Depth-dependent sampling to identify short-circuit pathways to public-supply wells in multiple aquifer settings in the United States

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Abstract Depth-dependent water-quality and borehole flow data were used to determine where and how contamination enters public-supply wells (PSWs) at study sites in different principal aquifers of the United States. At each of three study sites, depth-dependent samples and wellbore flow data were collected from multiple depths in selected PSWs under pumping conditions. The chemistry of these depth-dependent samples, along with samples of the surface discharge from the PSWs, was compared to that of adjacent nested monitoring wells. The results of depth-dependent analyses from sites in Modesto (California), York (Nebraska), and Tampa (Florida) are summarized and compared. Although the exact mechanisms for transport of contaminants to the PSWs varied among these hydrogeologic settings, in all three settings the presence of wells or boreholes or natural preferential flow paths allowed water and contaminants to bypass substantial portions of the aquifer and to reach PSWs or depths in the aquifer more quickly than would have occurred in the absence of these short-circuiting flow paths. The chemistry and flow data from multiple depths was essential to developing an understanding of the dominant flow paths of contaminants to PSW in all three settings. This knowledge contributes to developing effective strategies for monitoring and protection.

Keywords Groundwater monitoring · Groundwater protection · Borehole leakage · Depth-dependent sampling · USA

Introduction

About one-third of the U.S. population obtains drinking water from public-supply wells (PSWs) (Hutson et al. 2004). The occurrence of contaminants in these wells is variable and often unpredictable (U.S. Environmental Protection Agency 1999). To safeguard public health, a better understanding is needed of how wells can become contaminated. Understanding PSW contamination is also an economic issue because remediating contaminated groundwater or replacing supply wells is expensive and difficult.

In 2001, the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program began a study to assess the vulnerability of PSWs to contamination from a variety of constituents (Eberts et al. 2005). The Transport of Anthropogenic and Natural Contaminants to Supply Wells (TANC) study is focused on the transport and geochemical processes affecting selected anthropogenic and naturally occurring contaminants within that part of the groundwater 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. This study identifies and compares the effect of differences, as well as similarities, in hydrology, well-construction practices, and land-use settings, on contaminant movement to wells in a complementary set of aquifer systems on the basis of data that were collected and analyzed using consistent methods (Eberts et al. 2005).

Depth-dependent flow and chemistry profiles in pumping supply wells have been shown to be useful for understanding sources and pathways for contaminants to supply wells (Collar and Mock 1997; Gossell et al. 1999; Izbicki et al. 1999, 2003, 2005a, 2006, 2008; Danskin and

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Church 2005; Hanson 2005). Some of these studies have included comparisons of depth-dependent sampling results in PSWs with those in nearby monitoring wells (Izbicki et al. 1998, 2005b). However, depth-dependent profiles in PSWs and multiple monitoring wells have not been used previously to compare flow paths that facilitate contaminant movement to wells (hereafter referred to as short-circuit pathways) in complex aquifers having varied hydrogeologic characteristics.

Short-circuit pathways in the saturated zone can be man-made (e.g., wells) or natural (e.g., breaches in a confining layer) and result in reduced travel times of water having impaired water quality to PSW by allowing water to bypass aquifer or aquitard materials that would otherwise restrict its movement. While movement of water and contaminants along preferential flow paths in the unsaturated zone can greatly influence contaminant loading to the water table (Selker et al. 1999; Gurdak et al. 2008), only the effects of short-circuit pathways in the saturated zone on the quality of water withdrawn from PSW are hereafter discussed in this paper. The effects of short-circuit pathways in the saturated zone on groundwater quality and supply have been discussed in previous studies. Gass et al. (1977) described cases of groundwater contamination caused by abandoned wells. Hydrologic methods to identify abandoned wells were described by Aller (1984) and Javandel et al. (1988). Santi et al. (2006) described potential pathways that allow shallow aquifers to cross-contaminate deeper aquifers and discussed hydraulic, geochemical, and geophysical approaches for identifying these potential pathways. Chesnaux et al. (2006) described a field method for characterizing hydraulic short-circuit pathways in defective borehole seals. Silliman and Higgins (1990) and Avci (1992) described analytical solutions for calculating the flow rate in a borehole between two aquifers. Lacombe et al. (1995), Konikow and Hornberger (2006), and Zinn and Konikow (2007) investigated the effects of leaky boreholes on solute and age distribution in layered aquifers using numerical models. Modeling investigations have identified vertical leakage through multilayer wells as a process that can influence the water balance of confined aquifers on a regional scale (Williamson et al. 1989; Hanson et al. 2004; Hart et al. 2006). In other areas, movement of water through boreholes has been shown to be a locally important source of groundwater contamination even if the quantity of water is only a minor source of recharge to deeper aquifers (Izbicki et al. 2003). Redistribution of solutes as a result of vertical flow along long-screened wells has been described by Reilly et al. (1989), Gosselin et al. (1994), Church and Granato (1996), and Reilly and LeBlanc (1998). With respect to natural short-circuit pathways, Renken et al. (2005) described the results of tracer tests to identify preferential flow paths to PSW in a karst aquifer. However, the use of depth-dependent chemistry and flow data in PSW under pumping conditions to identify short-circuit pathways to PSW was not discussed in previous literature related to identification and effects of short-circuit pathways.

Each TANC study area conducted flow measurements and collected water samples at multiple depths from inside a pumping PSW to ascertain where contaminants in the surrounding aquifer enter the PSW. In this investigation, depth-dependent chemical data from the PSWs were then compared to data from nearby nested monitoring wells screened at different depths in the aquifer system. This paper summarizes the results of depth-dependent and monitoring-well sampling in TANC study areas in three different hydrogeologic settings, and discusses how these data provided insight into where and how contamination-susceptible water enters PSWs in diverse settings.

Description of study areas

Depth-dependent investigations were conducted within the simulated zone of contribution (ZOC) of a single PSW in three study areas in selected aquifers of the United States (USGS 2003) during 2003-2006 (Fig. 1). The ZOC is the three-dimensional volumetric part of the aquifer through which groundwater flows from the contributing recharge area to the discharging well (Morrissey 1989). These local-scale investigations (less than 100 km^2) took place in Modesto, California in the Central Valley Aquifer system; York, Nebraska in the High Plains Aquifer; and near Tampa, Florida in the Floridan Aquifer system (Eberts et al. 2005). Conceptual illustrations of the aquifer systems in the three study areas are shown in Fig. 2. The study areas are briefly described below.

The Modesto study area in the Central Valley Aquifer system is typical of cities in the San Joaquin Valley having high population growth rates resulting in gradual urbanization of adjacent farmlands. More than 90% of the 1995 water demands for the region were for agricultural irrigation. However, approximately half of the demand for municipal and industrial supply is met by groundwater withdrawals. The aquifer in the study area is comprised of a series of overlapping, stacked alluvial fan sequences deposited by streams during Pleistocene glacial cycles (Burow et al. 2004). In the Modesto 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. Irrigation return water is the primary form of groundwater recharge, and irrigation pumping is the primary form of groundwater discharge. As a result, groundwater is driven vertically downward within the regional and local flow systems (Burow et al. 2007), and water moving laterally may be pumped and reapplied at the surface multiple times (Fig. 2a). The PSW selected for study (Fig. 3a) was drilled in 1961 to a depth of approximately 115 m. It is screened from 27.7–111.6 m below land surface (bls) and was pumped at a rate of approximately 5,700 l/min (1,500 gallons/min (gpm)) at the time of the depth-dependent measurements; this pumping rate is within the range of normal operating conditions for this well.

The York study area in the High Plains Aquifer is located in east-central Nebraska. The aquifer is a source of water for agricultural irrigation and drinking-water supply

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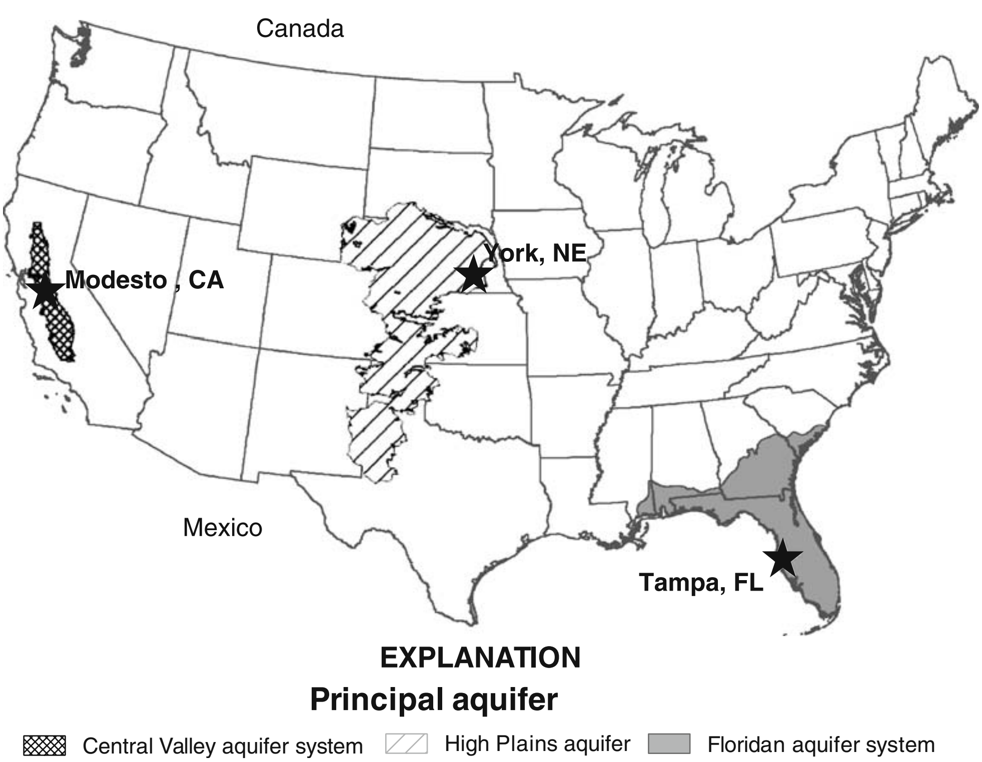

Fig. 1 Location of the principal aquifers and communities where public-supply wells were studied. *CA* California; *NE* Nebraska; *FL* Florida

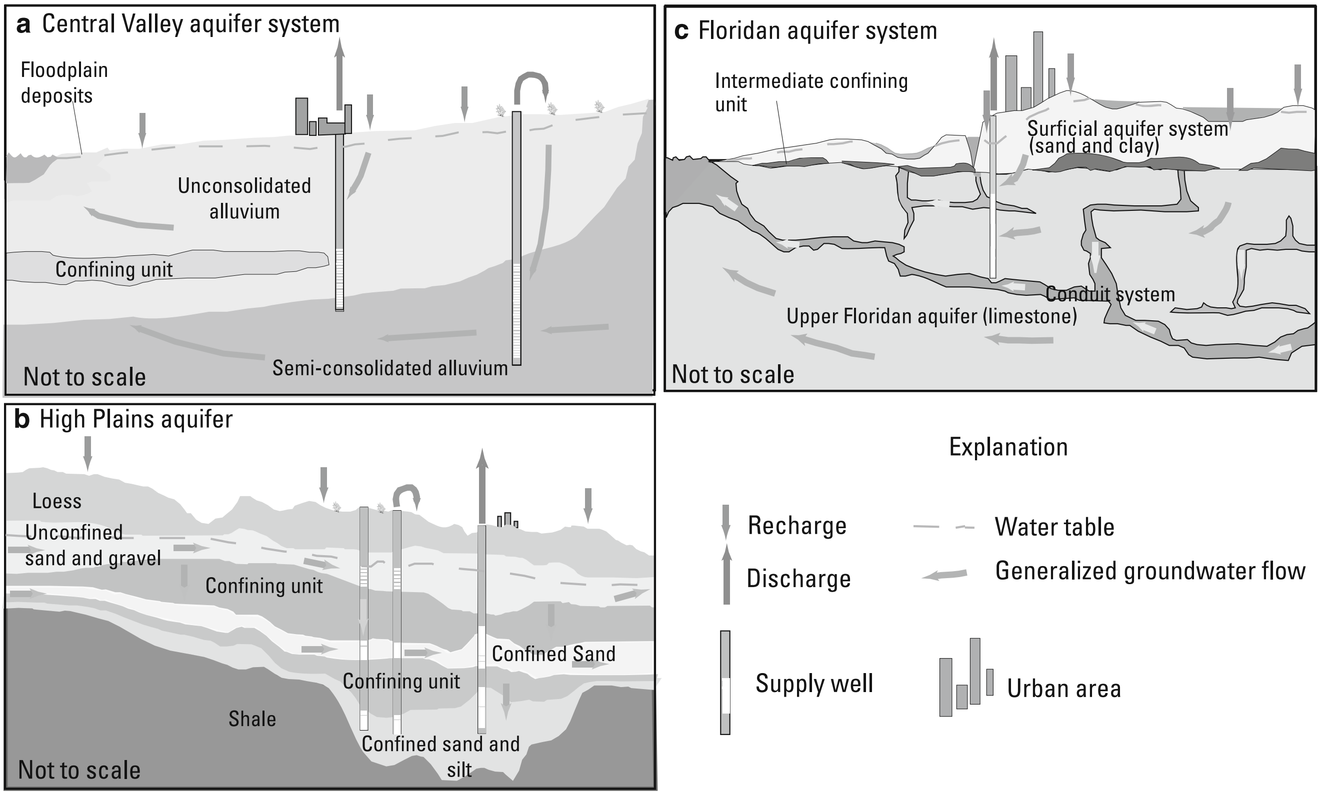

Fig. 2 Conceptual models of groundwater flow in the three study areas investigated: **a** Central Valley Aquifer system. **b** High Plains Aquifer. **c** Floridan Aquifer system

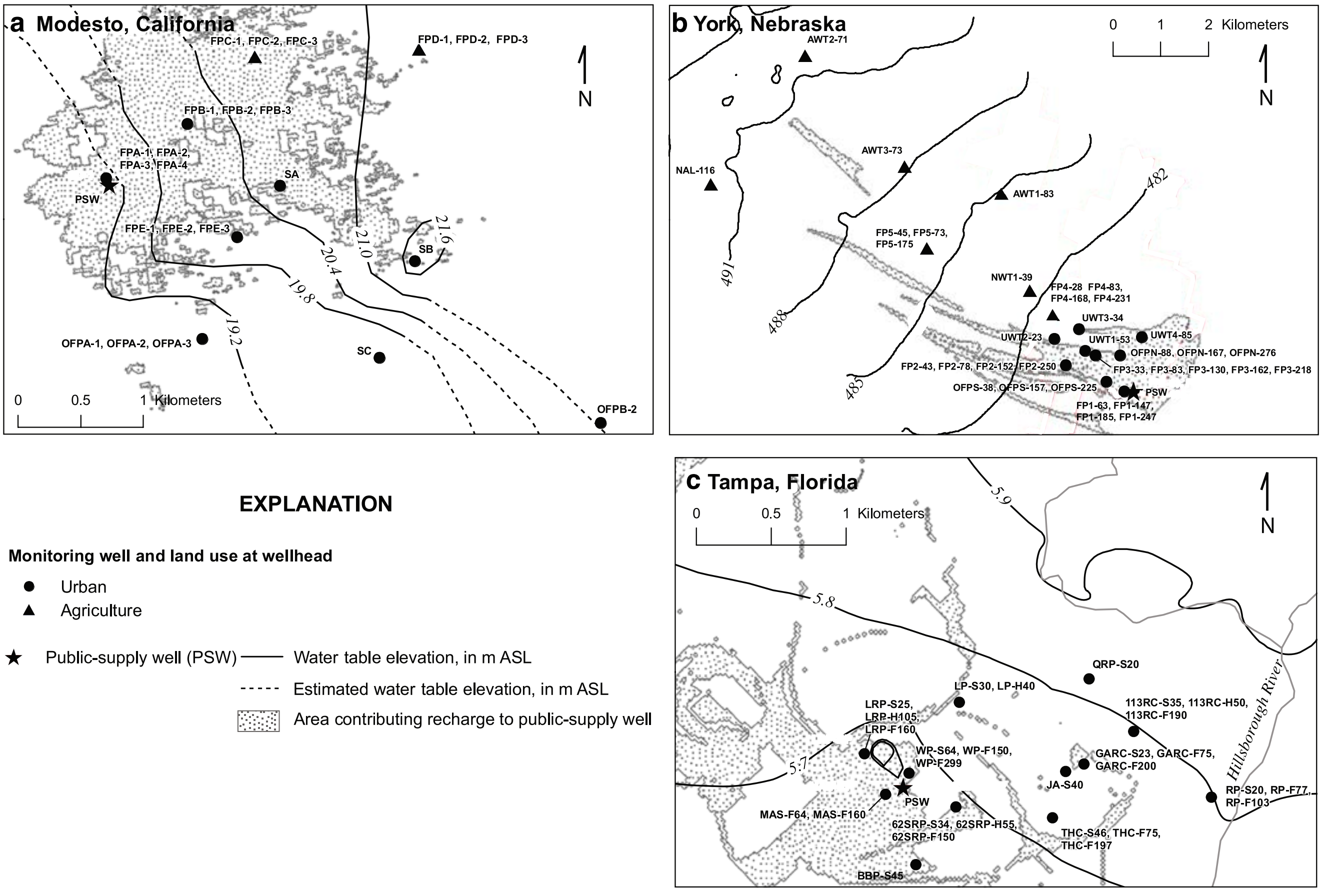

Fig. 3 Maps of the three study areas, showing public-supply and monitoring well locations, water-table elevations, and simulated areas contributing recharge to the study public-supply wells: **a** Modesto, California. **b** York, Nebraska. **c** Tampa, Florida

throughout the region. Although groundwater withdrawals for public supply are small in comparison to withdrawals for irrigation, groundwater is the sole source of drinking water for 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, some commercial, and older public-supply wells are screened in both the unconfined and confined aquifers within the High Plains Aquifer. Irrigation withdrawals from the confined aquifer result in large downward hydraulic head gradients, creating conditions where water from the unconfined aquifer can move downward to the confined aquifer through boreholes that cross the confining unit (Fig. 2b). The PSW selected for study (Fig. 3b) 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 aquifer separated from an upper confined fine sand aquifer that is the principal unit providing drinking water for public supply. The intervening silty clay till confining unit is found throughout the study area. The selected PSW is screened only in the upper confined aquifer from 42.7–61.0 m bls and was pumped at a rate of about 1,900 l/min (500 gpm) during data collection and under normal operating conditions.

The Tampa 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 a surficial aquifer system. The Upper Floridan Aquifer and the surficial aquifer system are separated by a discontinuous clay-rich 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 sediments. 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. Rainfall and downward movement from the surficial aquifer provides the majority of recharge to the Upper Floridan Aquifer. The PSW selected for study in the Floridan study area (Fig. 3c) has an open borehole completion in the Upper Floridan Aquifer from 36–53 m bls, and is typically pumped at a rate of about 2,500 l/min (660 gpm).

Methods

In all three study areas, a network of short-screened monitoring wells was installed throughout the ZOC to the selected PSW (Fig. 3), including one multiple monitoring well site located adjacent to the PSW itself. ZOCs to the PSWs were estimated using groundwater flow models (Burow et al. 2008; Clark et al. 2008; Crandall et al. 2009). 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: field parameters (water temperature, specific conductance, pH, dissolved oxygen); major and minor elements (11 constituents); trace elements (22 constituents); nutrients (five constituents); volatile organic chemicals (VOCs, 88 constituents); pesticides and pesticide degradates (83 constituents); age-dating tracers (tritium, noble gases [including helium-3, helium-4, neon], carbon-14, sulfur hexafluoride, chlorofluorocarbons); radium isotopes and radon; arsenic species (arsenate, arsenite); and isotopes of water (oxygen [δ^{18}O], hydrogen [δD]), nitrate (δ^{15}N, δ^{18}O) sulfur (δ^{34}S), carbon (δ^{13}C), and uranium (^{234}U, ^{238}U, ^{235}U). Groundwater samples were collected from wells using procedures described by Koterba et al. (1995) and the USGS National Field Manual (U.S. Geological Survey, variously dated). Water samples were processed on-site in a mobile laboratory using methods designed to minimize changes to the water-sample chemistry. Sample bottles were preserved according to the requirements of the various laboratory methods and included chilling, filtration, and (or) chemical treatment (U.S. Geological Survey, variously dated). Sampling equipment was cleaned after samples were collected at each well to prevent cross-contamination between wells (U.S. Geological Survey, variously dated). Additional samples were collected to evaluate the reliability of sample collection and analysis procedures. Approximately 15% of the total samples analyzed were quality-control samples including blanks, replicates, and spikes. All samples analyzed for organic constituents were analyzed for surrogate compounds to monitor laboratory method performance. Data collection methods are described in more detail for the Modesto study area by Jurgens et al. (2008), the York study area by Landon et al. (2008), and the Tampa study area by Katz et al. (2007).

Samples were collected from monitoring wells, at different depths in the PSW during pumping conditions (and non-pumping [ambient] conditions in the Tampa, Florida study area), and from the surface discharge of the PSW. “Surface-discharge sample”, the terminology of Izbicki et al. (2005a, 2005b), is used hereinafter to describe samples collected from the flow of the entire PSW at the wellhead near land surface, integrating flow from all screened depths. Depth-dependent, surface-discharge, and adjacent monitoring well samples were collected from the York, Nebraska study area in June 14-21, 2004, Modesto, California during August-September 2004, and Tampa, Florida during October 21–28, 2004.

Depth-dependent flow and chemistry collection

Because of the wide range of pumping rates, well construction, 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 Modesto and York study areas, the tracer-pulse method of Izbicki et al. (1999) was used to collect flow profiles through the PSW. This technique uses a high pressure hose, having an outside diameter of 1.25 cm, which can be used in wells having limited access, and differs from typical geophysical or flowmeter methods of obtaining borehole flow data that require 7.5 cm or more of clearance to enter the well. The high pressure hose was lowered into the well casing during pumping and fluorescent dye was injected into the wells at regular depth intervals. The fluorescence of water was measured continuously in the discharge at the wellhead using a fluorimeter, and the time of travel between the injection and arrival of the fluorescent dye at the wellhead was recorded. The difference in time-of-travel between injection depths was used to calculate the velocity of the water between the injection depths (Izbicki et al. 1999). In the Modesto PSW, tracer pulse tests were done in two profiles, each consisting of measurements at ten depths, typically 6.1 m apart, between 49 and 108 m bls (Jurgens et al. 2008). In the York PSW, tracer-pulse tests were done in two profiles, each consisting of measurements at six or seven depths, typically 3.0 m apart, between 42.7 and 61.0 m bls (Landon et al. 2008).

Samples were collected from five depths in each of these two PSWs under typical pumping conditions; sample depths were selected to bracket screen intervals having large flow contributions determined on the basis of borehole flow data. A submersible pump was used to collect the samples from the different depths. In the Modesto PSW, some samples were collected with a 5-cm diameter submersible pump and some were collected using a small-diameter gas displacement pump developed for depth-dependent sampling (Izbicki 2004). In the York PSW, samples were collected using a 2-cm diameter bladder pump. Water samples were also collected from the surface discharge under normal pumping conditions in all study areas during the period when depth-dependent sampling was done.

In the Modesto PSW, the pump intake was located at approximately 47 m bls; water entering the well above this depth flowed downward, while water entering the well below the pump intake flowed upward. In the York and Tampa PSWs, the pump intake was located above the well screen or open borehole so that all water within the PSW flowed 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.

The depth-dependent chemistry data was used to check whether the depth-dependent flow estimates were consistent with reasonable solute concentrations in aquifer inflow. The concentration of a constituent in water that entered the well from the aquifer between sample-collection points was calculated, assuming simple mixing within the well, according to the equation of Izbicki et al. (1999, 2005b). For the purposes of constraining estimates of concentrations in aquifer inflow and to bound uncertainties in the borehole flow profile, flow values were modified until aquifer inflow concentrations were reasonable for most constituents, particularly conservative constituents such as $\delta^{18}O$, δD, and chloride. These adjusted flow values determined from chemical mixing were not unique but were constrained by maintaining calculated flows as close as possible to measured values at the pump intake and the tracer-pulse test depths.

In the Tampa 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 a uniform borehole diameter. 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 (Katz et al. 2007). Borehole geophysical logs collected as part of this study included caliper, gamma, spontaneous potential, fluid resistivity, temperature, flowmeter, and optical televiewer. On the basis of borehole geophysical logs, three depths (38 m, the depth of the pump intake; 49 m, just above a high-flow zone into the borehole; and 43 m, approximately half-way between the top and bottom sample depths) were selected for sample collection under both pumping and non-pumping conditions. Water samples collected during pumping and ambient conditions at 38, 43, and 49 m represented a composite of water that entered the well at and below each sampling point. Water samples were collected from these three intervals using a Grundfos submersible pump (pumping rate approx. 3.8 l/min under two conditions, one with a large-capacity submersible pump lowered to 38 m (set the same place as regular pump intake) and a pumping rate of 1,320 l/min (compared to approximately 2,500 l/min for the turbine pump), the other with no pumping (ambient conditions).

Adjacent monitoring wells

Groundwater samples were collected from multiple monitoring wells screened at different depths in the aquifer adjacent to the PSW during the same week as depth-dependent sample collection. The adjacent multiple-depth monitoring well sites in the Modesto (FPA, four wells) and York (FP1, four wells) study areas were located <40 m and <30 m, respectively, from the PSW; the adjacent monitoring well site in the Tampa (WP, three wells) study area was located approximately 100 m from the PSW. The monitoring wells in the Modesto and York study areas were 5.1-cm-diameter poly-vinyl chloride (PVC) with 1.5-m-long screens; the monitoring wells in the Tampa study area were 10.2-cm-diameter PVC with 3- to 4-m-long screens. Materials, methods, and designs used for well construction followed protocols of the USGS NAWQA program (Lapham et al. 1995) including use of flush-jointed and threaded (not glued) PVC casing and screens that was selected as the best compromise casing material for the range of analytes monitored (Wilson 1995). The absence of VOCs in samples from many wells suggests that PVC casing materials were not a source of VOCs in samples. The vertical placement of adjacent monitoring well screens is shown in Figs. 4a (Modesto), 7a (York), and 10a (Tampa, two of three adjacent monitoring wells shown). In the Tampa study area, an additional monitoring well (not shown in Fig. 10) was screened from 88 to 91 m bls, in the Upper Floridan Aquifer and below the PSW open interval.

Results and discussion

For each setting, selected constituents that serve as tracers of contamination-susceptible water reaching PSWs are discussed. Contamination-susceptible water is groundwater that was recharged in the modern era (approximately 1950 to present) and is more likely to contain contaminants introduced during this period than groundwater recharged before 1950. In all three study areas, constituents naturally present within the aquifer such as uranium (e.g., Jurgens et al. 2008; Landon et al. 2008), arsenic, and (or) radon (Katz et al. 2007) were mobilized by anthropogenically altered flow fields and served as tracers of contamination-susceptible water. Evidence for mobilization of natural constituents included correlations of uranium, arsenic, and (or) radon with anthropogenic constituents such as nitrate, VOCs, and pesticides as well as atmospherically derived and isotopic tracers. Detailed discussions of sources and transport processes affecting these constituents are not included in this paper but are discussed by Brown et al. (2007), Burow et al. (2008), Clark et al. (2008), Jurgens et al. (2008), Katz et al. (2007), Landon et al. (2008), and McMahon et al. (2008).

Modesto, California study area

Samples of surface discharge from the Modesto PSW contained concentrations of uranium (11.2-23.9 µg/l), nitrate (as nitrogen (4.5–7.2 mg/l), VOCs, including chloroform (0.04–1.65 µg/l) and tetrachloroethylene (PCE, 0.05–0.23 µg/l), and pesticides (atrazine and simazine, 0.009 to 0.013 µg/l), that were below drinking-water standards but of concern as indicators of contamination (Jurgens et al. 2008). On the basis of depth-dependent water quality samples and borehole flow from the long-screened PSW, the surface discharge from the well was a mixture of water from three depth zones within the aquifer system: shallow, intermediate, and deep (Fig. 4).

Flow estimates based on the tracer-pulse measurements indicated that about 20% of the flow was from the shallow zone, about 55% was from the intermediate zone, and 25% was from the deep zone (Fig. 4b). The proportion of water contributed from each of the depth zones was similar for the two velocity profiles of the PSW.

Depth-dependent sampling indicated that most contaminants (e.g., uranium, nitrate, VOCs, pesticides) enter the PSW from the shallow zone, where only about 20% of the total inflow to the well originates. Of the PSW depth-dependent samples, the shallowest (DDS-shallow) had the highest uranium and specific conductance (Figs. 4c, d, 5), as well as the highest concentrations and number of detections of VOCs (4) and pesticides (3), and the highest nitrate, alkalinity, sulfate, and arsenic (Jurgens et al. 2008). Elevated uranium in shallow groundwater was attributed by Jurgens et al. (2008) to desorption of uranium from sediments by irrigation and urban recharge having high bicarbonate (alkalinity) concentrations, which in combination with higher nitrate, sulfate, and other major ions derived from agricultural fertilizers and soil amendments, results in higher specific conductance in shallow waters. The deepest depth-dependent sample (DDS-97.5 m) had higher uranium and SC than aquifer inflow in two of the three sampled intervals at shallower depths in the intermediate and deep aquifer zones (Fig. 4c, d). Similarly, higher concentrations and numbers of detections of organic compounds and higher concentrations of inorganic constituents occurred in the deepest sample compared to intermediate zone depth-dependent samples (Jurgens et al. 2008).

The chemistry of DDS-shallow was consistent with the type, number, and concentrations of inorganic and organic constituents found in the adjacent shallow monitoring wells (Fig. 4c, d) as well as shallow monitoring wells further from the study PSW (Fig. 5; Jurgens et al. 2008). The deepest depth-dependent sample (DDS-97.5 m) had chemistry that was between that detected in the shallow zone and the deep zone (Fig. 5), suggesting that this sample represented mixtures of waters from these zones. Flow-adjusted concentrations in aquifer inflow to the PSW between 88.4 and 57.9 m bls were also higher in uranium and SC than overlying and underlying sample intervals in the intermediate zones (Fig. 4c, d), also consistent with mixing of waters from deep and shallow zone. The aquifer is oxic throughout the depths studied; thus, decreases in concentrations of constituents such as uranium and nitrate with depth reflect that high concentrations have not yet

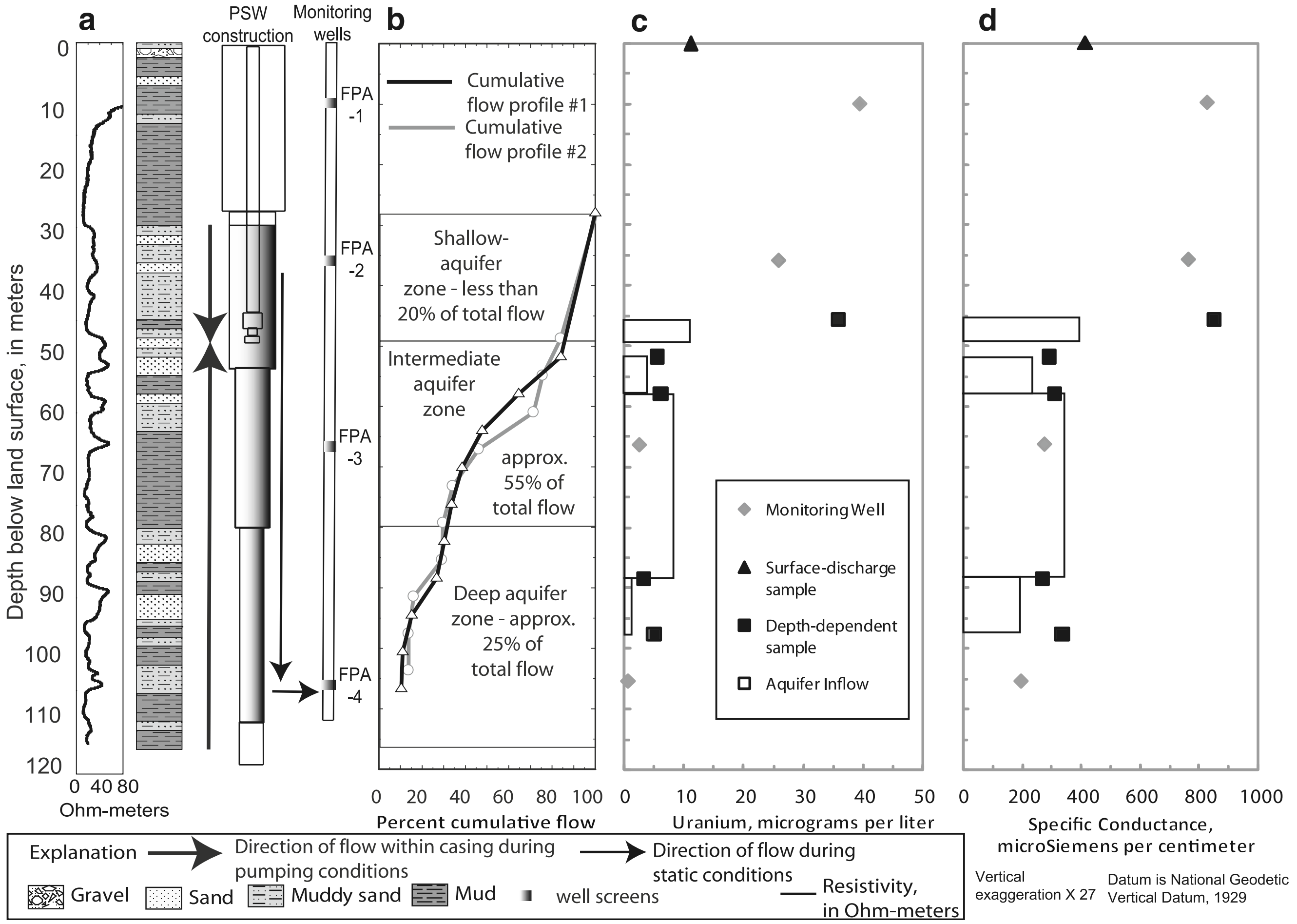

Fig. 4 Modesto, California study public-supply well and adjacent monitoring wells: **a** Geology, schematic public-supply and monitoring well construction, and flow directions under pumping and ambient conditions. **b** Percentage of cumulative flow at 6.1-meter intervals and approximate distribution of flow contributed from the shallow, intermediate, and deep aquifer zones. **c** Uranium concentrations. **d** Specific conductance measurements for depth-dependent samples collected from the study PSW and samples collected from monitoring wells at site FPA in August-September 2004

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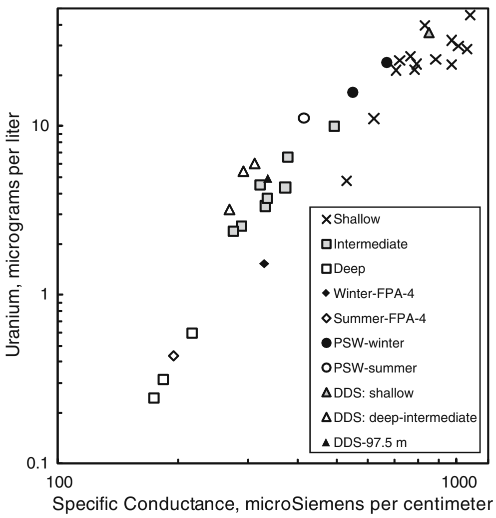

Fig. 5 Modesto, California study area: specific conductance and uranium for samples collected from monitoring wells in different aquifer depth zones (shallow, intermediate, deep), the FPA-4 monitoring well and study public-supply well (PSW) surface discharge during summer and winter, and depth-dependent samples (DDS) from shallow and deep-intermediate zones and the 97.5 m depth (deepest)

reached large depths rather than removal of these constituents due to oxidation-reduction reactions (Jurgens et al. 2008).

The chemical composition of water from the three depth zones in the PSW was generally consistent with data from nearby monitoring wells in the shallow and intermediate zones but differed slightly in the deep aquifer zone. The SC and uranium concentrations in the DDS-97.5 m sample were higher than those observed in FPA-4 and other deep aquifer zone monitoring wells (Figs. 4c, d, 5). Similar patterns were evident for other inorganic and organic constituents (Jurgens et al. 2008).

The age of the water varies from less than 50 years (on the basis of $^3H/^3He$ and SF_6) in the shallow and intermediate aquifer zones to thousands of years (on the basis of carbon-14) in the deep aquifer zone (Jurgens et al. 2008). The shallow and intermediate zones contain contamination-susceptible water; the deeper zone does not in the absence of mixing with shallow waters. Water from the surface discharge of the well is susceptible because it is a mixture of water from susceptible and less susceptible depths.

Data from a continuous recorder of hydraulic head and specific conductance installed in the adjacent deep monitoring well (FPA-4) indicated that the specific conductance and hydraulic head was at a minimum during May–September (summer) when pumping was largest, whereas specific conductance and hydraulic head increased during November–March (winter) when pumping from the PSW was at a minimum (Fig. 6). Head gradients at site FPA and other multiple monitoring well locations were vertically downward throughout the study (Jurgens et al. 2008). Concentrations of inorganic (e.g., uranium, Fig. 5) and organic constituents were greater in FPA-4 in the winter, following periods of little or no pumping of the PSW, than during the summer, following periods of extensive pumping of the PSW.

Jurgens et al. (2008) hypothesized that the long-screened interval or gravel pack of the PSW acts as a conduit for flow from the shallow aquifer zone to the deep aquifer zone during periods of low or no pumping at the PSW, causing the water chemistry in the deep aquifer zone surrounding the well to be periodically influenced by the high concentrations in the shallow zone. Evidence for this hypothesis includes: (1) the concentrations and numbers of detections of inorganic and organic constituents in the PSW deep zone samples were higher than those observed in deep aquifer zone monitoring wells (Figs. 4 and 5), (2) data from a continuous recorder of hydraulic head and specific conductance installed in the adjacent deep monitoring well showed increases during the winter when pumping decreased and decreases during the summer when pumping increased (Fig. 6), (3) concentrations of organic and inorganic constituents were greater in the deep monitoring well following periods of little or no pumping of the PSW (winter) than following periods of extensive pumping of the PSW (summer) (Fig. 5), (4) 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; similarly, in samples collected since 1989, median uranium concentrations from winter samples have been higher than the median of summer samples (Jurgens et al. 2008). These observations suggest that when pumping is increased during summer to meet increased demand, the stored shallow-intermediate zone 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.

Whereas flow through the borehole or gravel pack in the Modesto PSW was identified, it is important to note

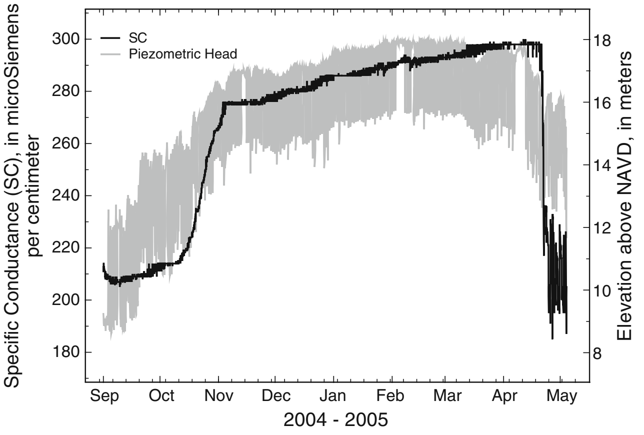

Fig. 6 Modesto, California study area: piezometric head and specific conductance measured in well FPA-4 from September 2004 through May 2005, illustrating increases during winter season as a result of reduced pumping and increased downward leakage of water from shallow depths through the nearby study PSW borehole

that regionally, the primary process allowing movement of contaminants to PSW is likely to be flow through hydraulically connected high-permeability sands in the heterogeneous alluvial fan deposits that provide natural fast flow paths from shallow recharge areas to production wells screened at depth (Burow et al. 1999; 2008). Nevertheless, vertical transport of contamination-susceptible water through long-screened wells may be an important secondary process, especially given regional downward head gradients and many long-screened wells.

York, Nebraska study area

Samples of surface discharge from the York PSW, which integrate water from the entire screened interval within the upper confined aquifer (Fig. 7a), contained concentrations of the VOCs PCE (0.80–0.92 μg/l) and trichloroethylene (TCE) (0.36–0.51 μg/l), and uranium (15.5–18.4 μg/l) that were below drinking-water standards but of concern as indicators of contamination (Landon et al. 2008). On the basis of data from monitoring wells and the long-screened study PSW, the surface discharge from the well was a mixture of water from the confined and unconfined aquifers.

Flow estimates based on the tracer-pulse measurements indicated that 73–86% of the total flow of water entering the PSW screen came from the upper half of the screen, above 51.8 m bls, (Fig. 7b). The adjusted flow profile calculated on the basis of chemical concentrations in depth-dependent samples was generally similar to profile estimated directly from the initial tracer-pulse measurements (Fig. 7b).

Depth-dependent sampling indicated that most contaminants (e.g., VOCs, uranium) enter the PSW in the bottom half of the screened interval, where <27% 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 7c-e shows profiles of $\delta^{18}O$, chloride, and PCE as examples, but similar profiles were observed for many other tracers and constituents, including uranium, major ions, TCE, δD, radium isotopes, and radon (Landon et al. 2008). Above the middle of the screened interval, concentrations decreased as they were diluted by inflow of waters having lower values.

The chemistry of the depth-dependent and surface-discharge samples from the PSW reflect mixing of contamination-susceptible waters from the unconfined aquifer with mostly contaminant-free waters from the upper confined aquifer. These interpretations become more evident when considering data from additional monitoring wells located in or near the ZOC to the PSW. Monitoring wells were classified with respect to whether they were screened in unconfined or confined aquifers, and unconfined wells were classified by agricultural or urban land-use areas. Monitoring wells in the confined aquifer also were classified on the basis of their $\delta^{18}O$ and δD values, which differed between the unconfined aquifer and tightly clustered values in most monitoring wells in the confined aquifer (Landon et al. 2008). Mixing calculations between these end-members indicated that monitoring wells in the confined aquifer could be classified into two groups: confined unmixed wells, containing mixtures of <10% unconfined water, and

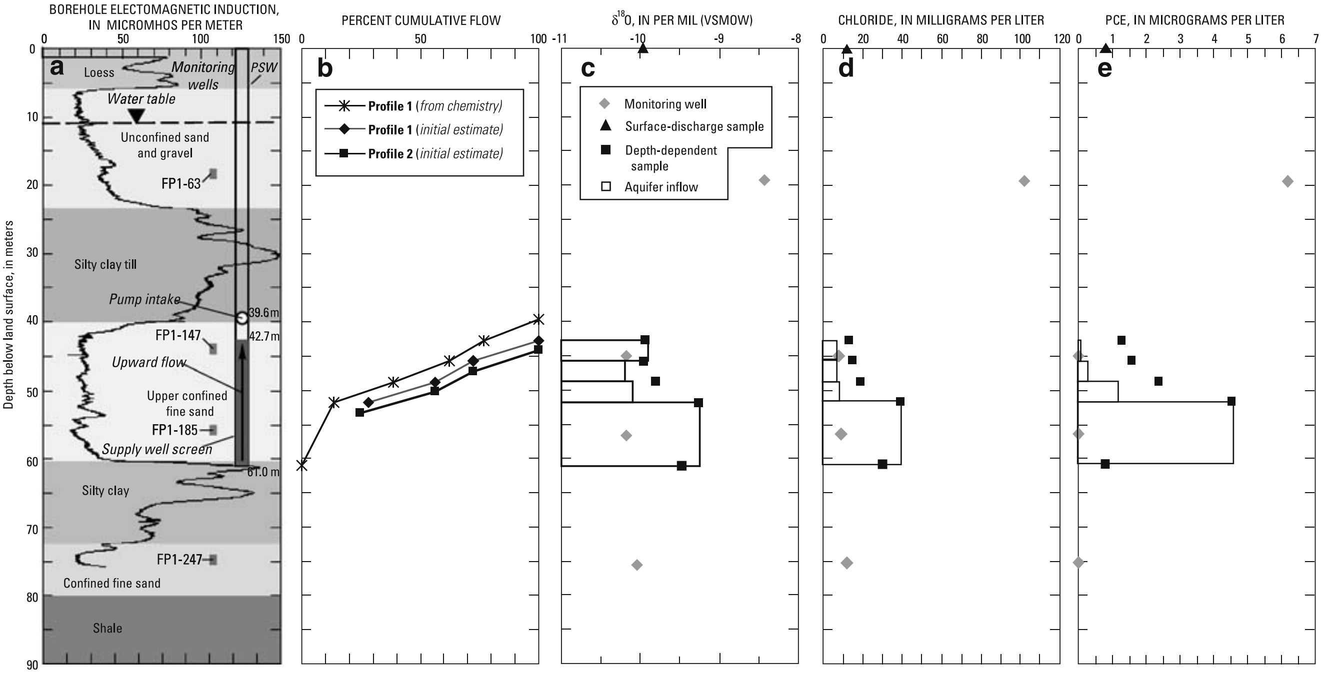

Fig. 7 York, Nebraska study public-supply well (PSW) and adjacent monitoring wells: **a** geology, schematic public-supply and monitoring well construction, **b** vertical distribution of flow in study PSW, and values of **c** $\delta^{18}O$, **d** chloride, and **e** tetrachloroethylene (PCE), in depth-dependent and surface-discharge samples from the study PSW and adjacent monitoring wells under pumping conditions, June 2004

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confined mixed wells, containing mixtures of >10% unconfined water (Landon et al. 2008).

Values of several inorganic and organic constituents in wells, in addition to $\delta^{18}O$ and δD values, showed a contrast between unconfined shallow urban, unconfined shallow agricultural, and confined unmixed end-member water compositions and mixtures of these different end-members. For example, analysis of $\delta^{18}O$ and chloride, tracers expected to behave conservatively, showed a clear contrast between unconfined shallow urban, unconfined shallow agricultural, and confined unmixed wells (Fig. 8). Most confined unmixed wells plotted in a tight cluster with low $\delta^{18}O$ and chloride values. Unconfined shallow urban wells had intermediate $\delta^{18}O$ and high chloride values. Confined urban mixed wells had intermediate values of $\delta^{18}O$ and chloride along an apparent mixing line between unconfined shallow urban and confined unmixed wells. Depth-dependent samples from the PSW also plotted between unconfined shallow urban and confined unmixed wells but along a mixing line different from that of confined urban mixed wells (Fig. 8). Similar results were evident from other tracer-tracer plots (Landon et al. 2008). Mixing calculations with $\delta^{18}O$ and δD values indicate that the depth-dependent sample from the middle of the screen contained approximately 50% unconfined shallow urban water (Fig. 9). The unconfined mixing fraction decreased to about 10% in the PSW surface discharge, at which inflow had been integrated from the entire screened interval. Samples in six confined mixed monitoring wells upgradient of the PSW represented mixtures of up to 85% unconfined water (Fig. 9). However, six other monitoring wells in the confined aquifer (confined unmixed wells) contained little or no unconfined water (< 10%).

For most constituents, concentrations in the depth-dependent samples from the PSW and from short-screened monitoring wells located <30 m away in the upper confined aquifer were different (Fig. 7c–e). In particular, flow-adjusted concentrations in aquifer inflow to the PSW in the lower half of the screen were higher than concentrations in the nearby monitoring well located in that depth interval.

The age of the water varies from less than 50 years (on the basis of $^{3}H/^{3}He$ and CFCs) in the unconfined aquifer to thousands of years (on the basis of carbon-14) in most of the confined aquifer (Landon et al. 2008). The unconfined and confined mixed waters are contaminant susceptible. The confined aquifer is not (or would not be without preferential movement of water through upgradient boreholes) and the water from the surface discharge of the well is susceptible because it is a mixture of water from susceptible and less susceptible depths. On the basis of SF6 and CFC-11 in combination with $\delta^{18}O$, and δD tracers, the surface-discharge sample is consistent with being a mixture of 7 to 14% unconfined water younger than 15 years mixed with 86 to 93% confined water older than 50 years (Landon et al. 2008).

Results from PSW depth-dependent and monitoring well sampling, in combination with ancillary well construction and hydraulic head data, led to the conceptual model of the system shown in Fig. 2b, which shows multilayer wells as conduits for movement of contamination-susceptible water to depths where PSWs are screened. The chemical and isotopic data from PSW depth-dependent and monitoring well samples (Fig. 8) indicate: (1) the water from the unconfined aquifer in the study PSW came from an urban source area and (2) the confined mixed wells and the PSW did not all plot along the same mixing lines, indicating that there were multiple pathways from the unconfined aquifer source areas to zones of mixing in the confined aquifer. Irrigation, commercial, and older PSWs that are screened in both the unconfined and confined layers are the most likely preferential flow paths that permit water leakage from the unconfined to confined aquifers. There are large downward hydraulic-head gradients between the unconfined and confined aquifers that result from withdrawals, particularly for irrigation during the summer, from the confined aquifer (Landon et al. 2008). Results of a numerical groundwater-flow and solute-transport model

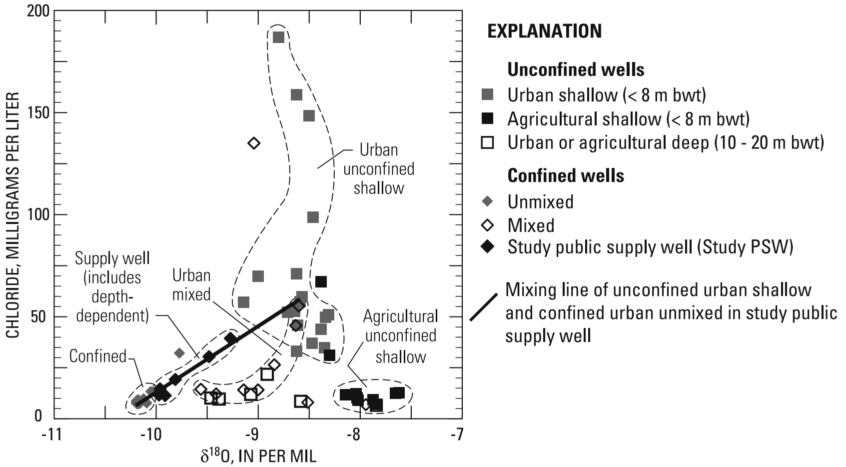

Fig. 8 York, Nebraska study area: $\delta^{18}O$ and chloride for samples from monitoring wells and the study public-supply well (modified from Landon et al. 2008). [*bwt* below water table; *m* meters; < less than]

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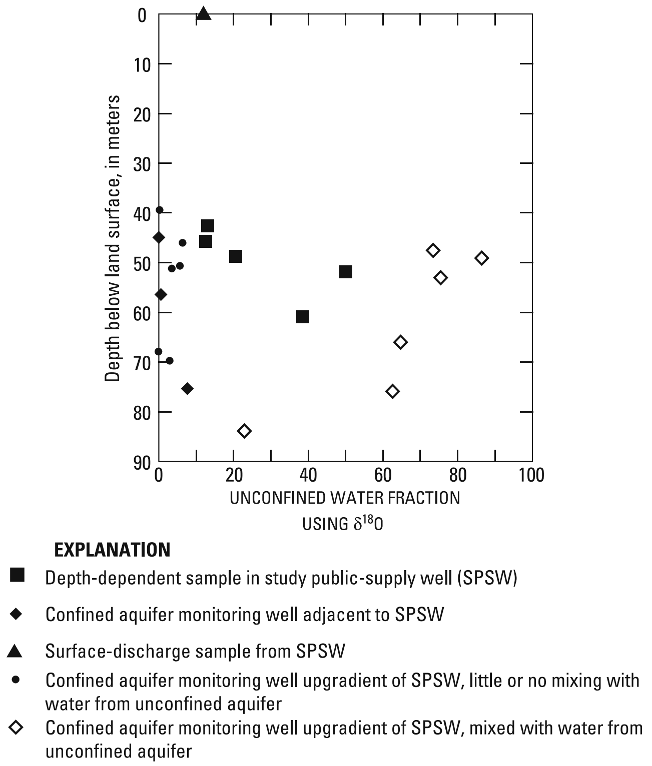

Fig. 9 York, Nebraska study area: mixing fractions of water from the unconfined aquifer based on δ^{18}O values in monitoring wells and the study public-supply well screened in the confined aquifer during October 2003-April 2005

are consistent with an interpretation that the vulnerability of the PSW to contamination is dependent upon wells open to multiple layers (Clark et al. 2008). The simulations indicate that about 25% of the water flow, and all of the flow of relatively young contamination-susceptible water, through the confining unit moves through boreholes rather than as matrix flow leakage through the confining unit. The presence of water from the unconfined aquifer in the confined aquifer is not likely to reflect cross-layer borehole flow in the PSW itself, which is screened only in the confined aquifer. Hydraulic heads in the unconfined aquifer adjacent to the PSW showed no response to withdrawals (Landon et al. 2008). Significant downward leakage of water from an unconfined to a confined aquifer should be apparent from hydraulic responses during extended pumping (Santi et al. 2006). Also, leakage down the PSW borehole would be expected to result in the greatest abundance of water from the unconfined aquifer near the top of the screened interval of the PSW, the opposite of what was observed (Figs. 7c, 9). Moreover, water from the unconfined aquifer was present in other confined-aquifer monitoring wells away from the study PSW, indicating that pathways for cross-layer flow exist upgradient of the PSW. Although unidentified natural discontinuities could also 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.

Tampa, Florida study area

Samples of surface discharge from the Tampa PSW, which integrate water from the entire open interval, contained concentrations of VOCs, including chloroform (0.05–0.36 μg/l) and TCE (0.03–0.14 μg/l), pesticides, including atrazine and prometon (0.003 to 0.014 μg/l), nitrate (as nitrogen, 0.72–1.4 mg/l), and radon (780 picocuries/l), indicating the presence of contamination-susceptible water in the well (Katz et al. 2007). On the basis of data from the study PSW and monitoring wells, the surface discharge from the PSW was a mixture of water from the Upper Floridan and surficial aquifers.

Zones of high groundwater inflow to the PSW were identified at 46.8 and 49.2 m bls on the basis of the flowmeter (Fig. 10b, c), fluid resistivity (Fig. 10a), and specific conductance (Fig. 10d) logs. Caliper (Fig. 10a) and televiewer logs revealed large solution openings in the Upper Floridan Aquifer limestone at depths >47 m in the PSW. In contrast to the Modesto and York study areas, data was collected from the Tampa PSW under ambient (non-pumping) as well as pumping conditions. Under pumping conditions, the lower high-flow zone at 49.2 m contributed 70% of the surface discharge from the well during the test (Fig. 10b; Katz et al. 2007). Under ambient conditions, borehole flow was primarily downward to the high-flow zones (Fig. 10c). Flowmeter model analysis indicated that the lower zone had a transmissivity about three times higher than that of the upper zone (Katz et al. 2007). Under ambient conditions (downward flow), specific conductance decreased substantially in the zones of high flow below about 47 m (Fig. 10d). This lower specific conductance is consistent with the presence of water moving downward to the high flow zones from the surficial aquifer, which has lower conductance than water from the Upper Floridan aquifer.

Depth-dependent sampling results under ambient and pumping conditions differed but both data sets were consistent with anthropogenic constituents (VOCs, pesticides, nitrate) and naturally occurring constituents derived from shallow source areas (radon) entering the PSW from the high flow zone below 49 m and naturally occurring constituents mobilized from the Upper Floridan Aquifer (dissolved solids, arsenic, strontium, iron, manganese) entering the PSW above the high flow zones. For example, the deepest PSW depth-dependent sample at 49 m, representing the high flow zone, had the highest concentration of chloroform under both ambient and pumping conditions (Fig. 10e). Similar patterns were evident for several other constituents including nitrate, orthophosphate, radon, and atrazine (Katz et al. 2007). Higher concentrations of these constituents during ambient than pumping conditions (e.g., chloroform in Fig. 10e), probably reflect less mixing of water from the high flow zone, having high concentrations, with other water from the Upper Floridan Aquifer under ambient conditions. In contrast, the deepest PSW depth-dependent sample at 49 m had the lowest dissolved solids concentration under ambient conditions (Fig. 10f). Similar patterns were evident for several other constituents including arsenic,

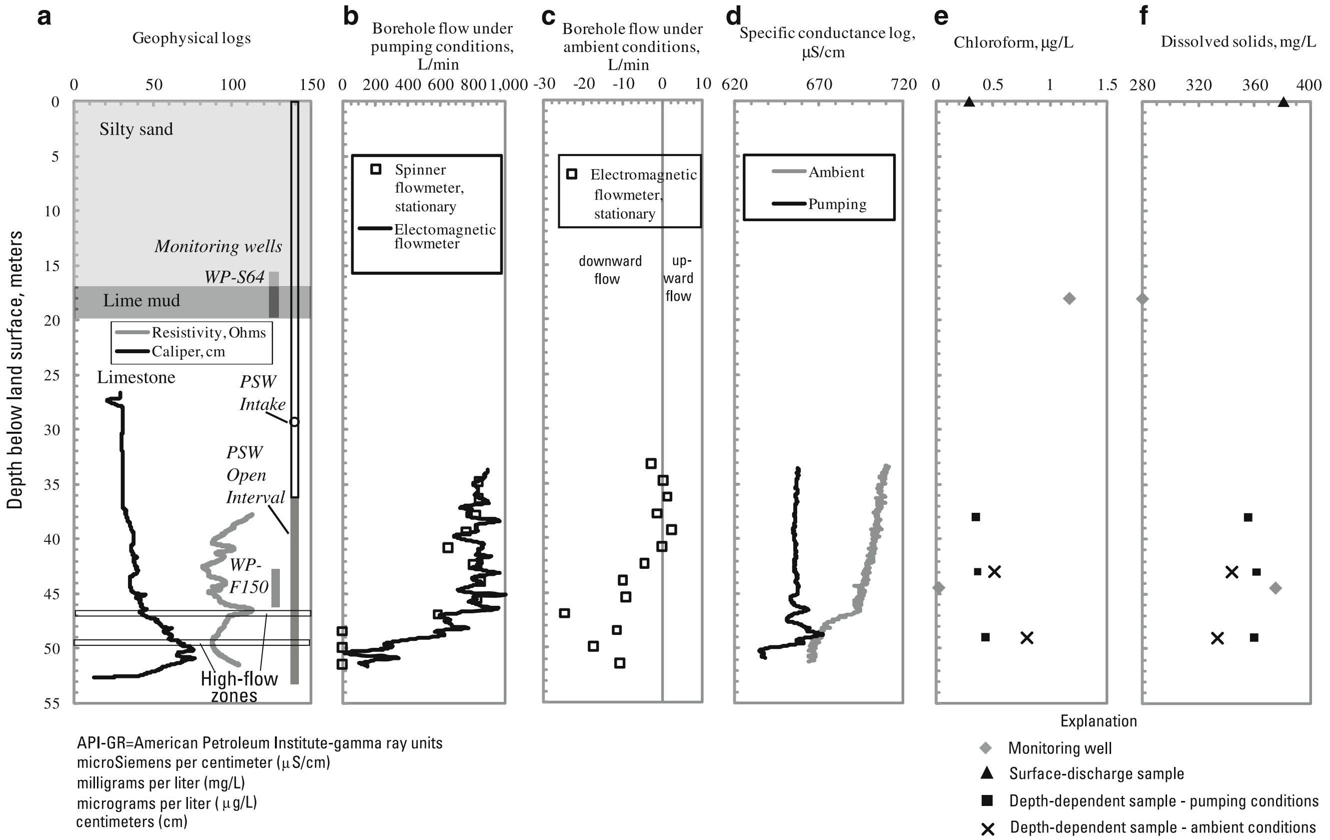

Fig. 10 Tampa, Florida study public-supply well (PSW) and adjacent monitoring wells: **a** geology, schematic public-supply and monitoring well construction, vertical distribution of flow in study PSW under, **b** pumping conditions and, **c** ambient conditions, **d** specific conductance logs of study PSW under pumping and ambient conditions, values of **e** chloroform, and **f** dissolved solids, in depth-dependent and surface-discharge samples from the study PSW and adjacent monitoring wells under pumping and ambient conditions, June 2004

strontium, iron, and manganese (Katz et al. 2007). In contrast to anthropogenic and natural constituents from the surficial aquifer, concentrations of naturally occurring constituents mobilized from the Upper Floridan Aquifer were higher during pumping than ambient conditions, probably because larger amounts of water from the Upper Floridan Aquifer enter the PSW under pumping than ambient conditions. Differences in water chemistry of depth-dependent samples were greater under ambient than pumping conditions. During pumping conditions, concentrations of most constituents varied relatively little between depths (Figs. 10e, f), probably because of greater mixing of waters with different chemistry compared to ambient conditions.

Samples from the 49-m depth in the PSW and samples from monitoring wells in the surficial aquifer system had similar chemistry (Katz et al. 2007). For example, values of δ^{18}O, nitrate nitrogen, and chloroform in depth-dependent samples under pumping and ambient conditions as well as the surface discharge under pumping conditions, were within the range of values from the surficial aquifer and differed from values in the Upper Floridan Aquifer (Figs. 11 and 12). Values of δ^{18}O are expected to be conservative whereas nitrate nitrogen and chloroform may be affected by degradation under the predominantly sulfate-reducing conditions of the Upper Floridan Aquifer (Katz et al. 2007; McMahon et al. 2008).

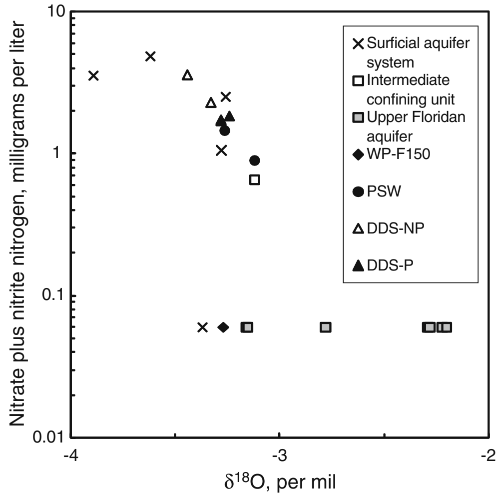

Fig. 11 Tampa, Florida study area: δ^{18}O and nitrate nitrogen for samples from monitoring wells classified by hydrogeologic unit, including the monitoring well in the Upper Floridan Aquifer adjacent to the public-supply well open interval (WP-F150), and the study public-supply well (PSW, surface discharge of study public supply well; *DDS* depth-dependent sample under pumping (-P) and non-pumping (-NP) conditions)

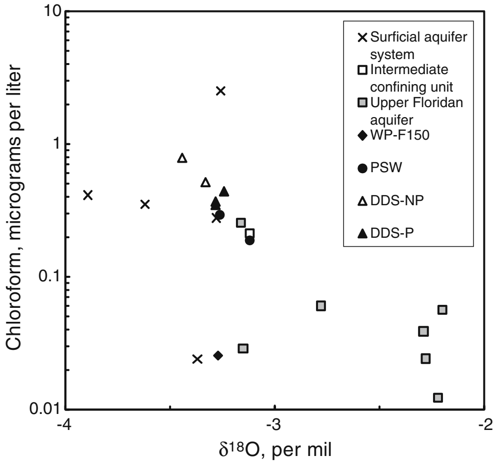

Fig. 12 Tampa, Florida study area: $\delta^{18}O$ and chloroform for samples from monitoring wells classified by hydrogeologic unit, including the monitoring well in the Upper Floridan Aquifer adjacent to the public-supply well open interval (WP-F150), and the study public-supply well (PSW, surface discharge of study public supply well; *DDS* depth-dependent sample under pumping (-P) and non-pumping (-NP) conditions)

Water chemistry in the depth-dependent samples from the PSW under pumping and ambient conditions differed from the adjacent monitoring well (WP-F150) screened within the open interval of the PSW (Fig. 10a). WP-F150 had lower concentrations of anthropogenic constituents such as chloroform (Figs. 10e, 12), and higher concentrations of tracers of natural mobilization processes in the Upper Floridan Aquifer such as dissolved solids (Fig. 10f).

The age of the water varies from less than 7 years (on the basis of SF_6 and $^3H/^3He$) in the surficial aquifer system to greater than 50 years in most wells in the Upper Floridan Aquifer (Katz et al. 2007). The PSW had SF_6 and $^3H/^3He$ values indicating mixtures of water less than 7 years old with water greater than 50 years old. The surficial aquifer system and mixed waters in the Upper Floridan Aquifer are contamination susceptible.

Depth-dependent and monitoring well sampling results indicate that the highly transmissive zone intersecting the PSW below 49 m bls is hydraulically connected to the surficial aquifer system, probably through sinkholes that breach the confining unit, and results in a mixture of water from the surficial aquifer system and the Upper Floridan Aquifer within the PSW (Fig. 2c). Several lines of evidence support this interpretation: (1) A majority of flow into the well under pumping conditions comes from the highly transmissive zone below 49 m bls (Fig. 10b), (2) Chemical signatures in surface-discharge and depth-dependent samples from the PSW consistently were similar to the samples from the surficial aquifer systems and indicated a mixture of water from the surficial aquifer system and the Upper Floridan Aquifer (Figs. 11 and 12), (3) Depth-dependent sampling in the PSW under ambient and pumping conditions indicated that the chemistry of the PSW was dominated by constituents entering the PSW from the highly transmissive zone below 49 m bls. Under ambient conditions, higher concentrations of anthropogenic constituents (e.g. nitrate, chloroform) and lower concentrations of natural constituents (e.g., dissolved solids, arsenic, strontium) in the deepest depth-dependent sample (49 m bls) representing the highly transmissive zone, compared to the sample at 43 m, is consistent with water from the surficial aquifer system entering the PSW borehole from the highly transmissive zone. Under pumping conditions, more uniform vertical concentration profiles with generally lower concentrations at shallower depths are consistent with greater dilution of solutes entering the PSW in the highly transmissive zone with other water from the Upper Floridan Aquifer than under ambient conditions. Higher concentrations of anthropogenic and surficial-aquifer-derived natural constituents in the PSW depth-dependent samples under ambient than pumping conditions probably occur because the high-flow zone is directly connected to the surficial aquifer system and feeds water into the PSW under ambient conditions. Under pumping conditions, concentrations of anthropogenic constituents decrease and natural constituents increase as water entering the PSW through the highly transmissive zone at 49-53 m is diluted with water drawn to the well from the Upper Floridan Aquifer. Geochemical mass-balance models indicate that the proportion of surficial aquifer system water produced by the PSW was between 30 and 62% (Katz et al. 2007). Increases in concentrations of natural constituents (dissolved solids, arsenic, strontium) are considered to reflect mobilization of these constituents from the Upper Floridan Aquifer as oxic water from the surficial aquifer system is drawn into the Upper Floridan Aquifer and interacts with sediments under anoxic conditions (Katz et al. 2007). The presence of sometimes cavernous highly transmissive zones in the Upper Floridan Aquifer is well documented as well as the presence of sinkholes that breach the intermediate confining unit underlying the surficial aquifer system (Stewart et al. 1978; Katz et al. 2007). These natural short-circuit pathways represent the most likely flow path for water from the surficial aquifer system to reach the bottom of the open interval of the PSW.

Comparisons between study areas

The depth-dependent chemistry and flow data in all three study areas were key interpretative tools allowing the mechanisms for contaminant movement to the PSW to be identified. The use of these data with monitoring well data, ancillary information on the hydrogeologic systems, and simulation results led to refined conceptual models for each system (Fig. 2).

In the three hydrologically diverse aquifers included in this study, depth-dependent chemistry data revealed that PSW vulnerability is strongly influenced by movement of contamination-susceptible water along short-circuit pathways to the PSW open intervals. In general, development of groundwater systems for water supply induces changes in hydraulic gradients and groundwater velocities, leading to pathways with shorter residence times than would be

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expected under non-pumping 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 flow paths 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 York and Tampa study areas, 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. Whereas the short-circuit pathways are primarily natural features in the Tampa study area, they are primarily man-made features (boreholes) in the York study area. Where intact, the confining layers in the York and Tampa study areas not only restrict the downward movement of potentially contaminated groundwater affected by 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 York and Tampa study areas suggest that nitrate is completely denitrified in the confining unit of both systems (McMahon et al. 2008). In the York study area, vertical movement of water occurs as a result of regional pumping stress resulting primarily from irrigation withdrawals in the confined aquifer; while local pumping stress could contribute to vertical movement of contamination-susceptible water from the unconfined aquifer, it is not necessary for a local pumping stress to be present for vertical movement of water from the unconfined to the confined aquifers to occur if boreholes crossing the confining unit and a downward vertical gradient reflecting regional pumping are present. In the Tampa study area, the combination of breaches in the confining unit intersecting transmissive zones in the Upper Floridan Aquifer and local pumping stress from PSWs result in vertical movement of contamination-susceptible water from the surficial aquifer system to PSW. Thus, the presence of natural breaches or man-made holes in confining units in combination with regional or local pumping stress are critical factors increasing the vulnerability of PSWs to contamination in both the York and Tampa study areas.

While the details of where borehole leakage occurred and how the water quality at the PSW was affected differed between the Modesto and York study areas, in both areas, boreholes crossing relatively low permeability confining or semi-confining layers served as short-circuit pathways for contamination-susceptible shallow groundwater to affect the quality of the water produced by the PSW. In the case of the Modesto study area, vertical movement occurred through the long screen or gravel pack of the PSW spanning shallow and deep zones in a generally unconfined to semiconfined aquifer. In the case of the York study area, vertical movement occurred through boreholes open to unconfined and confined aquifers located upgradient of the PSW.

Implications for monitoring and management

Differences in water chemistry for similar depths between depth-dependent samples collected from PSW under pumping conditions and samples from monitoring wells located a short distance (< 30–100 m) from the PSW occurred at all three study sites (Figs. 4, 7, and 10). The differences probably result from the three-dimensional convergence of many groundwater flow paths on the PSW as a consequence of large withdrawal rates, resulting in mixing of waters from many flow paths in the PSW. In contrast, the much lower withdrawal rates and the shorter-screened intervals in the monitoring wells makes it likely that these wells intersected a much smaller number of groundwater flow paths moving from one direction toward the PSW. These interpretations are consistent with those of Izbicki et al. (2005b), who attributed differences in chemistry between depth-dependent data in a production well and monitoring wells about 100 m away in a coastal aquifer in California to greater convergence of flow paths to production wells than monitoring wells. The chemistry of depth-dependent samples from the PSW and the monitoring wells may differ because the PSW intersects groundwater flow path(s) having relatively high concentrations of solutes that were not intersected by the monitoring wells. In other cases, depth-dependent profiles in PSW and adjacent monitoring wells may be similar. For example, in the Modesto PSW the vertical patterns in water chemistry based on depth-dependent and monitoring well samples were similar apart from the relatively subtle differences in chemistry between the deepest samples reflecting the local effects of downward leakage down the PSW borehole. In the Modesto study area, vertical chemical gradients are present regionally as a result of downward migration of contamination-susceptible water along hydraulically connected sands in the alluvial deposits. These vertical chemical profiles were observed both from depth-dependent data in the PSW and in adjacent monitoring wells. Thus, as short-circuit flow paths become less dominant as a mechanism for contamination-susceptible water to reach PSWs, greater similarity of chemical profiles in PSW depth-dependent and monitoring well data might be expected to occur.

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 ZOC of the PSWs enabled possible pathways of contaminants to the PSWs to be identified in three study areas. Collection of flow and sample data 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 et al. 2005a, 2005b, 2008). The combination of flowmeter logging and depth-dependent water-quality data has also been used for designing production wells to improve the quantity and quality of the water produced (Gossell et al. 1999). For this study, the addition of monitoring-well data provided insight into the mechanisms and flow paths linking contaminant sources and PSWs. It is not unusual for samples collected from PSW wellheads to indicate at least

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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.

Knowledge of short-circuit pathways contributes to developing effective strategies for monitoring and protection. For example, in the Modesto study area, monitoring programs could be modified to include seasonal sampling to identify effects of borehole leakage and short-term storage of shallow zone water in deep zones in the aquifer. For wells particularly strongly affected by cross-contamination between shallow and deep zones during winter low-pumping periods, reductions in borehole flow and aquifer storage could potentially be achieved by changes in seasonal pumping schedules or by modifications to well construction. In the York study area, monitoring strategies could include additional depth-dependent sampling or borehole logging to identify wells or areas where vertical movement of poor quality water through boreholes is occurring. Wells or boreholes open to more than one aquifer with construction that needs to be modified to prevent PSW water quality degradation could be prioritized on the basis of this information. In the Tampa study area, knowledge of the degree to which the water quality in PSWs reflects that of the surficial aquifer because of short-circuit pathways could be used to prioritize monitoring and land use planning efforts to protect the most vulnerable wells.

Conclusions

In the three aquifers included in this study, depth-dependent chemistry and flow data, in combination with supporting data from monitoring wells adjacent to or within the ZOC of the PSW, revealed movement of contamination-susceptible water along short-circuit pathways to the PSW. In the Modesto study area (Central Valley Aquifer), the vertical movement of poor-quality water from shallow to greater depths was the result of downward flow of water in the borehole of the PSW itself during periods of low or no pumping. The poor quality water was temporarily stored at depth in the aquifer and flushed out at the initiation of greater pumping rates, temporarily increasing concentrations of chemicals of concern. In the York study area (High Plains Aquifer), the movement of poor-quality water to the PSW, which was screened only in the confined aquifer, was the result of downward movement of water from the shallower unconfined aquifer into the confined aquifer through wells or boreholes completed in both the confined aquifer and the overlying unconfined aquifer located upgradient of the PSW but within the ZOC to the well. In the Tampa study area (Upper Floridan Aquifer), the movement of poor-quality water to the PSW (open solely to the Upper Floridan Aquifer) occurs because the PSW intersects a highly transmissive zone in the Upper Floridan Aquifer that is hydraulically connected to the overlying surficial aquifer system.

Despite substantial differences between the hydrogeologic settings (unconfined heterogeneous alluvial fans, layered unconfined and confined aquifers, and karst), contamination-susceptible water reached PSWs in each setting by moving along anthropogenic or natural flow paths that bypassed substantial portions of the aquifer. The chemistry and flow data from multiple depths was essential to developing an understanding of the dominant flow paths of contaminants to PSW in all three settings. This knowledge contributes to developing effective strategies for monitoring and protection.

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