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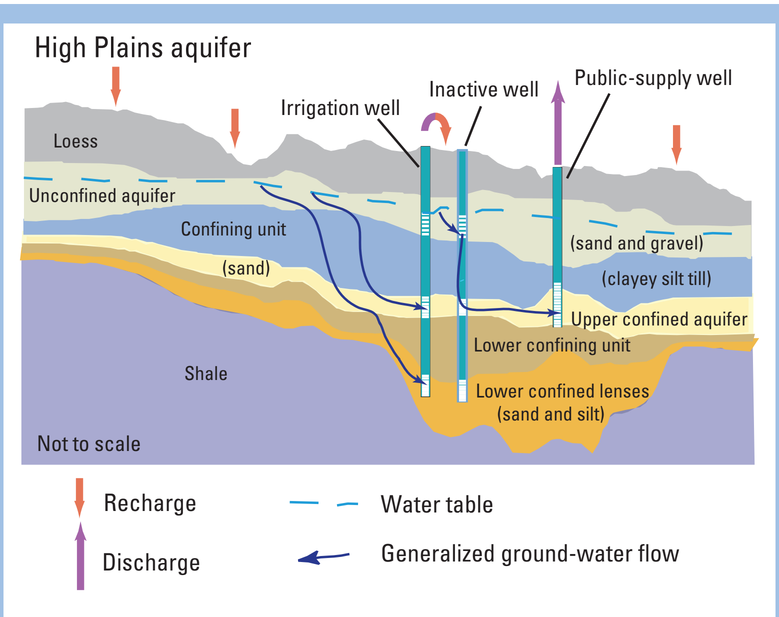
Assessing the Vulnerability of Public-Supply Wells to Contamination: High Plains Aquifer Near York, Nebraska

The U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program found, in studies from 1991 to 2001, low levels of mixtures of contaminants in ground water near the water table in urban areas across the Nation. Although contaminants were detected less frequently in deeper ground water typically developed for public supply (Hamilton and others, 2004), the proximity of contaminant mixtures to underlying public-water-supply sources prompted the NAWQA Program to begin, in 2001, an intensive study to assess the vulnerability of public-supply wells to contamination. As part of this study, the pathways and processes by which contaminants reach public-supply wells in nine aquifer systems across the country are being investigated. In addition to studying the processes that occur below land surface—whereby contaminants are mobilized or attenuated—scientists are also investigating how human activities can affect the vulnerability of public-supply wells to contamination.

This fact sheet highlights findings from the vulnerability study of a single, representative public-supply well in York, Nebraska (Clark and others, 2008; Landon and others, in press). The selected high-capacity well typically produces more than 720,000 gallons per day from the upper confined aquifer of the High Plains aquifer. (See text box describing the aquifer.) A possible source of contamination to the well is intensive, irrigated agriculture, which can sometimes result in elevated concentrations of nitrate and pesticides in ground water. In addition, a sampling of the selected public-supply well by the USGS in 2002 found low concentrations of the solvents trichloroethylene (TCE), tetrachloroethylene (PCE), and their degradation products, which may be linked to historical chemical use in urban and residential areas of York. Uranium and arsenic (which occur naturally in the sediments that make up the aquifers in the area) also were detected in 2002 at concentrations less than drinking-water standards but still of concern.

Overall, the current NAWQA study found that three primary factors affect the movement and fate of contaminants and the vulnerability of the public-supply well in York: (1) timing of water entry (recharge) to the aquifer, (2) short-circuiting of natural flow paths through inactive wells, and (3) natural geochemical conditions of the aquifer. Study findings are intended to help water managers, drinking-water suppliers, policymakers, and scientists to better understand how and why contamination of public-supply wells occurs and whether water quality may improve or degrade. Additionally, study findings may be used to evaluate various pumping, resource-development, and land-management scenarios.

The High Plains aquifer near York, Nebraska, is composed of layered alluvial deposits. The uppermost layer is loess (windblown dust), which is unsaturated in most locations. Below the loess is a layer of mostly sand and gravel that is referred to as the "unconfined aquifer." Under typical flow conditions, some precipitation and irrigation water will infiltrate from land surface to the water table and then move downward and laterally over time through the unconfined aquifer. Upon reaching the base of the unconfined aquifer, water then travels almost vertically through the underlying layer of clayey silt till. This till is much less permeable than surrounding layers and acts as a confining unit, greatly slowing the movement of water into lower layers. Once through the confining unit, water enters the upper confined aquifer and resumes flowing in a primarily lateral direction and at a relatively rapid rate compared to that in the confining unit. The upper confined aquifer is the primary source of ground water for public-supply wells in the region. Beneath the upper confined aquifer is another confining unit underlain by discontinuous sand lenses (referred to as "lower confined lenses"). Many irrigation, commercial, and some older public-supply wells are screened in the unconfined aquifer, the upper confined aquifer, and the lower confined lenses.



Well Vulnerability Increased by Mixing of Recent Recharge With Older Water

"Ground-water age" refers to the elapsed time since water entered or "recharged" an aquifer at the water table. Because water in an aquifer typically flows downward and laterally over time, it is expected that "young" (recently recharged) water will be found near the water table and older waters will be found at greater depths.

Ground-water samples in the York area were analyzed for modern age tracers (concentrations of chlorofluorocarbons, sulfur hexafluoride, and (or) ratios of helium and tritium). Age-tracer data indicate that the two primary aquifers near York—the unconfined aquifer and the upper confined aquifer—generally contain water of different age groups. The presence of modern age tracers in water from the unconfined aquifer indicates young water recharged within the last 60 years. In contrast, most of the water from the upper confined aquifer (which is a deeper unit and is the primary source of water for public supply) contains no detectable concentrations of modern age tracers and thus is old water recharged more than 60 years ago.

Water entering the public-supply well at various depths also was analyzed for modern age tracers. As is typical of a production well, the long screened interval of the well (60 feet) captures a mixture of water that recharged at different times. However, the finding that young water is entering the well screen underneath older waters in the upper confined aquifer was surprising. Specifically, water with a mean age of about 1990 or younger enters the well through the bottom half of the screen and accounts for about 7 to 14 percent of the total amount of water produced by the well. Young water entering the well beneath older water suggests that short-circuiting of natural flow paths is occurring, allowing water from the unconfined aquifer to flow to depth below the confining unit more rapidly than expected. The presence and proportion of young water relative to old water is of concern because young ground water is more vulnerable to contamination from human activities associated with urban or agricultural land use than older ground water (which recharged before the use of manmade chemicals became prevalent).

Inactive Wells Serve as Short Circuits for Movement of Contaminants Across the Confining Unit

Study findings in York indicate that the mechanism for short circuits in the natural ground-water flow system is well-construction methods used in the area. Many irrigation wells, and some commercial and public-supply wells, are screened across both the unconfined and upper confined aquifers to maximize yields. Such wells are hereafter referred to as "multiscreened wells." Multiscreened wells open to both aquifers offer conduits for downward movement of water (and associated contaminants) when the well is not in use—and movement along this short-circuit path is years to centuries faster than flow of water through the confining unit. During periods when a multiscreened well is not pumped (as usually occurs with irrigation wells during the fall, winter, and spring), contaminants that flow down the well and out of the well screen in the confined aquifers may travel beyond the capture zone of the well before pumping is resumed.

Further evidence for multiscreened well leakage is the mixed chemical characteristics found in 6 of the 16 monitoring wells completed in the upper confined aquifer. These mixed waters are characterized by (1) stable-isotopic and major-ion signatures intermediate between those found either in the unconfined aquifer or in most wells completed in the upper confined aquifer, (2) the anomalous presence of young waters, and (3) the presence of contaminants derived from human activity at the land surface (such as volatile organic compounds (VOCs) and pesticides) below the confining unit. For the six confined monitoring wells exhibiting mixed characteristics, the fraction of water from the unconfined aquifer was calculated to range from 41 to 94 percent, based on stable hydrogen isotope values. The occurrence of mixed water in only 6 of the 16 wells completed in the upper confined aquifer suggests that the mixing is the result of flow from the unconfined aquifer to the confined aquifer(s) along localized short-circuit paths, consistent with the source being leakage through multiscreened wells.

Incorporating multiscreened well leakage into computer-model simulations of ground-water flow and solute transport produced results that correspond to the observed chemistry in the mixed monitoring wells and in the supply well. Modeled findings show that leakage through multiscreened wells accounts for about 25 percent of the total flow from the unconfined to the confined portion of the ground-water system. The majority of ground water (75 percent) follows slower, natural flow paths through the confining unit. The computer model was then used to determine the blend of water of different ages (or "age distribution of water") produced by the public-supply well (fig. 1). All water produced by the well that is less than about 60 years old travels to the upper confined aquifer by way of short circuits (shown in green). It is this young water that contains low levels of anthropogenic contaminants.

Study Design

A computer model was constructed to estimate the zone of contribution to the selected public-supply well (Landon and Turco, 2007). The zone of contribution is the three-dimensional volume of the aquifer material through which ground water flows from the time it enters the ground-water system at the water table until it eventually discharges at the selected public-supply well. A network of 36 monitoring wells was installed in or near the simulated zone of contribution to the well to understand ground-water flow and geochemistry along apparent ground-water flow paths to the well. Water samples were collected from the monitoring wells and the supply well during October 2003 through April 2005 and analyzed for naturally occurring contaminants (such as uranium and arsenic) and anthropogenic contaminants (caused by human activities). Other physical and chemical characteristics of water (such as major ions, age-dating tracers, and selected stable isotopes) were analyzed for, so that sources of water and reactions affecting the chemical composition of ground water can be better understood. In addition, water samples were collected from the supply well at various depths while it was being pumped to determine where water and contaminants enter the well.

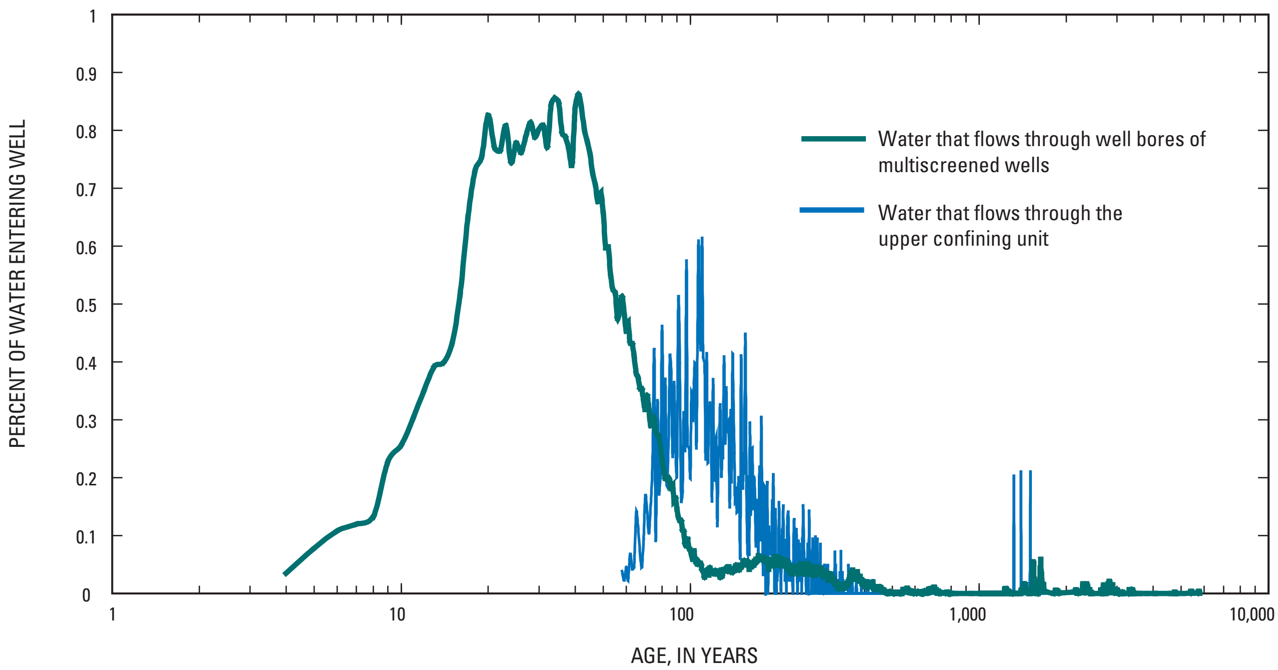


Figure 1. A ground-water flow model was used to simulate age distribution of water (the mixture of water of different ages) produced by the selected public-supply well in York, Nebraska. "Water age" refers to the time elapsed since water entered the ground-water system as recharge at the water table. The age distribution of water from this well is a combination of the age distribution of water that slowly flows across the confining unit, shown in blue, and the water contributed by leaking, inactive wells that are screened in both the unconfined and upper confined aquifers, shown in green. All water produced by the public-supply well that is less than about 60 years old travels to the upper confined aquifer by way of short circuits. Without short circuits, the well might not contain low levels of anthropogenic contaminants.

Natural Geochemical Conditions Affect the Fate of Contaminants

Short-circuiting of water through multiscreened wells not only speeds the arrival of contamination-susceptible young water to the upper confined aquifer; it also circumvents the contaminant-attenuating capacity of the confining unit. Whether specific contaminants are attenuated or mobilized in the subsurface depends on the natural geochemical conditions encountered.

The fate of several contaminants in the High Plains aquifer—particularly nitrate, TCE and PCE, and uranium—is greatly affected by the oxygen content of ground water. In the oxic conditions (dissolved oxygen concentrations greater than 2.5 milligrams per liter (mg/L)) found throughout most of the unconfined aquifer, nitrate, TCE and PCE, and uranium are stable and can be transported long distances. Following natural ground-water-flow paths, these constituents would eventually reach the generally anoxic environment (dissolved oxygen concentrations mostly less than 0.5 mg/L) of the confining unit and upper confined aquifer. Here, these constituents would be naturally attenuated, given enough residence time. Attenuation of nitrate is due to a process known as denitrification, in which nitrate is converted to harmless nitrogen gas in the absence of oxygen. Analysis of pore-water chemistry in the upper confining unit indicates that complete denitrification occurs across the upper 10–13 feet of this layer. TCE and PCE are degraded by microbes in the anoxic layers, as evidenced by greater concentrations of degradation products *cis*- and *trans*-1,2 dichloroethylene compared to parent compounds (TCE and PCE) in the upper confined aquifer than in the unconfined aquifer. Uranium is generally attenuated under anoxic conditions because it precipitates out of ground water as an insoluble mineral or sorbs onto aquifer sediments in anoxic conditions.

When natural flow paths are not followed and young, oxic water short-circuits through inactive wells, the time available for attenuating reactions is greatly reduced. Water that would normally spend years to centuries moving through the confining unit is now shunted directly to the upper confined aquifer, where it may spend relatively little time in an anoxic environment before it is captured and discharged by the supply well. Thus, attenuating reactions may not be carried to completion. For example, the presence of PCE and TCE in the selected supply well indicates that, once these contaminants reach the upper confined aquifer by short-circuit pathways, degradation rates are not fast enough relative to residence time to prevent all PCE and TCE from reaching the well.

Paradoxically, short-circuiting seems to override the expected attenuation of uranium in the upper confined aquifer. Instead, it actually mobilizes uranium: the greatest uranium concentrations were found in mixed waters in the upper confined aquifer that were the result of multiscreened well leakage. It is thought that uranium sorbed to tiny particles of organic carbon and iron oxides from the unconfined aquifer travels down the leaking wells. Once in the anoxic conditions of the upper confined aquifer, the iron dissolves, releasing uranium that then complexes with the calcium and bicarbonate in the upper confined aquifer. The uranium-calcium complex facilitates transport of uranium under anoxic conditions that would otherwise cause the uranium to precipitate.

Human Activities Influence Public-Supply Well Vulnerability

Well-construction methods cause vulnerability. Well-construction methods used in development of the High Plains aquifer to supply large quantities of irrigation and drinking water have, upon retrospect, introduced short-circuit pathways that adversely affect quality of water produced by public-supply wells near York. Currently, contaminated water entering the base of the selected public-supply well by way of inactive wells that tap both aquifers is being diluted by enough old water from the upper confined aquifer that contaminant concentrations are less than Federal drinking-water standards. Uranium concentrations, in particular, in the mixed water entering the base of the well screen would cause the water-supply well to exceed the U.S. Environmental Protection Agency Maximum Contaminant Level allowed in drinking water if dilution by old water were not occurring. Human activities that might decrease the ratio of old to young water being produced by the public-supply well could have adverse impacts on drinking-water quality.

Pumping rate of the public-supply wells has little effect on movement of contaminants to the upper confined aquifer relative to pumpage of irrigation wells. Because the amount of water withdrawn by irrigation wells in the area is so much greater than withdrawals by public-supply wells, the pumping of public-supply wells generally has little effect on the magnitude of the downward flow between aquifers or the volume of young, contaminated water migrating down inactive wells. However, the pumping of a public-supply well may affect direction of contaminant movement once the young water reaches the upper confined aquifer because a pumping well captures water that would, under non-pumping conditions, flow past the well. A greater pumping rate will have a greater zone of contribution that is likely to capture leakage from more multiscreened wells. However, the overall effect of a greater zone of contribution is difficult to predict because a greater volume of old water also is likely to be intercepted. The impact on water quality would depend on the resulting ratio of old to young water that is produced. Another effect of greater pumping rate is to increase the rate of ground-water flow to the well, which shortens the time available for natural geochemical reactions to attenuate contaminants in the upper confined aquifer.

Number and proximity of leaking wells to the public-supply well strongly influences vulnerability. The volume of water that leaks into the upper confined aquifer through multiscreened wells will depend on the number of leaking wells, their pumping rate (if they are seasonally pumped or pumped at a low rate that does not overcome downward flow between aquifers), and well construction (well diameter and length of screened or open interval). The difference in water level between the confined and unconfined aquifers also affects volume of leakage. A greater volume of water coming from leaking wells means that a greater proportion of young water to old water will be produced by the public-supply well, which will reduce the amount by which contaminants are diluted by old water.

Figure 2 (next page) shows the simulated area contributing recharge to the selected public-supply well in York. The odd shape of the area contributing recharge—especially the isolated zones to the west of the primary contributing recharge area—is influenced by the location of wells simulated to be leaking as well as by the location of other pumping wells in the area. Figure 2 also shows that a public-supply well is more susceptible to contamination from a leaky multiscreened well located nearby than one located at a distance. For example, in the dark-blue zone in figure 2, a simulated 71 to 80 percent of the recharge water to the multiscreened well in that area is captured by the public-supply well. Compared to this is one of the more distant, light-green zones, where less than 10 percent of the recharge water to the multiscreened well in that area reaches the public-supply well. Note that the location and condition of multiscreened wells or boreholes may be difficult to determine (especially those that have been abandoned)—making it difficult to estimate the number and proximity of leaking wells to the public-supply well.

All factors mentioned above, as well as the types of contaminants captured by the leaking wells and the pumping rate of the supply well relative to other pumping centers in the area, interact to influence the quality of water produced by a well. For instance, although nitrate concentrations in the public-supply well studied in York were very low (less than 0.2 mg/L), nitrate concentrations in other public-supply wells in York have exceeded drinking-water standards in the past, indicating that short-circuiting and pumping stress can overcome dilution and attenuation processes under some circumstances.

Protection Effort Implications

Efforts to protect drinking-water supplies derived from ground water generally rely on restricting activities within the area contributing recharge to a public-supply well. For confined aquifers, the general area of protection around the wellhead may be defined by use of a time-of-travel calculation (U.S. Environmental Protection Agency, 1991). Although it has long been recognized that discrete short-circuit pathways through a confining unit can exist and that such areas should be afforded a higher level of

Collecting samples at multiple depths in a pumping public-supply well.

protection (U.S. Environmental Protection Agency, 1991), figure 2 shows the actual complexity that may arise when numerous short-circuit pathways (in this case, leaky multiscreened wells) are present in the surrounding aquifer. Because it is unlikely that all leaking wells can be accurately identified, the role of a confining unit as a hydrogeologic barrier to movement of contaminants may be compromised in ways that cannot be anticipated.

Land-use management within the area contributing recharge to a public-supply well can affect the quality of water produced by the well. Changes such as converting land use from agricultural to urban, increasing the number of septic systems because of population growth, or restricting development as part of wellhead-protection efforts can all affect the concentration of anthropogenic chemicals in recharge. The lag time between changes in chemical input concentrations near the land surface and resulting changes in concentrations of the chemical in a public-supply well will depend upon the mix of water of different ages produced by the well; this mix is a direct consequence of the section of aquifer intersected by the well screen and the proximity of any short-circuiting feature. For example, using the simulated age distribution of water produced by the selected public-supply well in York (fig. 1), the effects of changes in concentrations of nitrate in ground-water recharge were estimated. The calculations included leakage through multiscreened wells and denitrification in the upper confined aquifer. Projections of nitrate concentrations expected in the future indicate that the peak value of nitrate reaching the selected public-supply well lags behind the peak input concentration in recharge by approximately 30 years because of the particular mix of water of different ages produced by the well. Knowledge of the speed with which changes in land use would be expected to affect water quality in supply wells is critical when implementing and evaluating the effectiveness of management actions on ground-water quality.

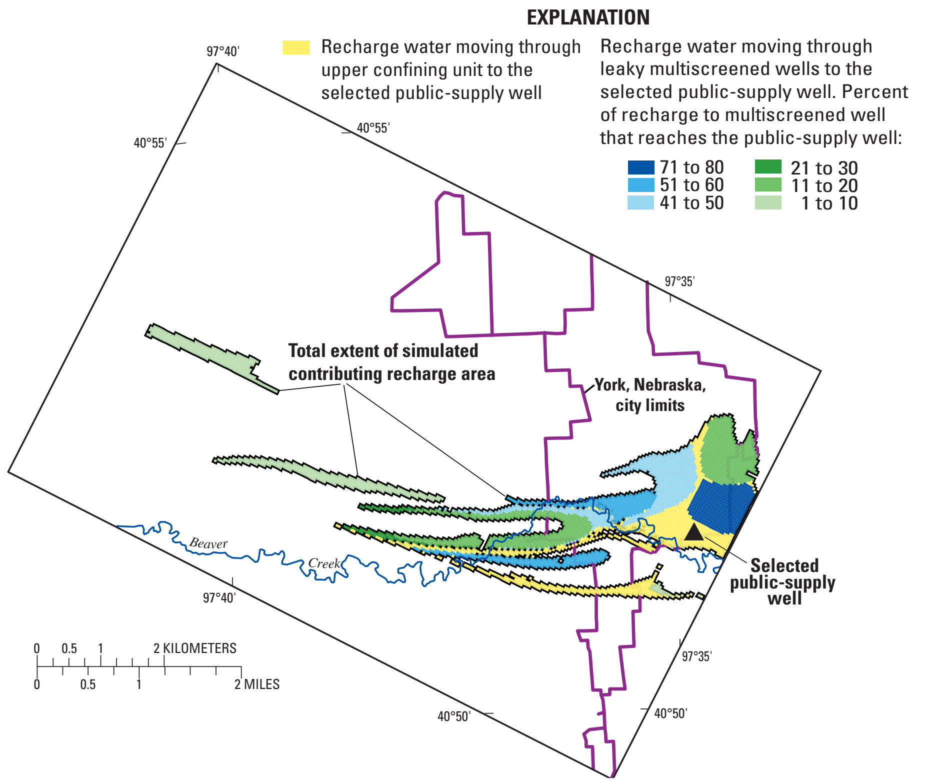


Figure 2. The shaded zones on the map show the simulated area contributing recharge to a supply well in York, Nebraska. These zones indicate where water that eventually reaches the selected supply well enters the ground-water system at the water table. Inactive wells in the surrounding aquifer system allow water in the unconfined aquifer to short-circuit the underlying confining unit and travel to the supply well in unexpected ways. This process results in a contributing area that is relatively complex and difficult to predict. Note that the area contributing recharge will be altered if the ground-water flow modeler simulates that a different set of inactive wells are leaking.

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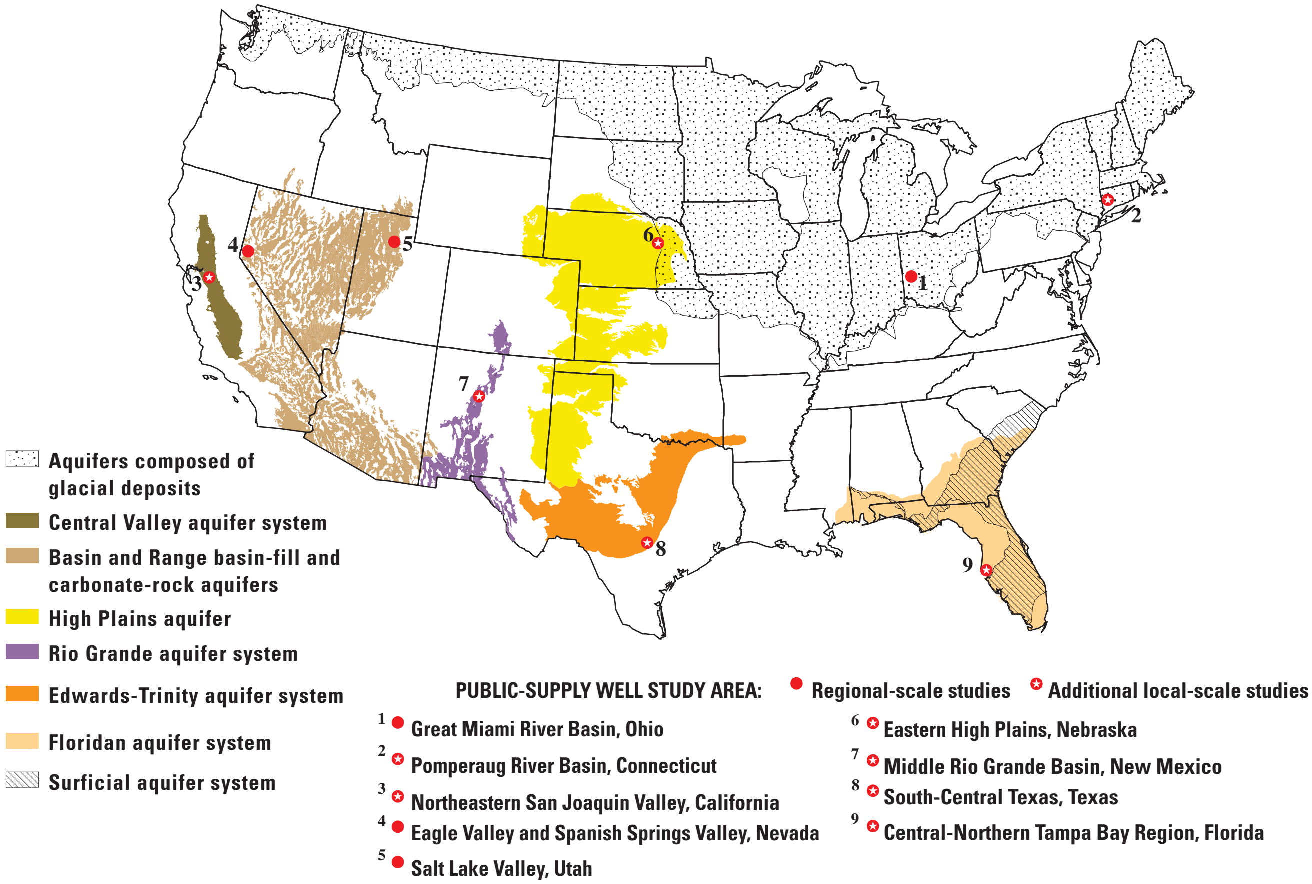

Locations of previous or ongoing studies of public-supply well vulnerability to contamination from urban, agricultural, and natural sources. Studies began in seven states in 2001 and in Texas and New Mexico in 2005; one study is scheduled for New Jersey in 2009.

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The NAWQA Program

The study of public-supply well vulnerability is one of five national priority topics being addressed by the NAWQA Program in its second decade, which began in 2001. Other topics include effects of urbanization on stream ecosystems; ecological effects of nutrient enrichment; mercury in stream ecosystems; and sources, transport, and fate of agricultural chemicals. In addition, anthropogenic organic contaminants in source waters for many of the Nation's largest community water systems are being assessed; concentrations in source waters are being compared to concentrations in finished waters. During the Program's first decade, NAWQA scientists assessed surface- and ground-water chemistry, stream hydrology, habitat, and biological communities in 51 major river basins ("Study Units"; see map at http://water.usgs.gov/nawqa). Baseline assessments of pesticides, nutrients, VOCs, trace elements, dissolved solids, and radon, and of the condition of aquatic habitats and fish, insect, and algal communities are described in hundreds of reports, available at the Web site above. Reassessments planned in 42 of the Study Units in the Program's second decade will determine trends at many of the streams and ground-water sites; fill critical gaps in the characterization of water quality; and build upon findings that show how natural features and human activities affect water quality and aquatic ecosystems.

For more information on the Transport of Anthropogenic and Natural Contaminants to Supply Wells (TANC) topical study, see

http://oh.water.usgs.gov/tanc/NAWQATANC.htm