate the effect of pumping on the quality of the water produced by the PSW. Samples represented a composite of water that entered the well at and below each sampling point.

Sampling results indicate that the highly transmissive zone at 49-53 m likely is hydraulically connected to the surficial aquifer system, and receives a mixture of water from the surficial aquifer system and the Upper Floridan aquifer. Specifically, there were substantial differences in the concentrations of chemical constituents at this and the other sampled depth intervals, whereas there were similarities between samples from this depth and samples from monitoring wells in the surficial aquifer system (Katz and others, 2006). Water samples from the 49-53 m zone collected during nonpumping conditions contained higher concentrations of nitrate, orthophosphate, radon, atrazine, and chloroform and lower concentrations of strontium, iron, manganese, dissolved solids, and some isotopic tracers than water collected from other depth zones. Concentration differences for these constituents between the 49-53 m zone and the other zones are consistent with water that moves downward from the surficial material into the highly transmissive zone in the Upper Floridan aquifer.

It is likely that pumping of ground water by the PSW and other wells in the immediate area enhance the rapid downward movement of surficial aquifer system waters containing various contaminants to the PSW. Concentrations of anthropogenic (nitrate, chloroform) and naturally-occurring (arsenic, radon) contaminants were higher during pumping (stressed) conditions than during non-pumping conditions but did not exceed maximum contaminant levels for drinking water.

Isotopic and other chemical signatures in multiple water samples collected from the PSW during 2002-2005 consistently pointed to a mixture of water from the surficial aquifer system and the Upper Floridan aquifer. Geochemical mass-balance models indicate that the proportion of surficial aquifer system water produced by the PSW was somewhere between 30 to 62 percent (Katz and others, 2006). The extensive chemical results for this study area, along with the geophysical logs from the PSW, indicate that the PSW—open solely to the Upper

Floridan aquifer—intersects a highly transmissive zone in the Upper Floridan aquifer that is hydraulically connected to the overlying surficial aquifer system and parts of the intermediate confining unit. Comparison of depth-dependent-sampling results in the PSW with monitoring-well results were the key interpretative tools allowing the mechanisms for contaminant movement to the PSW to be identified.

Glacial Aquifer Study Area

The PSW that was selected for study in the glacial aquifer was installed in 1967 to a depth of 18.3 m in this glacial aquifer setting, and is pumped at a rate of about 270 L/min (72 gpm). Although the PSW is located adjacent to the Pomperaug River, results of a ground-water flow model and geochemistry data, indicate that the water produced at the PSW is not under the direct influence of surface water.

Concentrations of VOCs in samples collected at the PSW wellhead were intermediate between concentrations in monitoring wells screened near the top and middle of the PSW's screened interval (13.7 to 18.3 m bls). Mixing calculations based on $\delta^{18}O$ and δD suggest that the water in the PSW was predominantly composed of water with a similar isotopic composition as water in the monitoring well screened near the top of the PSW screen, with only minor contributions from water located near the center of the screened interval.

Flowmeter (EM) measurements in a 20.7 m deep borehole that was located near the PSW showed increased upward flow during ambient conditions in two discrete zones adjacent to the top and bottom of the PSW screen. These zones coincided with coarse material (sand and gravel) defined by the geophysical log and by core sample descriptions. The flow diminished almost completely during production-well pumping, altering the natural upward gradient, but preferential flow during ambient conditions can affect the quality of the supply well. Measurements taken with a water-quality monitor lowered down the borehole showed an increase in temperature and specific conductance and a decrease in dissolved oxygen concentrations in the lowermost high permeability zone. This interval is located near the bottom of the supply well screen, and these results suggest that the stratified nature of the deposits leads to zones that are sufficiently more permeable than adjacent zones, and that are likely the primary pathways for ground-water flow. These zones of preferential flow can be very thin (<0.1 m) and may not be adequately assessed with monitoring wells alone.

Analysis of water-quality data from monitoring wells and boreholes near the PSW suggest that there may be variability in aquifer chemistry over short vertical intervals near the PSW. These vertical variations in aquifer chemistry are thought to be the consequence of both heterogeneities in the aquifer deposits and the presence of upgradient point sources of contaminants. Sampling results from nested monitoring wells located throughout the zone of contribution to the PSW were consistent with the results from near the PSW, indicating that the water quality in this setting is primarily influenced by the distribution of point sources, such as septic systems, solvent or fuel leaks or spills (Brown and others, 2006), and aquifer characteristics.

Discussion

In three of the four aquifers included in this study (Central Valley aquifer system, High Plains aquifer, Floridan aquifer system) the combination of depth-dependent sampling in pumping PSWs and in nearby monitoring wells revealed that PSW vulnerability is strongly influenced by movement of contamination-susceptible water along short-circuit pathways to the well screens. Contamination-susceptible water is ground water that was recharged in the modern or industrial era and is more likely to contain contaminants introduced during this period than is older ground water. In general, development of ground-water systems for water supply induces changes in hydraulic gradients and vertical ground-water velocities, leading to pathways with shorter residence times than would be expected under more natural conditions. Short-circuit pathways can further reduce travel times by allowing water to bypass aquifer or aquitard materials that it would otherwise flow through. These short-circuit flowpaths can be man-made (wells) or natural (breaches in a confining layer), and knowledge of their influence in a given setting can be critical to understanding the vulnerability of PSWs to contamination in that setting.

In spite of having very different hydrogeologic settings, in both the High Plains and Upper Floridan aquifers, anthropogenic contaminants primarily reached the selected PSW by moving along short-circuit pathways that bypass relatively low permeability confining layers under the influence of local or regional pumping stress. Such confining layers would have otherwise protected the lower layers to a greater degree from contaminants in the overlying unconfined layers. Whereas the short-circuit pathways are primarily natural features in the Floridan aquifer system, they are primarily man-made features (wellbores) in the High Plains aquifer. Where intact, the confining layers in the Floridan and High Plains study areas not only restrict the downward movement of potentially contaminated ground water affected by surficial land use, but can facilitate degradation of contaminants. For example, geochemical and isotopic mass balance studies on core samples in the confining layers of the Floridan and High Plains study areas suggest that nitrate is completely denitrified in the confining unit of both systems (McMahon and others, 2005). In the Floridan study area, the combination of local pumping stress from PSWs and breaches in the confining layer result in vertical movement of contamination-susceptible water from the surficial aquifer system. In the High Plains study area, vertical movement of water occurs as a result of regional pumping stress resulting primarily from irrigation withdrawals in the confined layer; while local pumping stress could contribute to vertical movement of contamination-susceptible water from the unconfined layer, it is not necessary for a local pumping stress to be present for vertical movement of water from the unconfined to the confined layer to occur if wellbores crossing confining layers are present. Thus, the presence of natural breaches or man-made holes in confining layers in combination with local or regional pumping stress are critical factors increasing the vulnerability of PSWs to contamination in both the Floridan and High Plains study areas.

In the Central Valley study area, the vertical movement of poor quality water from shallow to greater depths was the result of downward flow of water in the wellbore of the PSW itself during periods of low or no pumping (Burow and others, 2005). The poor quality water was temporarily stored at depth in the adjacent aquifer and flushed out at the initiation of greater pumping rates, sporadically increasing concentrations of chemicals of concern. While the details of where wellbore leakage occurred and how the water quality at the PSW was affected differed between the Central Valley and High Plains study areas, in both areas, wellbores crossing relatively low permeability confining or semi-confining layers served as short-circuit pathways for contamination-susceptible shallow ground-water to affect the quality of the water produced by the PSW.

Although short-circuit pathways were not identified in the glacial aquifer study area, ground water throughout this setting can be considered to be relatively vulnerable to contamination when compared to other study areas because of the combination of high recharge rates and small aquifer thickness (less than 45 m), resulting in relatively short residence times. As a result, poor quality water has the potential to reach PSWs relatively quickly and vertical changes in water quality are likely to reflect the distribution of highly conductive aquifer materials and sources of contamination. In comparison, the shallow, poor-quality portion of the Central Valley aquifer system is about 45 m deep, and ground water has a residence time of about 10 to 40 years. However, because the aquifer is much thicker (more than100 m) than the glacial aquifer, PSWs are typically screened over long intervals and thus poor quality water is mixed with older, unaffected water. With the exception of the short-circuiting through the wellbore and short term storage of affected water near the bottom of the well, PSWs in the Central Valley study area are less vulnerable to rapid degradation due to inputs at the land surface than PSWs in the glacial study area.

The approach of collecting samples from multiple depths during pumping in selected PSWs combined with collection of samples from adjacent nested monitoring wells within the contributing area of the PSWs enabled pathways of contaminants to the PSWs to be identified in four study areas. Collection of samples from different depths in PSWs has been previously employed to understand where contaminants enter PSWs, as well as to interpret sources of the contaminants (Izbicki and others, 2005a, 2005b). For this study, the addition of monitoring-well data provided further insight into the mechanisms and flowpaths linking contaminant sources and PSWs. It is not unusual for samples collected from PSW wellheads to indicate at least trace levels of contaminants, even in PSWs that have deep completions, sometimes in confined aquifer systems. Depth-dependent sampling in a pumping PSW provides information on where contaminants likely enter the PSW screen. Combining this depth-dependent data with data from monitoring wells adjacent to the PSW and further upgradient in the contributing area can provide a context in which to interpret how the contaminants got to the PSW well screen. For example, depth-dependent sampling results from the Central Valley and High Plains study areas both indicated contaminant occurrences near the bottom of the PSW. However, results from monitoring wells provided the supporting data that indicated that the contaminants were moving down the PSW wellbore during periods of low pumping in the Central Valley study area; in contrast, the monitoring-well data in the High Plains study area indicated that the contaminants were moving down wellbores further upgradient in the flow system rather than in the PSW wellbore itself.

Implications for Monitoring and Protection

Knowledge of where, why, and how contamination-susceptible water enters PSWs can be used to improve monitoring strategies and protection plans. In the Central Valley study area, reduction of cross contamination between shallower and deeper parts of the aquifer system within the PSW wellbore during periods of low or no pumping could be achieved by changes in pumping schedules at the well. Longer periods of pumping during winter months could help prevent contamination of the deep aquifer zone. Monitoring strategies could be modified to include seasonal sampling to identify effects of wellbore leakage and short-term aquifer-storage. Similar consideration of seasonal pumping effects may be useful for improving monitoring and protection strategies throughout this setting. In the High Plains study area, protection plans could include identifying active wells screened above and below the confining layer and modifying their construction to prevent vertical leakage, or properly abandoning such wells. In addition, careful review of historical records could reveal locations of unsealed wells abandoned before proper well abandonment procedures were practiced. Monitoring strategies could include additional depth-dependent sampling in PSWs and suspected wellbore leakage zones to refine understanding of locations of vertical movement of poor quality water across confining layers throughout this setting. In the Floridan study area, the knowledge that PSW vulnerability is strongly linked to both surficial-aquifer system chemistry and PSW pumping rates as a consequence of breaches in confining units could be used to focus monitoring and protection efforts on the surficial aquifer system and the most transmissive zones in the Upper Floridan aquifer in areas of high-density PSW pumping. In the glacial aquifer study area, vertical variations in water chemistry near the PSW and the surrounding aquifer are likely the result of the distribution of point sources of contamination combined with aquifer heterogeneity. Preferential flow along coarse-grained lenses may result in short-circuit flowpaths for contaminants, but to a lesser extent than the other study areas where the range of ground-water age is much wider. Protection plans that focus on determining the distribution and density of point sources would substantially contribute to understanding the vulnerability of PSWs in this setting to contamination.

References

Brown, C.J., McMahon, P., and Starn, J., 2006, Effects of organic carbon distribution on redox chemistry in a glacial aquifer, Woodbury, Connecticut [abs.]: 2006 National Monitoring Conference: Posters, May 7-11, 2006, San Jose, California, available online at http://oh.water.usgs.gov/tanc/pubs/Brown_NWQMC_Abstract.doc

Burow, K.R., Jurgens, B., Dalgish, B.A., and Shelton, J.L., 2005, Effects of well operation on quality of water from a public-supply well in Modesto, California [abs.]: GSA Annual Meeting, Oct. 16th-19th, 2005, Salt Lake City, Utah, available online at http://oh.water.usgs.gov/tanc/pubs/BurowEtal05.pdf

Burow, K.R., Shelton, J.L., Hevesi, J.A., and Weissmann, G.S., 2004, Hydrogeologic characterization of the Modesto area, San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2004-5232, 54 p.

Clark, B.R., Landon, M.K., Kauffman, L.J., and Hornberger, G.Z., 2006, Simulations of solute movement through wellbores to characterize public supply well contaminant vulnerability in the High Plains Aquifer, York, Nebraska in Proceedings of MODFLOW and More 2006: Managing Ground-Water Systems, May 22-24, 2006: Golden, Colo., International Ground Water Modeling Center, available online at http://oh.water.usgs.gov/tanc/pubs/Clark_MF2006_paper.pdf

Danskin, W.R., and Church, C.D., 2005, Determining age and vertical contribution of ground water pumped from wells in a small coastal river basin: U.S. Geological Survey Open-File Report 2005-1032, 4 p.

Eberts, S.M., Erwin, M.L., and Hamilton, P.A., 2005, Assessing the vulnerability of public-supply wells to contamination from urban, agricultural, and natural sources: U.S. Geological Survey Fact Sheet 2005-3022, 4 p., accessible online at http://pubs.usgs.gov/fs/2005/3022/

Izbicki, J.A., Christensen, A.H., and Hanson, R.T., 1999, U.S. Geological Survey combined well-bore flow and depth-dependent water sampler: U.S. Geological Survey Fact Sheet 196-99, 2 p.

Izbicki, J.A., Christensen, A.H., Newhouse, and Aiken, G.R., 2005a, Inorganic, isotopic, and organic composition of high-chloride water from wells in a coastal southern California aquifer: Applied Geochemistry, 20, 1496-1517.

Izbicki, J.A., Christensen, A.H., Newhouse, M.W., Smith, G.A., and Hanson, R.T., 2005b, Temporal changes in the vertical distribution of flow and chloride in deep wells: Ground Water, v. 43, no. 4, 531-544.

Izbicki, J.A., 2004, A Small-Diameter Sample Pump for Collection of Depth-Dependent Samples from Production Wells Under pumping Conditions: U.S. Geological Survey Fact Sheet 2004-3096, 2 p.

Katz, B.G., Crandall, C.A., McBride, W.S., and Berndt, M.P., 2006, Use of Multiple Tracers and Geochemical Modeling to Assess Vulnerability of a Public Supply Well in the Karstic Upper Floridan Aquifer [abs.]: 2006 National Monitoring Conference: Concurrent Session F: F3-Assessing Ground Water Vulnerability Through Mechanistic Methods II, May 7-11, 2006, San Jose, California, available online at http://oh.water.usgs.gov/tanc/pubs/Katz_NWQMC_Abstract.doc

Kauffman, L., 2006, Comparison of intrinsic susceptibility of public-supply wells to contamination among selected regional aquifer systems [abs.]: 2006 National Monitoring Conference: Concurrent Session F: F3-Assessing Ground Water Vulnerability Through Mechanistic Methods II, May 7-11, 2006, San Jose, California.

Landon, M.A., Clark, B.R., and Christensen, A.H., 2006, Depth-Dependent Sampling to Determine Source Areas and Short-Circuit Pathways for Contaminants to Reach Public Supply Wells, High Plains Aquifer, York, Nebraska [abs.]: 2006 National Monitoring Conference: Concurrent Session F: F3-Assessing Ground Water Vulnerability Through Mechanistic Methods II, May 7-11, 2006, San Jose, California, available online at http://oh.water.usgs.gov/tanc/pubs/Landon_NWQMC_Abstract.doc

McMahon, P., Bohlke, J.K., Brown, C., Burow, K., Crandall, C., and Landon. M., 2005, Use of isotopes, age-dating, and numerical simulation to evaluate source histories and transport of NO_3 to public supply wells in principal aquifers of the United States [abs.]: 6th International Symposium on Applied Isotope Geochemistry, September 11-16, 2005, Prague , Czech Republic, available online at http://oh.water.usgs.gov/tanc/pubs/Mcmahonetal05.htm

Stewart, J.W., Goetz, C.L., and Mills, L.R., 1978. Hydrogeologic factors affecting the availability and quality of ground water in the Temple Terrace area, Hillsborough County, Florida: U.S. Geological Survey Water-Resources Investigations 78-4, 38 p.

U.S. Environmental Protection Agency, 1999, A review of contaminant occurrence in public water systems: USEPA Office of Water, EPA 816-R-99-006, 78 p.

U.S. Geological Survey, 2003, Principal aquifers of the 48 conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands, available online at http://www.nationalatlas.gov/mld/aquifrp.html

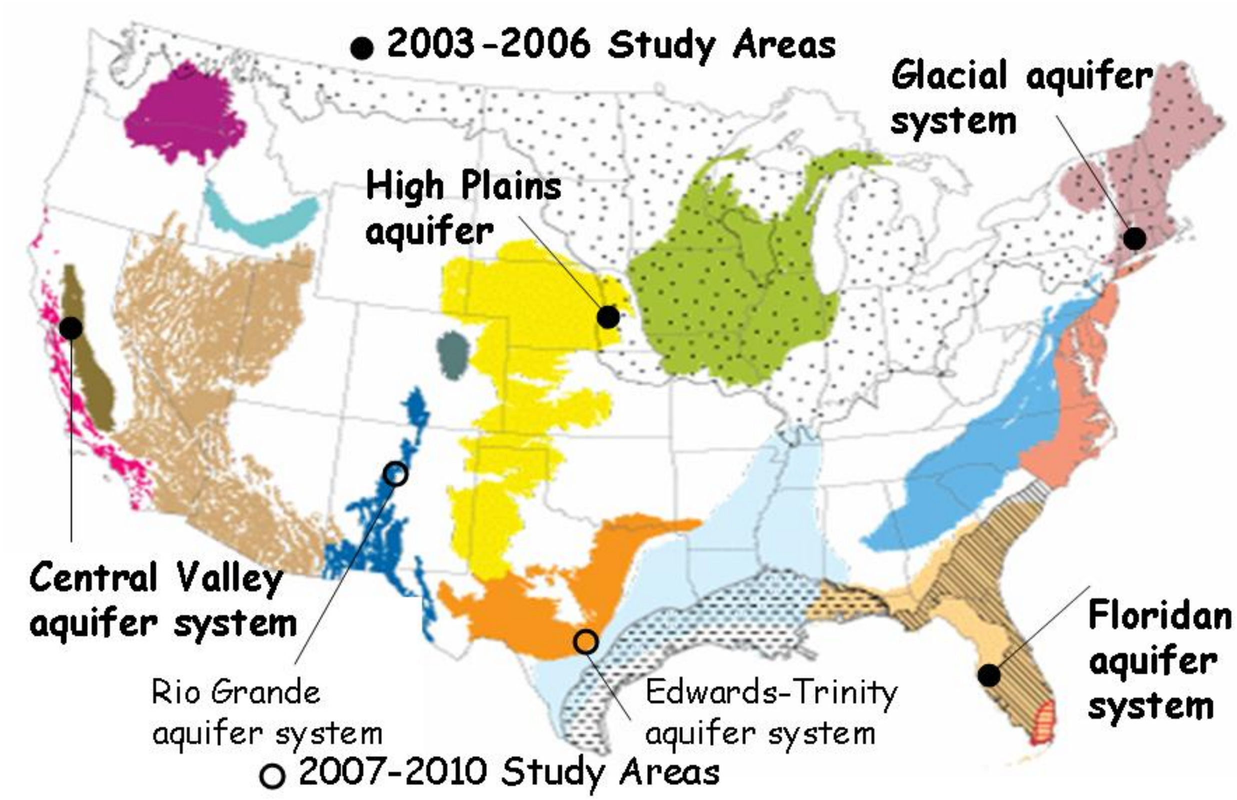

Figure 1. Study areas of the National Water Quality Assessment Program's study of transport of anthropogenic and natural contaminants to supply wells.

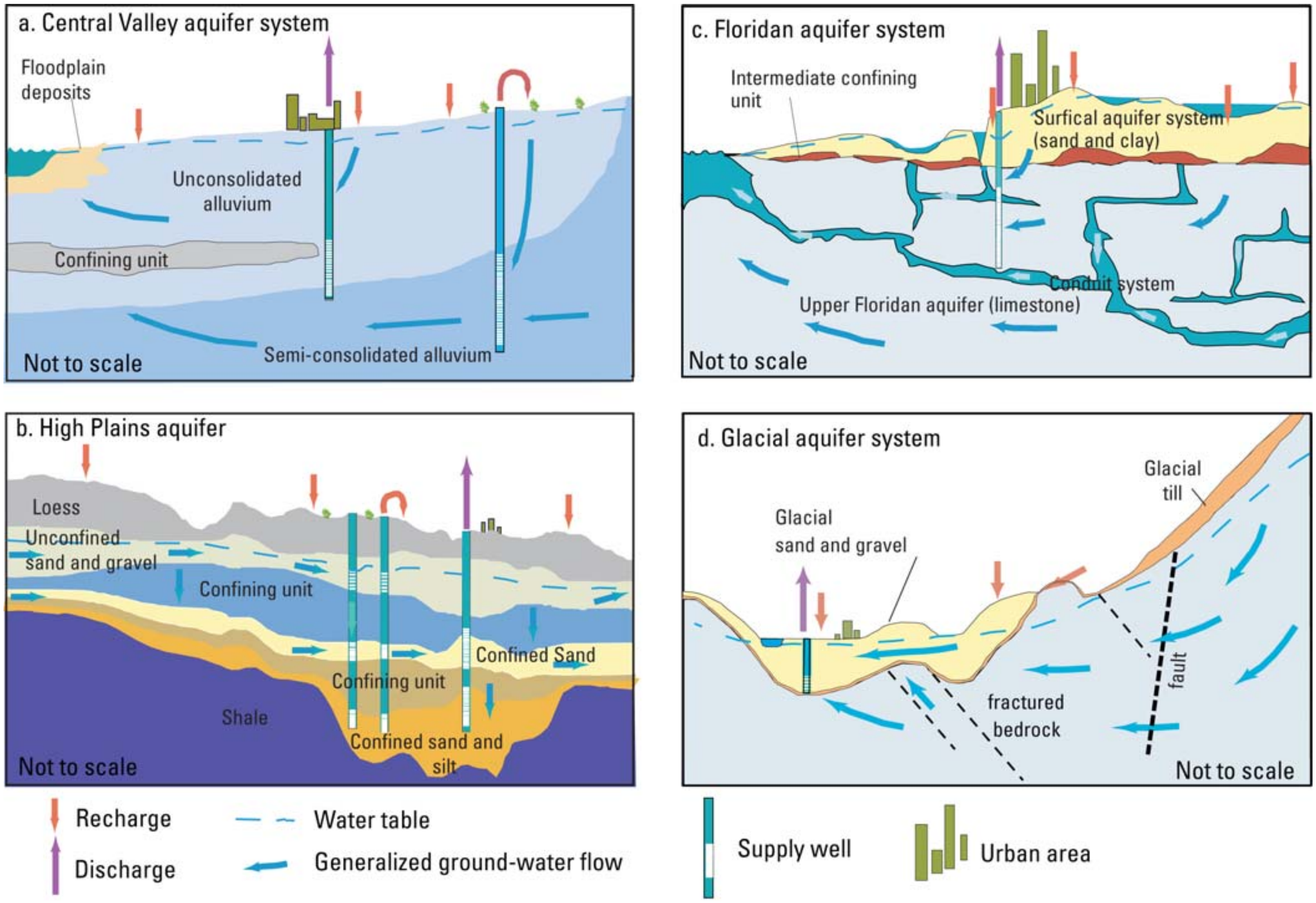

Figure 2. Conceptual models of ground-water flow in four aquifers included in a USGS investigation of transport of anthropogenic and natural contaminants to public-supply wells.

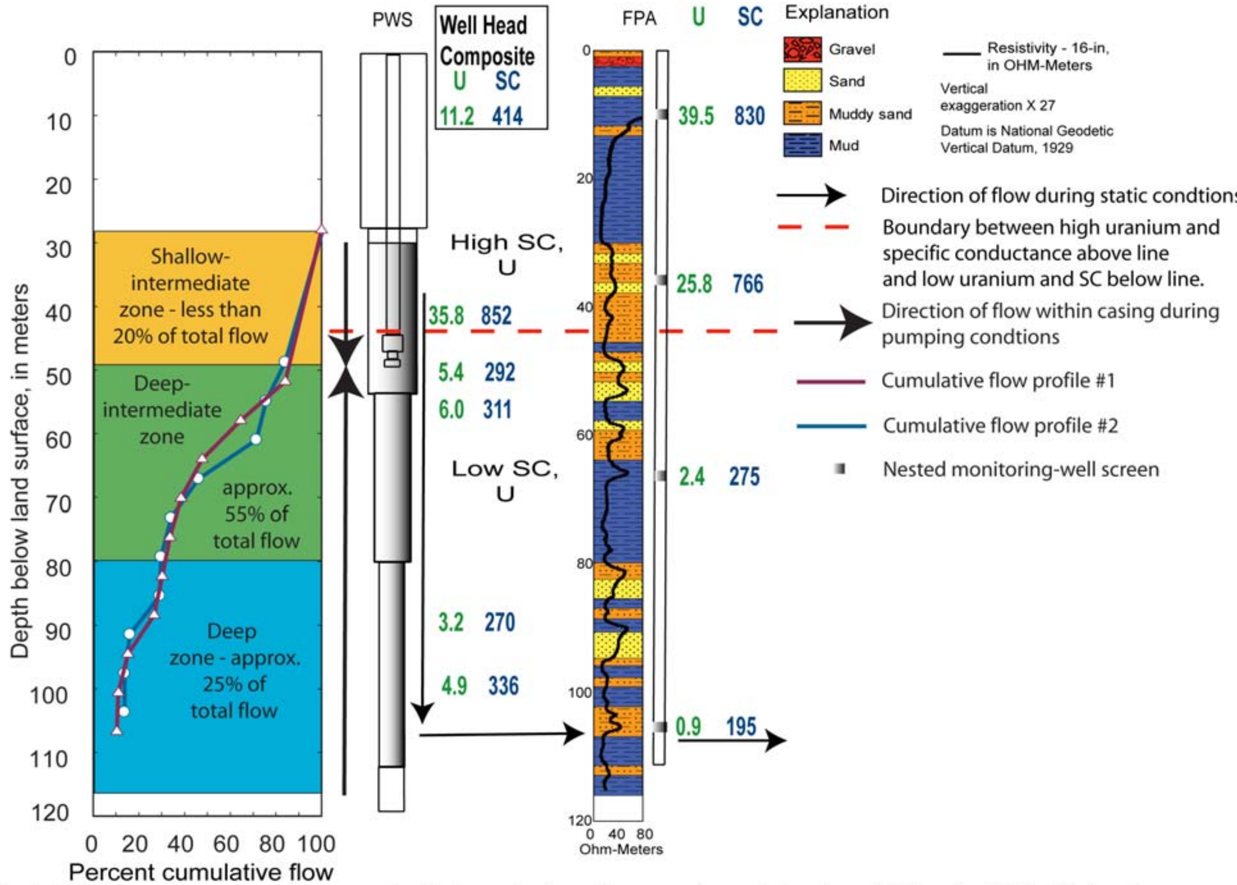

Figure 3. Central Valley aquifer system study area depth-dependent results: percent cumulative flow at 6.1 meter (20 feet) intervals and approximate distribution of flow contributed from the shallow-intermediate, deep-intermediate, and deep aquifer zones,uranium (U) concentrations (micrograms per liter) and specific conductance (SC) measurements (microSiemens per centimeter at 25 degrees celsius) from depth-dependent samples and ground-water samples collected from the monitoring well nest (FPA) adjacent to the public-supply well.

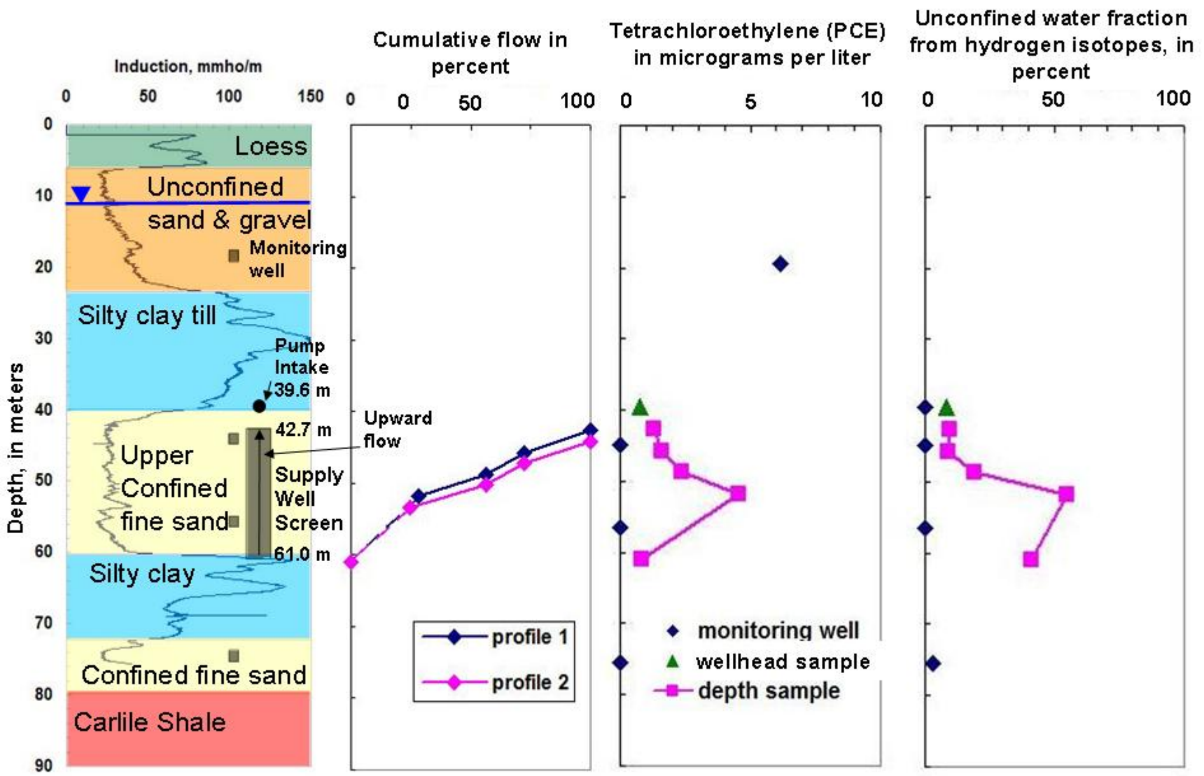

Figure 4. High Plains aquifer study-area depth-dependent results: lithology, induction log, and well construction, percent cumulative flow in public-supply well screened interval, PCE concentrations, and unconfined water fraction from mixing fractions with hydrogen isotopes.