

The Quality of Our Nation's Waters

Factors Affecting Public-Supply-Well Vulnerability to Contamination: Understanding Observed Water Quality and Anticipating Future Water Quality

National Water-Quality Assessment Program

Circular 1385

U.S. Department of the Interior
U.S. Geological Survey



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By Sandra M. Eberts, Mary Ann Thomas, and Martha L. Jagucki

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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (<http://www.usgs.gov/>). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (<http://water.usgs.gov/nawqa>). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and groundwater? How are conditions changing over time? How do natural features and human activities affect the quality of streams and groundwater, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studies/study_units.html).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and groundwater. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between sources of contaminants, the transport of those contaminants through the hydrologic system, and the potential effects of contaminants on humans and aquatic ecosystems. Included are studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

William H. Werkheiser

USGS Associate Director for Water

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NAWQA personnel across the Nation for their contributions of data, research results, and review of findings

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ABBREVIATIONS, ACRONYMS, AND UNITS OF MEASURE

ACR	Area contributing recharge	NLCDE	Enhanced National Land Cover Data
bls	Below land surface	NM	New Mexico
C/C_0	Ratio of predicted concentration to initial concentration	NO_3	Nitrate
CA	California	NV	Nevada
CFC	Chlorofluorocarbon	O_2	Oxygen
CFC-11	Trichlorofluoromethane	OH	Ohio
CFC-12	Dichlorodifluoromethane	PCE	Perchloroethene
CT	Connecticut	per mil	Parts per thousand
Delta	Enrichment or depletion relative to a standard of known composition	SF_6	Sulfur hexafluoride
Fe	Iron	SO_4	Sulfate
FL	Florida	TCE	Trichloroethene
ft	Foot (feet)	TX	Texas
gal/min	Gallons per minute	USEPA	U.S. Environmental Protection Agency
gpm	Gallons per minute	USGS	U.S. Geological Survey
H_2S	Hydrogen sulfide	U.S.	United States
HBSL	Health-Based Screening Level	UT	Utah
in.	Inch	VOC	Volatile organic compound
km	Kilometer	yr	Year
L	Liter	ZOC	Zone of contribution
MCL	Maximum Contaminant Level	ZOI	Zone of influence
mg	Milligram	ZOT	Zone of transport
mg/L	Milligrams per liter	^2H	Deuterium
mi	Mile	3-D	Three dimensional
mi^2	Square mile	^3H	Tritium
Mn	Manganese	^{18}O	Oxygen-18
MODFLOW	USGS modular groundwater-flow model	μg	Microgram
MTBE	Methyl <i>tert</i> -butyl ether	$\mu\text{g/L}$	Micrograms per liter
N	Nitrogen	>	Greater than
NAWQA	National Water-Quality Assessment Program (USGS)	\geq	Greater than or equal to
NE	Nebraska	<	Less than
NJ	New Jersey	\leq	Less than or equal to
		%	Percent



About 35 percent of the population in the United States receives its drinking water from public-supply wells, such as the one here. Consequently, it is important to understand what factors affect public-supply-well vulnerability to contamination from chemicals or microorganisms in the groundwater.

Overview— Major Findings and Implications

1

As part of the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program, a study was conducted from 2001 to 2011 to shed light on factors that affect the vulnerability of water from *public-supply wells** to *contamination*. The study was designed as a follow-up to earlier NAWQA studies that found mixtures of contaminants at low concentrations in *groundwater* near the *water table* in urban areas across the Nation and, less frequently, in deeper groundwater typically used for public supply (Hamilton and others, 2004). Although contaminants were less frequently detected in public-supply wells than in shallower *monitoring wells*, a separate study showed that contaminant concentrations were greater than drinking-water standards or other human health benchmarks in about 22 percent of public-supply-well samples (Toccalino and Hopple, 2010).

An Issue of Human Health and Economics

These previous NAWQA findings imply that water from nearly one in five public-supply wells in the United States might need to be treated or blended with more dilute water sources to decrease concentrations of *drinking-water contaminants* before delivery to the public. Therefore, understanding factors that affect the vulnerability of water from public-supply wells to contamination (also referred to herein as *public-supply-well vulnerability*) is important because removing contaminants from water intended for drinking is difficult, expensive, and becoming increasingly necessary (Job, 2011). Of particular concern is recent evidence that existing water-treatment systems do not effectively remove some contaminants now being found in groundwater (Hopple and others, 2009). Even when effective water-treatment technologies exist, it is especially difficult for small system operators to implement such technologies because their small customer base might not be able to cover the costs.

A Water-Management Challenge

Well-field operators, water-resource managers, drinking-water regulators, and scientists have long realized that water from public-supply wells is vulnerable to contamination. However, it has been unclear why water from some wells becomes more contaminated than water from other wells, even when contaminant sources are similar. The role that water resource development (drilling and pumping of



A better understanding of public-supply-well vulnerability to contamination can lead to a reduced need for treatment of drinking water.

*Italicized words are defined in the glossary.

new wells) and well operation play in public-supply-well water quality also has been unclear.

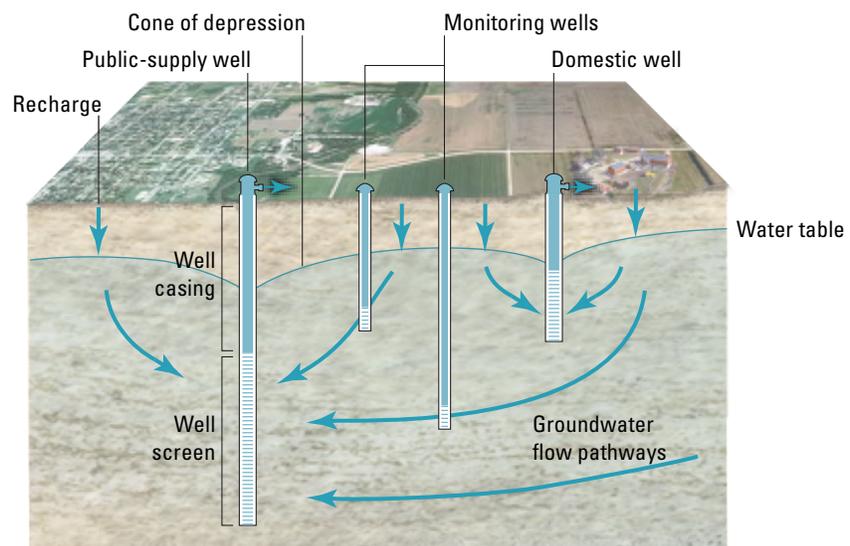
NAWQA's study of public-supply-well vulnerability to contamination found that it is possible to understand—as well as anticipate—the quality of water from a public-supply well by knowing what factors to evaluate and how to go about evaluating them. Factors affecting public-supply-well vulnerability to contamination are the topic of this circular. Measures that can be used to determine which factor (or factors) plays a dominant role at an individual public-supply well also are described. Case-study examples are used throughout the circular to show how such information can be used to improve water quality.

Study findings can be applied by drinking-water practitioners not only to devise improved programs for monitoring public-supply wells and the *aquifers* they tap but also to identify the most beneficial protection mechanisms for a particular well. Insights gained from the study will aid managers in making informed decisions in siting and constructing new public-supply wells and will help them anticipate the response of different wells to changes in management practices. Ultimately, the findings of this study can be used to update and enhance existing assessments of public-supply-well vulnerability across the Nation and to design strategies for preventing future contamination of such wells—thus helping to sustain the Nation's water supply.

Is There a Difference Between Groundwater Vulnerability and Public-Supply-Well Vulnerability?

Study findings demonstrate that *groundwater vulnerability* and public-supply-well vulnerability are not the same. Groundwater vulnerability depends on three factors. First is the presence of manmade or natural contaminant sources; for example, leaky underground petroleum storage tanks and arsenic-rich aquifer sediments can be sources of contaminants entering groundwater. Second is the combination of chemical and physical processes in the subsurface that affect contaminant concentrations in an aquifer; for example, microorganisms can break down or degrade some chemical contaminants in groundwater, and unsorted sediments can cause

The long well screens and high pumping rates that are typical of public-supply wells draw in water from multiple groundwater flow pathways within an aquifer. These flow pathways often originate over broad areas. In contrast, monitoring and domestic wells tend to capture water from more localized parts of an aquifer. Because groundwater contaminants generally are not uniformly distributed throughout an aquifer, differences in the location, design, construction, operation, and maintenance of different wells can lead to differences in the quality of water from different wells within the same aquifer.



dispersion of contaminants as they move through an aquifer. Third is the ease with which water and contaminants can travel to and through an aquifer, also referred to as *intrinsic susceptibility*; for example, a thick layer of dense clay can reduce groundwater vulnerability by acting as a barrier to the movement of water and contaminants.

The vulnerability of a public-supply well depends on all of the above factors (contaminant input, contaminant mobility and persistence, and intrinsic susceptibility) but is further affected by the location, design, construction, operation, and maintenance of the well. For example, the location of a well determines whether a particular contaminant source is in the area that contributes water to the well. The placement of the *well screen* determines which chemical and physical processes in the aquifer have influenced the water before it is pumped from the well and, therefore, which contaminants might be present in the water as it enters the well, and at what concentrations. The depth of the well screen and the pumping rate of the well determine how quickly water and contaminants can travel from the water table to that particular well, and from what distance. Because well design, construction, and operation directly influence water quality, water produced by different types of wells (public-supply, domestic, and monitoring wells) might not contain the same concentrations of contaminants, even if the wells are completed at similar depths within the same aquifer.

What Measures of Vulnerability are Useful for Individual Public-Supply Wells?

Study findings indicate that information on contaminant input, contaminant mobility and persistence, and intrinsic susceptibility within the area that contributes water to a well can help answer the question, “Which contaminants in an aquifer might reach the well, and when, how, and at what concentration might they arrive?”

Study-team scientists found that the following measures—each related to a different aspect of public-supply-well vulnerability—are particularly useful for understanding the quality of water pumped from individual public-supply wells:

- (1) the sources of *recharge* that contribute water to a well, and the contaminants associated with the recharge—a measure of contaminant input;
- (2) the *geochemical conditions* encountered by water drawn into a well—a measure of contaminant mobility and persistence; and
- (3) the *groundwater-age mixture* of different waters that blend (or mix) in a well—a measure of intrinsic susceptibility.

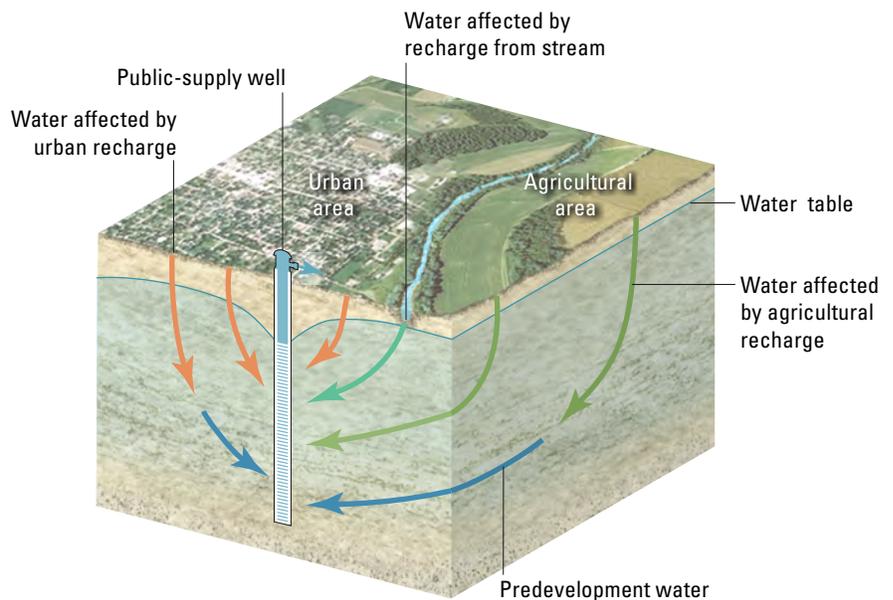
These measures of public-supply-well vulnerability and examples illustrating their utility for decisionmaking are discussed herein. Related implications for public-supply-well water quality are noted.

Sources of Recharge

SOURCES OF RECHARGE Implications

- Identifying the sources of recharge that contribute water to different wells will help explain differences in contaminants and contaminant concentrations in wells that are close to each other but that draw in water from different recharge areas.
- Changes in the quality of water produced by a public-supply well over time—even in general characteristics such as temperature, pH, alkalinity, and dissolved-solids concentration—warrant investigation so that any new source(s) of water (and associated contaminants) for the well can be identified and managed to minimize adverse effects.

The quality of water pumped from a public-supply well depends on the proportions of (and contaminant concentrations in) waters from different recharge areas that enter and mix in the well. In this study, several methods were used to identify the sources of recharge for public-supply wells so that the quality of water from the wells could be better understood. For example, study-team scientists used chemical characteristics that were unique to different water sources to determine the origins of water produced by a public-supply well in Nebraska. Contrary to original expectations, not all of the water from the well was from the *confined aquifer* tapped by the well. Instead, at least 12 percent of the water was from an overlying aquifer that was previously thought to be hydraulically isolated from the confined aquifer. Understanding that another aquifer was contributing urban recharge to the well helped explain why *anthropogenic* contaminants were detected in water from the well. Knowing which parts of an *aquifer system* contribute water to a well can prompt scientists or water-resource managers to explore the mechanism that enables low-quality water to reach the well, potentially uncovering an important vulnerability for the water supply.



Different groundwater flow pathways can bring different sources of water to a well. For example, different sources of water for the well in this figure include recharge through urban land (shown in orange), recharge through agricultural land (green), infiltrating stream water (blue green), and water that recharged centuries ago, before urban and agricultural development in the area (dark blue). The different sources of water would be associated with different types and amounts of contaminants, which would mix in the well and collectively contribute to the quality of water from the well.

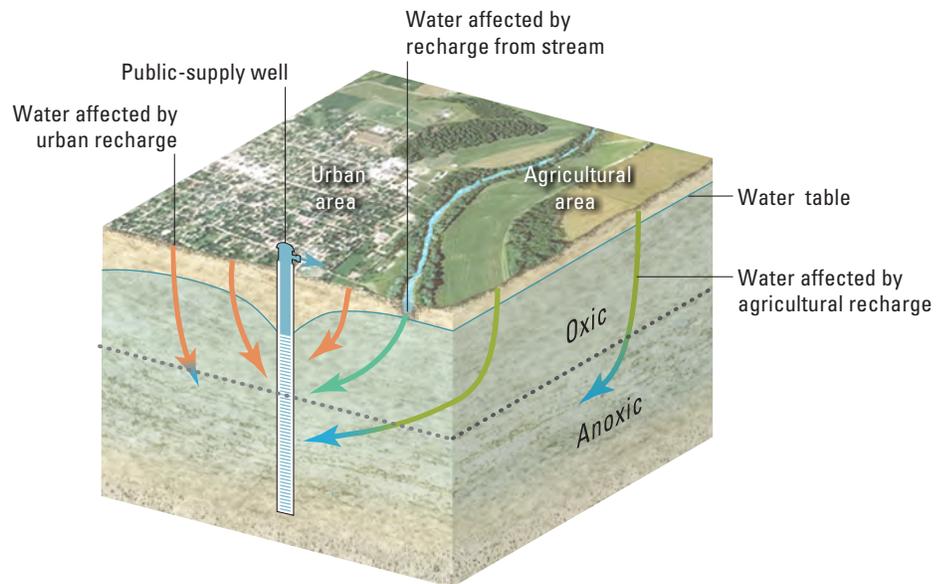
GEOCHEMICAL CONDITIONS Implications

- Communities that determine whether the water from their public-supply well(s) is being drawn from oxic, anoxic, or multiple geochemical zones within an aquifer will have insight into which drinking-water contaminants in the groundwater are likely to reach their well(s) and which are likely to be assimilated by the aquifer before the water arrives at a well.
- Caution is needed when developing aquifers for increased water supply because modifying groundwater flow in some aquifers has altered geochemical conditions and caused contaminants such as arsenic and uranium (which occur naturally in aquifer rocks and sediments) to dissolve into the groundwater, where they were then drawn into public-supply wells.

Geochemical Conditions

Geochemical conditions influence whether a contaminant that has been released to the groundwater will travel with the groundwater, react with the *aquifer material*, or degrade before reaching a public-supply well. USGS scientists used various methods to understand the effects of geochemical conditions on the quality of water from public-supply wells. Most notably, study-team scientists developed a simple and inexpensive method for characterizing whether the water from a well is derived from *oxic* (dissolved oxygen ≥ 0.5 milligram per liter), *anoxic* (dissolved oxygen < 0.5 milligram per liter), or mixed geochemical conditions in an aquifer, and the method was applied to wells in each study area. The utility of the method can be illustrated with the glacial aquifer system of the Northern United States. In the glacial aquifer system, geochemical conditions identified by using the method were a good indicator of the likelihood of detecting (or not detecting) arsenic concentrations greater than the drinking-water standard.

An unexpected finding of this study was that human activities altered recharge or changed groundwater flow in ways that led to changes in aquifer geochemical conditions in most study areas. These changes resulted in chemical reactions between the groundwater and the solid aquifer material, releasing naturally occurring drinking-water contaminants (such as arsenic or uranium) into the groundwater. As a result, concentrations of these chemicals in water from *study wells* increased.



Geochemical conditions in an aquifer—especially dissolved oxygen content, pH, and alkalinity—strongly influence whether chemical contaminants are mobile and travel with the groundwater, whether they are bound to aquifer materials, or whether they degrade before reaching a well. For example, nitrate is stable under oxic conditions but is converted to harmless nitrogen gas in anoxic conditions through a process called denitrification. In this figure, nitrate in the urban recharge (shown in orange) would persist along most flow pathways between the urban area and the well because the water remains within the oxic zone of the aquifer. However, nitrate in the agricultural recharge (green) would degrade (“denitrify,” shown as change to blue) before reaching the well because of the anoxic conditions encountered.

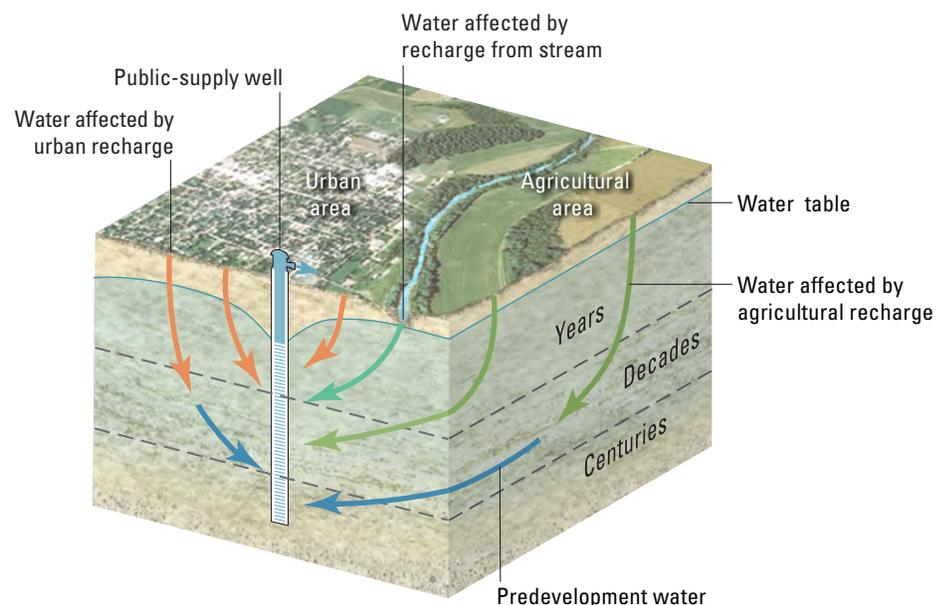
Groundwater-Age Mixtures

The water that is pumped from a public-supply well did not recharge the surrounding aquifer at a single point in time. Rather, public-supply wells produce water with a mixture of *groundwater ages*. (Groundwater age refers to the number of years since water entered an aquifer system at the water table.) The groundwater-age mixture for a well reflects recharge and *discharge* rates and physical properties of the aquifer that together control the movement of water and contaminants to a well. An estimate for the age mixture of the water from a well provides insight into the likelihood of contamination from both anthropogenic and natural sources. Young (recently recharged) groundwater that enters a well is more vulnerable to contamination from human activities near the land surface than older, deeper groundwater. Old groundwater, however, is not necessarily free of contaminants. Old groundwater can contain naturally occurring chemical elements that can contaminate the water for the purpose of drinking.

If the age mixture of a particular well's water corresponds to a period of recharge that is longer than the duration of contaminant input, then some in-well dilution of contaminants entering the well is indicated. The dilution will occur because some of the water entering the well will have recharged the aquifer either before or after the time during which the contaminants were released to the groundwater. Consequently, wells that produce water with a wide range of groundwater ages have some degree of protection from high levels of contamination.

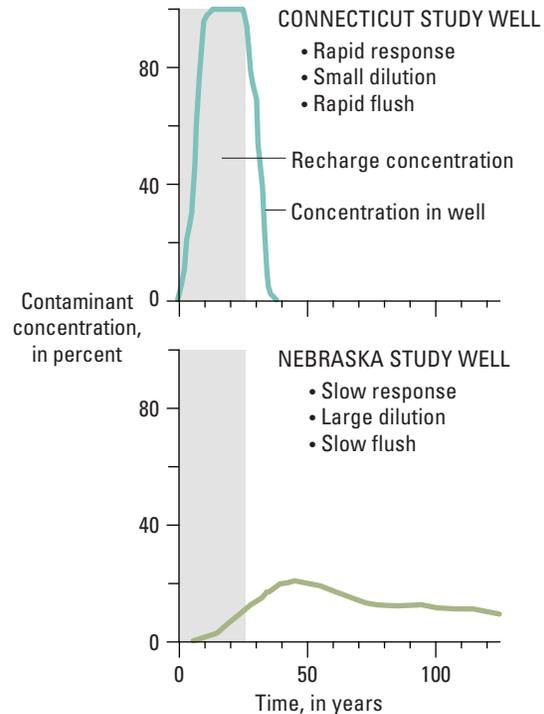
To help explain water quality in public-supply wells, study-team scientists developed a tool (TracerLPM) for estimating the groundwater-age mixture for a well on the basis of measured concentrations of chemical tracers. Once the groundwater-age mixture for a well has been estimated by using the tool, the age mixture can then be used to forecast water-quality changes at the well in response to changes in contaminant input across the water table.

Because public-supply wells have long well screens and are pumped at relatively high rates, they draw in water that has been in the surrounding aquifer for different amounts of time. The resulting "age mixture" for the water from a well can be used to estimate how long it will take contaminants in the surrounding aquifer to arrive at the well and can affect the concentration of contaminants in the water produced by the well. For example, groundwater flow pathways that converge on the well in this figure simultaneously deliver water to the well that recharged the aquifer a few years ago and centuries ago. Only the younger water would contain contaminants associated with recent land use. The water that takes centuries to reach the well would not contain anthropogenic contaminants and would dilute the contaminants in the young water as the different waters mix in the well. However, the older water could bring naturally occurring drinking-water contaminants to the well.



Groundwater-age mixtures affect water-quality response

USGS scientists used information on the age mixture of the water from study wells in Connecticut and Nebraska to forecast how the quality of water from two very different wells might change in response to the same hypothetical 25-year contaminant release to the water table across the area contributing recharge to each well. The maximum contaminant concentration likely to be reached at each well—relative to the concentration in the recharge—is shown by the height of the curves in this figure. How rapidly contaminants would be flushed from the wells after input at the water table ceases is shown by the horizontal extent of the curves. The very different response in the two wells is entirely due to differences in the groundwater-age mixtures for the wells. More than 90 percent of water entering the Connecticut well is less than 10 years old. As a result, a contaminant could rapidly reach the well but also could be rapidly flushed from the well. In contrast, more than 95 percent of the water entering the Nebraska well is greater than 10 years old, and much of the water is hundreds to thousands of years old. As a result, old water entering the well would continuously dilute contaminants in younger water entering the well, but the contaminants would not be completely flushed from the well for a very long time.



GROUNDWATER-AGE MIXTURES Implications

- Knowledge of groundwater-age mixtures is important for prioritizing protection efforts. For example, managing contaminant sources within source water protection areas defined by groundwater traveltime is more beneficial for wells that produce predominantly young water than for wells that produce water that is generally older than the specified traveltime.
- There is a tradeoff when a well is deepened to decrease vulnerability to anthropogenic contaminants in young, shallow groundwater: deeper water, which has been in contact with the aquifer material for a longer time, often contains higher concentrations of naturally occurring drinking-water contaminants.
- Several years or even decades of monitoring will not be enough to characterize water-quality changes in public-supply wells that result from changes in land use or land management if most of the water from the wells is relatively old. A combined monitoring and modeling approach is needed for such wells to determine how long contaminant concentrations will continue to increase in the produced water after nonpoint-source-contaminant input at the water table is reduced.

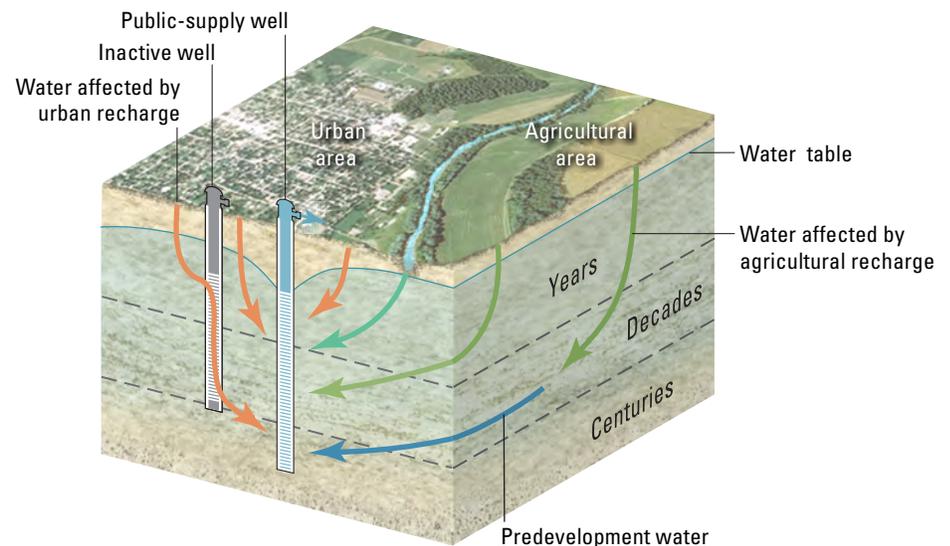
What Are Preferential Flow Pathways and Why Do They Matter?

Study findings show that vulnerability measures often reveal the presence of *preferential flow pathways* and their influence on the transport of groundwater and contaminants. Preferential flow pathways are pathways that provide little resistance to flow. They can be naturally occurring (for example, fractures in rocks or interconnected high-*permeability* sediments) or manmade (for example, a *wellbore*). Preferential flow pathways are widely present, because their effects were observed in all study areas. Although difficult to locate, they are important to understand because they can affect every other factor contributing to the vulnerability of water from a public-supply well.

Groundwater and contaminants traveling along preferential flow pathways will be accelerated more than groundwater and contaminants traveling through the aquifer *matrix* when pumping of a well begins. This acceleration can cause groundwater-flow rates within preferential flow pathways to be high compared with contaminant *degradation* rates, resulting in reduced effectiveness of natural processes that degrade groundwater contaminants (for example, *denitrification*). Rapid flow through preferential flow pathways has increased concentrations of anthropogenic and naturally occurring contaminants in groundwater, the latter by bringing together water and aquifer materials that are not in chemical equilibrium. Preferential flow pathways also create favorable conditions for the transport of *pathogens*: rapid *travel times* (which reduce the opportunity for microorganism die-off) and relatively large interconnected openings (which reduce the removal of microorganisms through filtration or *sorption* to sediments or rocks).

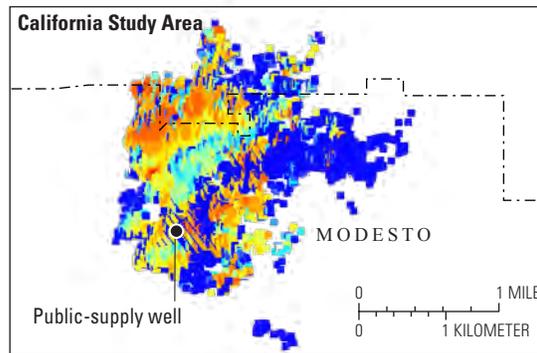
A USGS study of water quality in public-supply wells (Toccalino and Hopple, 2010) found that about one-third of the detections of anthropogenic contaminants were in groundwater from aquifers underlying low-permeability *confining units*. This surprising result suggests that preferential flow pathways across confining units might be common. As part of the study summarized in this circular, USGS scientists identified various ways to recognize instances in which preferential flow pathways are affecting the quality of water from a public-supply well.

Preferential flow pathways often deliver the youngest, most vulnerable water to public-supply wells, along with most of the anthropogenic contaminants that enter such wells. For example, in this figure, an inactive well near the public-supply well enables water with urban contaminants (shown in orange) to enter the public-supply well at a depth that would otherwise draw in only old, uncontaminated water (dark blue). As a result, the total amount of urban contaminants entering the well is higher than if the inactive well had not provided such an easy route for the contaminated water to travel.



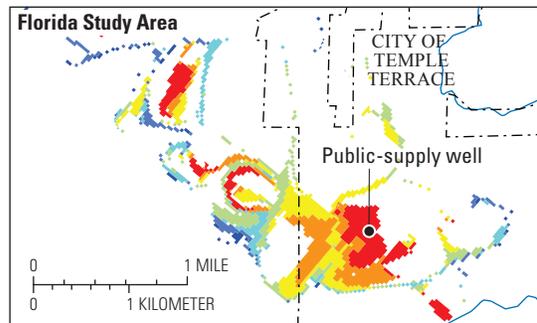
Preferential-flow pathways make it difficult to know which areas to protect

Local-scale *groundwater-flow models* were constructed for several study areas and used to estimate the area at the land surface that contributes recharge to a typical public-supply well in each study area. The groundwater traveltimes from these *recharge areas* to the wells also were calculated. Results from the California and Florida models, which include enough detail to simulate preferential flow, demonstrate that some of the shortest traveltimes to a well (shown in shades of red in the figures) can be associated with recharge areas that are at great distances from the well. In these study areas, preferential flow occurs either through overlapping lenses of coarse-grained sediments or naturally occurring conduits and cavernous zones in limestone bedrock. Source water protection efforts that focus on the areas closest to a public-supply well will not protect the well from contaminated recharge entering the aquifer further away from the well but traveling rapidly to the well along preferential flow pathways.



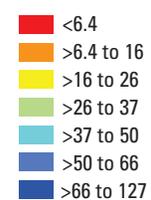
Groundwater travels preferentially through overlapping lenses of coarse-grained sediments.

Estimated traveltime from recharge area to public-supply well, in years



Preferential flow occurs within naturally occurring sinkholes and conduits caused by dissolution of limestone bedrock.

Estimated traveltime from recharge area to public-supply well, in years



PREFERENTIAL FLOW PATHWAYS

Implications

- A general campaign to engage everyone in groundwater protection is worthwhile because preferential flow pathways make it difficult to know where the youngest groundwater that is drawn into a well actually originates. Protecting a delineated area around a public-supply well from contamination is necessary but may be insufficient if preferential flow pathways are present.
- Characterizing the groundwater chemistry in different parts of an aquifer system (in addition to characterizing contaminant occurrence) increases the likelihood of detecting the influence of preferential flow pathways on the quality of water from a public-supply well. Although widely present, preferential flow pathways occupy just a fraction of an aquifer system and are difficult to locate, whereas groundwater-chemistry data have been successfully used to identify situations where water from unexpected parts of an aquifer system is entering a well.
- Seasonal water-quality fluctuations in deep public-supply wells should alert water-resource managers to the possibility of preferential flow because recharge water is unlikely to travel from the water table through the aquifer matrix to a deep well screen within a single season.
- If manmade preferential flow pathways (such as wells screened through multiple aquifers or screened through different geochemical zones within the same aquifer) are affecting the quality of water being produced by a public-supply well, resource managers have an opportunity to devise effective means of preventing or minimizing flow through these features and reduce the vulnerability of the water from the well to contamination.

How Can Information on the Factors Affecting Public-Supply-Well Vulnerability—including Preferential Flow Pathways—Be Used to Guide Protection Decisions?

Study findings indicate that most processes controlling water quality in public-supply wells are related to a limited number of factors; however, the relative importance of any one factor might be different for different wells. These differences can have implications for how managers would protect the different wells from contamination. To illustrate this point, the pathways and processes whereby contaminants reached four study wells—as determined from site-specific information that includes the sources of recharge, geochemical conditions, and groundwater-age mixtures for the wells—are summarized below. Findings point to management strategies that might afford the greatest protection for a particular well.

Operation of Public-Supply Well Caused Seasonal Increases in Nitrate and Uranium (See pages 70–71, 82–83)

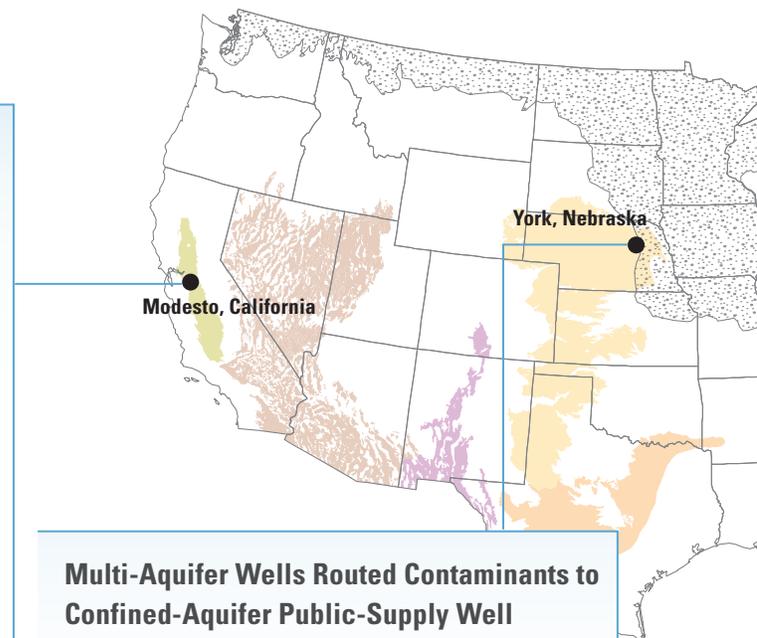
- Nitrate increased in young, shallow groundwater in response to agricultural and urban development.
- Uranium increased in shallow groundwater because irrigation-induced changes in aquifer geochemical conditions released uranium from sediments.
- Water from the study well had low concentrations of contaminants during summers because shallow, contaminated groundwater was diluted by older, uncontaminated groundwater as both types of water entered and mixed within the well.
- Water from the well had relatively high concentrations during winters because of preferential flow down the wellbore—contaminated water pooled in the aquifer around the bottom of the wellbore when the well was not pumping and then reentered the well along with shallow, contaminated water when the well resumed pumping.

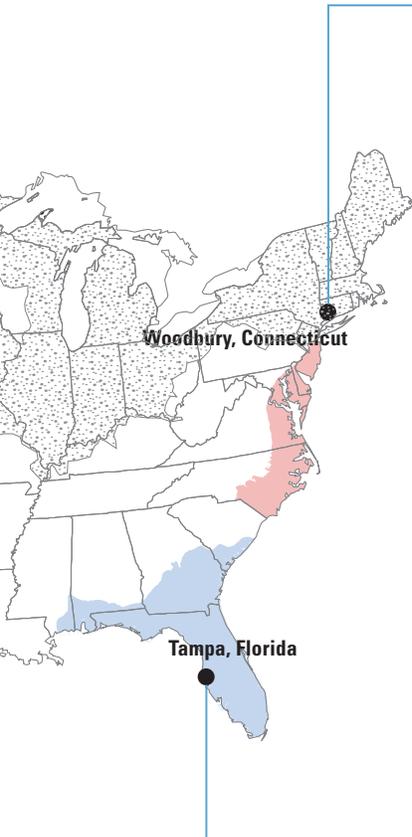
A short-term solution to this problem was less downtime between pumping periods during winter so that deep groundwater could retain its high quality and continuously dilute contaminants in shallow groundwater simultaneously entering the well.

Multi-Aquifer Wells Routed Contaminants to Confined-Aquifer Public-Supply Well (See pages 34–35, 72–73, 86–87)

- Low concentrations of several anthropogenic contaminants were detected in water from several confined-aquifer public-supply wells.
- Young, contaminated groundwater entered the study well beneath older, uncontaminated groundwater, indicating that the contaminants had traveled along a preferential flow pathway before reaching the well.
- Many irrigation wells in the surrounding area tapped both the confined aquifer and an overlying unconfined aquifer, creating pathways across the confining unit that enabled contaminants to enter the confined aquifer and travel to the supply wells.

Rethinking the use of multi-aquifer wells throughout the area could lead to improved protection of the confined-aquifer public-supply wells. For example, limiting irrigation wells to a single aquifer or making engineering modifications to prevent down-wellbore flow in existing wells could remove preferential flow pathways that allow anthropogenic contaminants to reach confined-aquifer public-supply wells in this area.





Young, Oxidic Groundwater Enabled Contaminants to Persist and Reach Public-Supply Well (See pages 67, 80–81)

- Urban recharge carried a variety of contaminants to the shallow groundwater—contamination was widespread, but concentrations were low.
- Traveltimes through the unsaturated zone were artificially short because dry wells (a type of preferential flow pathway) were used to redirect stormwater runoff into the aquifer.
- Many contaminants in the shallow groundwater remained in solution because of oxidic conditions.
- Short traveltimes between the water table and the study well (generally less than 10 years) enabled the contaminants to easily reach the well.

The many sources and types of contaminants in this area indicate that groundwater-quality protection depends on the entire community. If residents and businesses take steps to reduce input of anthropogenic contaminants to the groundwater, a positive effect on the study well might be seen in less than 10 years because of the short traveltimes between the water table and the well.

Pumping at Public-Supply Well Pulled Contaminants Through Karst Features (See pages 68–69, 84–85)

- Contaminants, such as nitrate, were commonly detected in shallow, oxidic groundwater in an unconfined sand aquifer but infrequently detected in monitoring wells in an underlying limestone aquifer.
- Water from the study well, which is open solely to the limestone aquifer, was chemically more similar to water in the shallow sand aquifer than to water in the limestone aquifer.
- Pumping at the study well pulled the shallow, contaminated groundwater into the deeper limestone and eventually into the well itself by accelerating the movement of groundwater and contaminants along karst features (sinkholes, conduits, and cavernous zones) that served as preferential flow pathways.

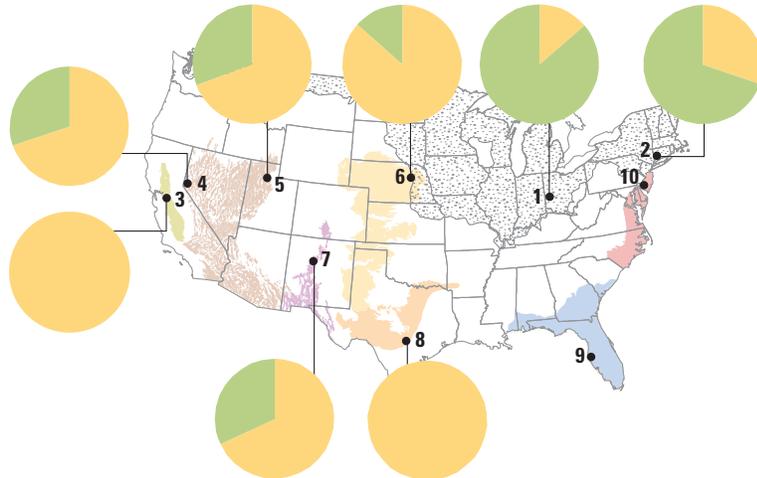
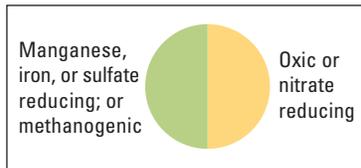
Not all public-supply wells are similarly connected to the sand aquifer. Therefore, one way to identify the most vulnerable public-supply wells in this area is to determine the degree to which the water from each well reflects that of the overlying sand aquifer. Protection efforts could then be intensified for the wells producing water most similar to that in the sand aquifer.

NOTE: Shaded areas on the map depict selected principal aquifers shown on page 19.

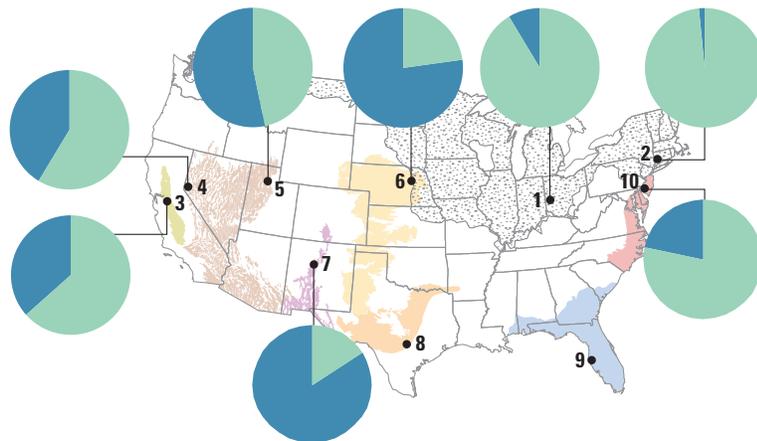
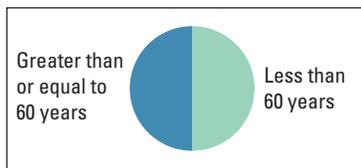
Can We See Patterns in Public-Supply-Well Vulnerability to Contamination?

Study findings demonstrate the existence of spatial patterns in the underlying factors affecting public-supply-well vulnerability to contamination. In other words, the input of contaminants to the groundwater, the mobility and persistence of contaminants once in the groundwater, the intrinsic susceptibility of the groundwater to contamination, and the presence and nature of preferential flow pathways are different for different aquifers. Consequently, systematic patterns in public-supply-well vulnerability to a variety of contaminants should be discernible and predictable, but vulnerability patterns for many commonly detected drinking-water contaminants remain largely unexplored in the United States. Nevertheless, the study described herein produced results that point to differences in the relative vulnerability of water from public-supply wells to contamination from *volatile organic compounds* (VOCs) in several sand and gravel aquifers. More specifically, water from public-supply wells in many sand and gravel aquifers in the Western United States was found to have low vulnerability to the gasoline components benzene, toluene, and MTBE (methyl *tert*-butyl ether) compared to water from wells in glacial aquifers in the Eastern United States. The difference is due to the predominantly oxic conditions in the western aquifers that promote the degradation of these compounds, together with the generally older water produced by the western-aquifer wells. The presence of older water indicates that (1) there is more time for degradation reactions to proceed before water reaches public-supply wells in the western aquifers, and (2) older water, which is generally free of anthropogenic contaminants, is available to dilute any such contaminants in younger water entering the western wells. (See pages 88–89.) With additional study, spatial and temporal patterns in the vulnerability of water from public-supply wells to contamination from additional contaminants could be uncovered.

A. Geochemical conditions



B. Age of groundwater



NOTE: Shaded areas on the map depict selected principal aquifers shown on page 19.

The vulnerability of each well is unique, but not necessarily random. Spatial patterns in the underlying factors affecting public-supply-well vulnerability to contamination exist, as illustrated in these figures depicting related measures of vulnerability obtained for this study. Individual maps portray the aggregate proportion of water from public-supply wells in each study area that was linked to various geochemical conditions and groundwater ages.

In figure A, public-supply wells in the California (3) and Texas (8) study areas generally produced oxic water, whereas wells in glacial aquifers in the Ohio (1) and Connecticut (2) study areas frequently produced more *reduced* water.

In figure B, public-supply wells in western aquifers withdrew a higher proportion of relatively old water than did wells in eastern aquifers.

Recognizing spatial patterns in the factors affecting public-supply-well vulnerability to contamination provides an opportunity to understand patterns in observed water quality and to anticipate which contaminants might show up in public-supply wells in different principal aquifers across the Nation.



When groundwater is the source of drinking water, a multi-barrier approach for protecting drinking water “from source to tap” must take into account the vulnerability of the water from the public-supply well(s) to contamination from chemicals and microorganisms released into the groundwater from activities near the land surface or from the solid aquifer material.

“...no water system should have to provide more treatment than that which is necessary to address naturally occurring pollutant concentrations...”

G. Tracy Mehan III,
U.S. Environmental Protection Agency,
Assistant Administrator for Water,
February 8, 2003, memo

More than 100 million people in the United States, or about one-third of the population, receive their drinking water from public-supply wells (USEPA, 2011). The water from such wells can be vulnerable to contamination from anthropogenic and naturally occurring chemicals, as well as microorganisms, in the groundwater. For example, the USGS analyzed water from more than 900 public-supply wells across the United States during 1993–2007. Twenty-two percent of the water samples—which were collected prior to treatment—contained at least one chemical contaminant at a concentration greater than a benchmark, indicating a potential concern for human health. Benchmarks were U.S. Environmental Protection Agency (USEPA) *Maximum Contaminant Levels* (MCLs) or USGS *health-based screening levels* (HBSLs) (Toccalino and others, 2010). More recently, a study of 383 public-supply wells distributed across 35 states showed that mixtures of two or more contaminants were present in more than 90 percent of the samples (Toccalino and others, 2012).

Well-field operators, water-resource managers, drinking-water regulators and scientists recognize that such vulnerabilities exist, but it is not always evident why some wells are more contaminated than others. Are there differences in the sources of recharge water (and contaminants) for the wells? Do processes below land surface differ in ways that result in *mobilization* of contaminants near some wells and *attenuation* of contaminants near others? Is it simply easier for contaminants to travel to some wells than to other wells? Do well operation and other water-management decisions contribute to differences in the quality of water from different wells?

Understanding factors that affect the vulnerability of water from public-supply wells to contamination is an issue that is relevant to both human health and economics. Water suppliers must be ever vigilant to ensure that the quality of the water they deliver to the public continually meets water-quality standards established to protect human health. However, removing contaminants from water intended for drinking is difficult and expensive. Furthermore, the water treatment processes currently used by many public water systems were never designed to remove many of the chemical contaminants now found in groundwater. For example, a USGS study found that concentrations of some herbicides, herbicide degradates, solvents, and several other chemicals in *finished water* were no different than concentrations detected in the source water (Hopple and others, 2009).

To ensure that high-quality drinking water is supplied to the public, multiple barriers to contamination must be in place: a risk prevention barrier, a risk management barrier, a risk monitoring and compliance barrier, and an individual action barrier (USEPA, 2002). USGS studies on public-supply-well vulnerability and water quality focus on the first line of defense against contamination of drinking water—that is, documenting and explaining the quality of groundwater that enters into and is pumped out of wells.

Understanding Water Quality in Public-Supply Wells

In 2001, the USGS NAWQA Program began an intensive study of public-supply-well vulnerability to contamination (Eberts and others, 2005). The purpose of the study was to increase understanding of detections of both anthropogenic and naturally occurring drinking-water contaminants (also referred to as “natural contaminants”) in water from the Nation’s public-supply wells. Study objectives were (1) assess the effects of natural processes and human activities on contaminant occurrence in water from public-supply wells, (2) identify factors that are important to evaluate when assessing public-supply-well vulnerability to contamination, (3) develop simple methods and models for screening public-supply wells for vulnerability to contamination, and (4) understand more clearly the potential effects of water-resource development and management decisions on the quality of water from public-supply wells. (Public-supply-well vulnerability to terrorist threats was not investigated.)

Translating Knowledge into Action

Findings from the study of public-supply-well vulnerability to contamination are summarized in this circular. The information can be used to help recognize which, when, how, and at what concentrations contaminants in an aquifer might occur in water pumped from public-supply wells. Several factors and related measures for assessing the vulnerability of individual public-supply wells to contamination—regardless of aquifer setting—are at the heart of the circular. Case-study examples are used to illustrate concepts and draw attention to findings with implications for the Nation’s groundwater sources of drinking water.

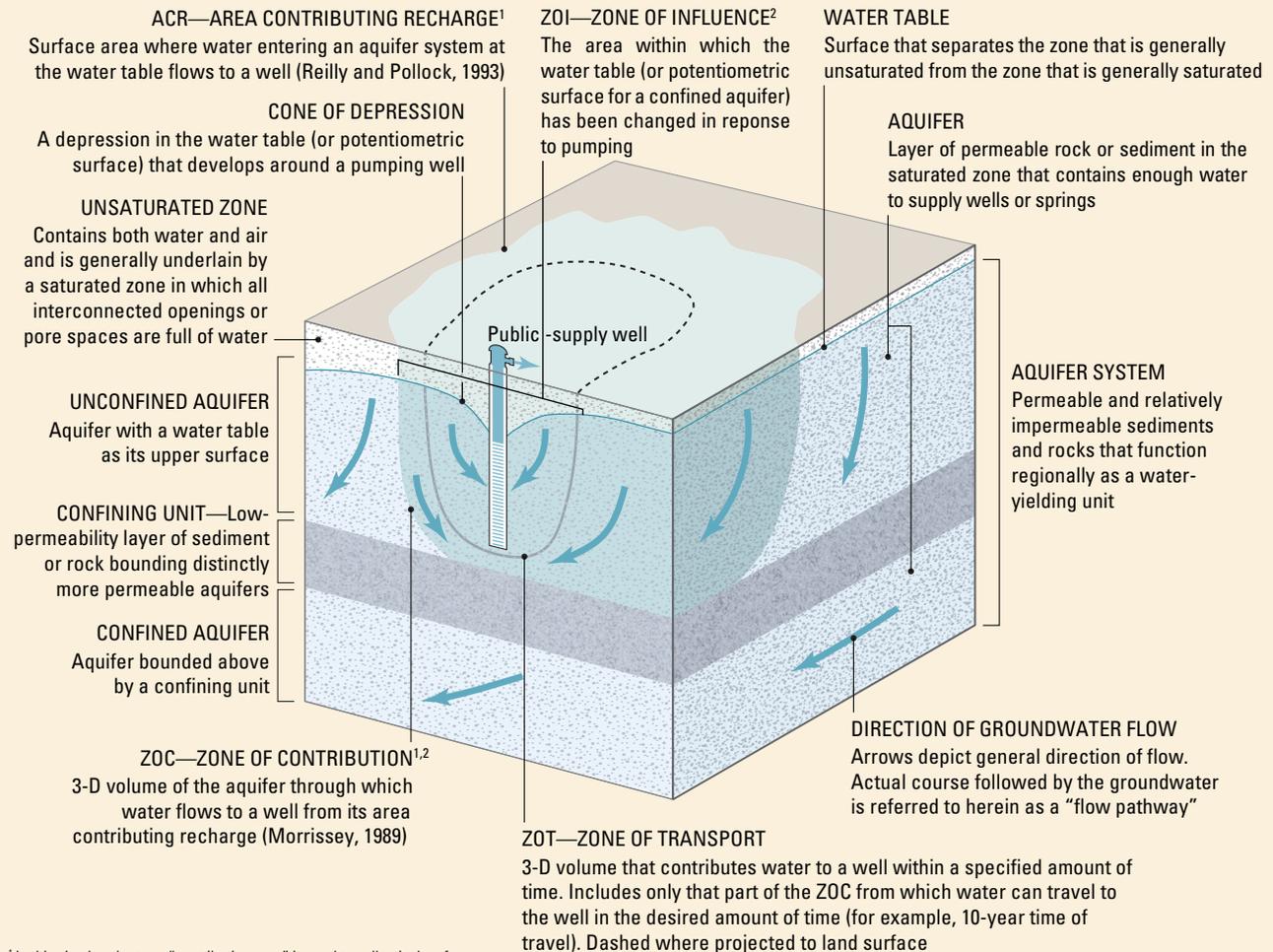
Source water assessment and protection— A part of the multi-barrier approach for ensuring safe, clean drinking water

The U.S. Environmental Protection Agency (USEPA) sets national drinking-water standards for public water systems and oversees state implementation of the standards to ensure safe drinking water. As outlined in the 1996 Amendments to the Safe Drinking Water Act, a comprehensive plan for drinking-water protection involves six steps to be taken by every community. The first three steps make up the assessment phase of a full prevention program and are required, whereas the last three steps constitute the actual protection phase and are not required. The six steps are (1) delineate (map) areas around surface-water intakes or public-supply wells to be protected from contamination, (2) inventory known and potential sources of contamination in these areas, (3) determine the susceptibility of the water-supply system to these contaminants, (4) notify and involve the public about identified threats and what they mean to their public water system, (5) implement management measures to prevent, reduce, or eliminate threats, and (6) develop contingency planning strategies to deal with water-

supply contamination or service-interruption emergencies (USEPA, 2002).

The USEPA has recommended five criteria for defining the area around a public-supply well that, if contaminated, could represent a threat to the quality of water from the well. These criteria are (1) distance, (2) drawdown (water-level decline), (3) time of travel, (4) flow boundaries, including the zone of contribution and zone of influence for a well, and (5) assimilative capacity (ability of the surrounding aquifer to reduce contaminant concentrations). States and local communities delineate source water protection areas by implementing these criteria, using a variety of methods. Depending on the needs and resources of the community, methods are at times as simple as computing a fixed radius around a well or as complex as applying a computer model of contaminant transport (USEPA, 1993; 1994). Ideally, protection of the mapped area will prevent contaminants from moving through the soil to the groundwater and subsequently being drawn into the well.

Relevant Terms and Definitions

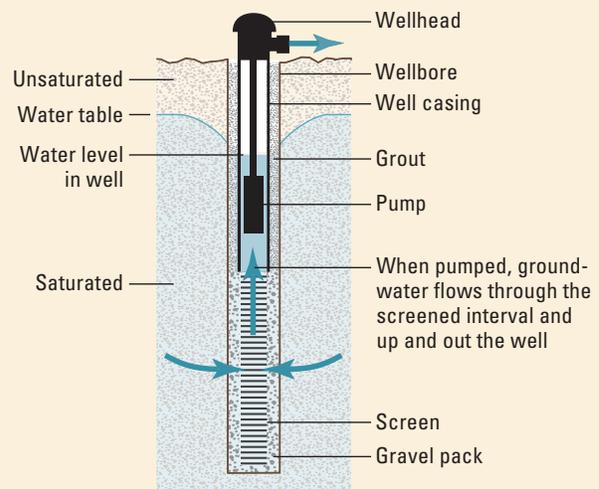


¹In this circular, the term "contributing area" is used to collectively refer to the area contributing recharge and zone of contribution for a well.

²For information on how the ZOI and ZOC may differ for confined-aquifer wells or for wells in aquifer systems with preferential flow pathways, see USEPA (1993).

Anatomy of a Well

A well is simply a hole in the ground (wellbore or borehole) from which water can be removed. The borehole is lined with a well casing, such as a pipe, to prevent the borehole from collapsing. The casing, along with a sealant (called grout), also prevents water from flowing into the well from land surface or parts of the aquifer where the water quality may be less desirable. The casing can be open at the bottom or perforated at a specific depth with a screen, allowing water to flow into the well where it can be pumped to the surface. Coarse sand or gravel (called sand pack or gravel pack) can be placed around the well screen to help improve the flow of water into the well.





This icon is used to flag paragraphs introducing tools that are discussed further in the Appendix

Although study results demonstrate the existence of spatial patterns in vulnerability, neither the study nor this circular provide a comprehensive description of all such patterns. Rather, the information, methods, and tools presented herein can be used to help fill knowledge gaps related to patterns in public-supply-well vulnerability and contaminant occurrence across the Nation.

Methods and tools in this circular also can be used to help update (enhance) existing source water assessments. (See box, page 16.) Updated assessments can be used by source water protection partners (for example, local officials, community-based environmental groups, farmers and businesses, concerned citizens, and state source water protection implementing agencies) to more effectively prioritize protection efforts and better anticipate and measure outcomes. Updating source water assessments is something that has been recommended by the USEPA because each state had only 3½ years to complete the initial assessments. Consequently, limited local information was incorporated into many early assessments (USEPA, 2006).

Study Design



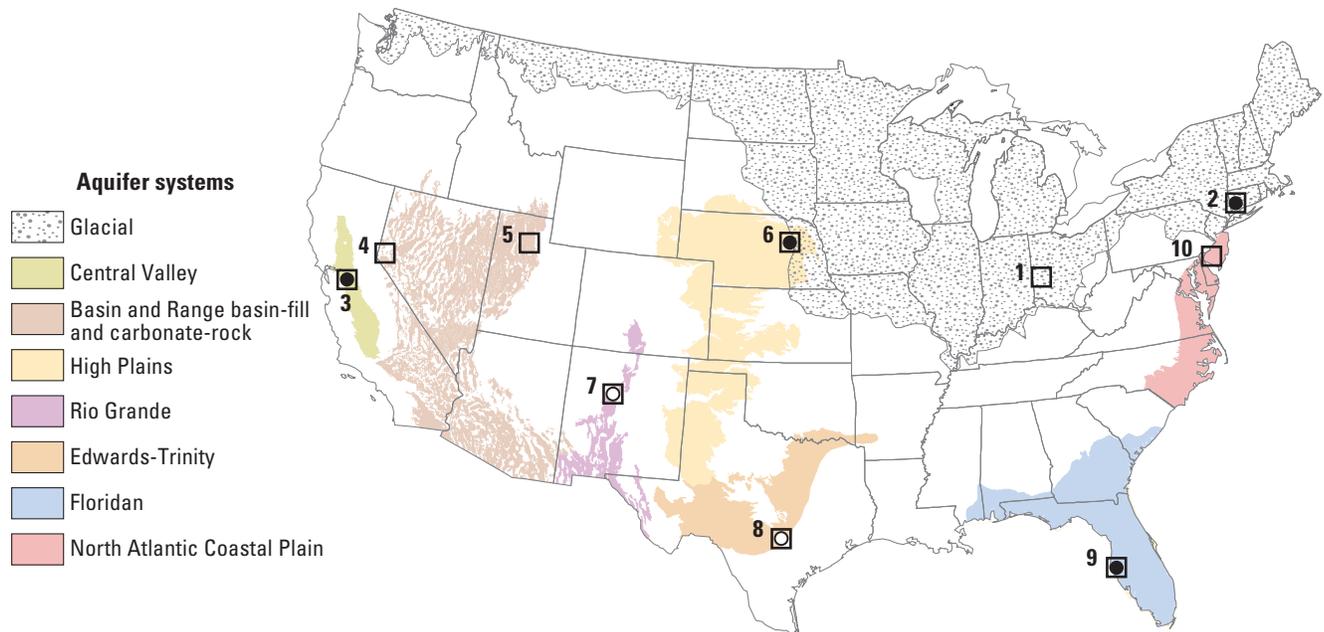
Drilling a monitoring well.

Ten areas across the United States were selected for inclusion in this study of public-supply-well vulnerability to contamination. The study areas are located in regional aquifer systems that together accounted for nearly one-half of the groundwater used for public drinking-water supply in the United States in 2000 (Maupin and Barber, 2005) and represent diverse aquifers and water management practices. Regional-scale investigations were conducted in all study areas (Paschke, 2007; Eberts, 2011), and local-scale investigations were conducted in six of the study areas (Katz and others, 2007; Starn and Brown, 2007; Burow and others, 2008; Clark and others, 2008; Jurgens and others, 2008; Brown and others, 2008; Crandall and others, 2009; Landon and others, 2008; Bexfield and others, 2011; Lindgren and others, 2011; Musgrove and others, 2011; Heywood, 2013). Water-quality samples from more than 1,500 public-supply wells were examined, along with output from 16 *groundwater-flow models*. Consistent data collection and methods of analysis were implemented across all study areas so that data and findings from the different areas could be compared. The shallow groundwater was considered to be the source of anthropogenic contaminants in most instances; processes within the *unsaturated zone* were not explicitly addressed.

Regional scale

Regional-scale investigations were conducted to identify aquifer and well characteristics that help explain differences in the occurrence of contaminants among wells in different aquifers. Study areas ranged in size from tens to thousands of square miles. Existing geologic, water-level, well-construction, water-use, and water-quality data were compiled for wells with records in USGS, USEPA, state, and local databases. Water samples were collected from a subset of the public-supply wells in each area. The samples were analyzed for a suite of constituents that included *nutrients*,

pesticides, pesticide degradation products, compounds found in wastewater, VOCs, VOC degradation products, *major ions*, and trace elements. Water-quality data were used to characterize geochemical conditions (for example, pH and *redox conditions*) in each area. A groundwater-flow model was constructed or refined for each study area to characterize (1) the areas that contribute recharge to the supply wells and (2) the zones of contribution for the supply wells in each location. (See page 17 for an illustration of these and other relevant terms.) This characterization was done by simulating the movement of water from recharge areas to individual wells by using the output from the groundwater-flow models in *particle-tracking models*. Results from particle-tracking models describe more than 150 characteristics of each public-supply-well contributing area, including *groundwater velocity*, traveltimes from recharge points at land surface to the public-supply well, traveltimes through different pH and redox zones, and potential contaminant sources overlying the areas that contribute recharge water to the wells. The aquifer and well information, water-quality data, and modeling results were stored in a database that was developed for the study (Paschke, 2007) so that the varied types of data could be used together in a variety of analyses (see for example, Hinkle and others, 2009; Kauffman and Chapelle, 2010; Katz and others, 2011).

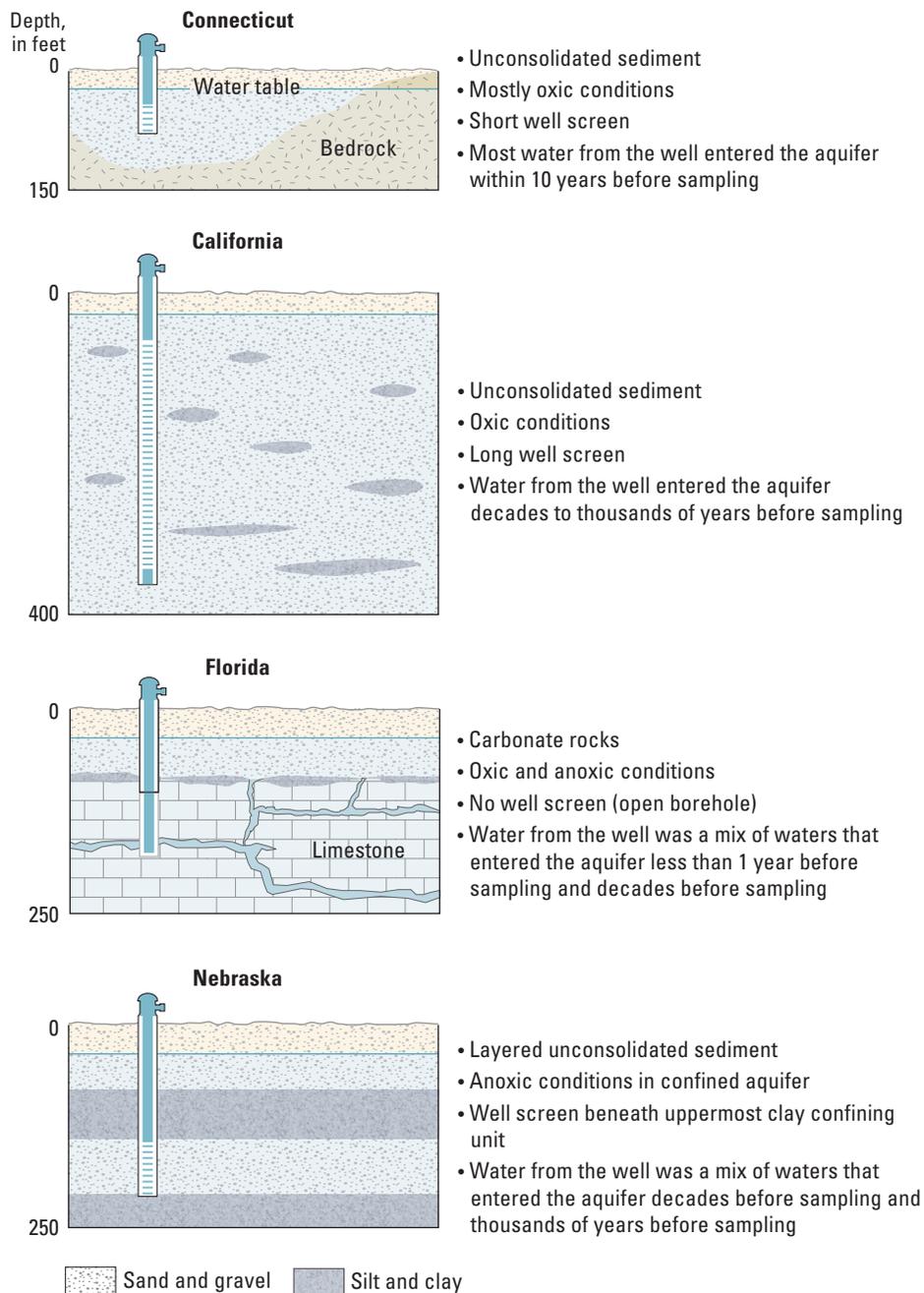


PUBLIC-SUPPLY-WELL STUDY AREAS

□ Regional-scale investigations 2001–11	● Local-scale investigations	
	● “First group” 2001–7	○ “Second group” 2006–11
1 Great Miami River Basin, OH	2 Pomperaug River Basin, CT	7 Middle Rio Grande Basin, NM
2 Pomperaug River Basin, CT	3 Northeastern San Joaquin Valley, CA	8 South-Central Texas, TX
3 Northeastern San Joaquin Valley, CA	6 Eastern High Plains, NE	
4 Eagle Valley and Spanish Springs, NV	9 Central-Northern Tampa Bay Region, FL	
5 Salt Lake Valley, UT		
6 Eastern High Plains, NE		
7 Middle Rio Grande Basin, NM		
8 South-Central Texas, TX		
9 Central-Northern Tampa Bay Region, FL		
10 Coastal Plain, NJ		

LOCAL-SCALE INVESTIGATIONS

CHARACTERISTICS OF SELECTED STUDY WELLS



Most of the case-study examples in this circular come from four study areas: Connecticut, in the glacial aquifer system; California, in the Central Valley aquifer system; Florida, in the Floridan aquifer system; and Nebraska, in the High Plains aquifer. These four areas represent a wide range of aquifer settings (for example, different sizes and shapes of aquifers, different aquifer materials, different geochemical conditions, different ages of groundwater) and public-supply-well characteristics (for example, different screen lengths, different pumping rates, different sources of recharge water). Characteristics of the four areas and the study well in each area are summarized in the figures (above) and table (opposite page).

Local scale

Local-scale investigations were conducted to explore how contaminants arrived at and entered a typical public-supply well in six of the study areas, four of which are featured extensively in this circular. The six study areas were selected from the larger group so that a variety of aquifer types and well sizes could be investigated in greater detail. Each selected well produced water with low concentrations (below drinking-water standards) of both anthropogenic and naturally occurring drinking-water contaminants. The wells also had recharge areas that included several types of land use; the recharge areas were determined by using the regional groundwater-flow models. Local-scale groundwater-flow models were constructed and calibrated for each study area by using data collected from monitoring wells installed for the study. The local-scale models were then used to refine the estimated recharge areas for the public-supply wells, to compute travel times in the aquifer for water entering the wells, and to explore the water sources, pumping stresses, and aquifer properties that resulted in the specific mixture of water produced by the wells. Sediment and rock samples were collected during drilling of the monitoring wells and were analyzed for physical properties and chemical characteristics that could affect the movement of water and contaminants in the subsurface. Water samples were collected from the completed monitoring wells and from the corresponding public-supply well over a period of several years. The samples were analyzed for a variety of drinking-water contaminants (nutrients, pesticides, VOCs, and trace elements) and for general groundwater chemistry (pH, dissolved oxygen, major ions, and selected *stable isotopes*). Samples also were analyzed for several chemical tracers that can be used to indicate groundwater age. Where conditions permitted, water samples were collected from the public-supply wells at several depths within their well screens (or open *boreholes*) while their pumps were running to determine where different waters and contaminants actually entered the wells. Data and models (groundwater flow, particle tracking, and geochemical) for the six local-scale investigations were used to corroborate regional-scale findings. They also were used to help study-team scientists answer questions such as, “How would the water quality at different wells respond to similar changes in contaminant input at the water table?”

LOCAL-SCALE INVESTIGATIONS

CHARACTERISTICS OF SELECTED STUDY WELLS

Location	Year of construction	Average pumping rate (gallons per minute)	Screened or open interval (feet below land surface)	Area contributing recharge (square miles)	Generalized land use in area contributing recharge (percent)				
					Agriculture	Urban	Forest	Wetland	Rangeland
Woodbury, Connecticut	1967	72	45 to 60	0.2	4.8	75	13	6.9	<1
Modesto, California	1961	1,600*	91 to 366	1.6	30	67	<1	<1	2.3
Tampa, Florida	1958	700	118 to 174	9.4	4.2	84	1	5.0	5.8
York, Nebraska	1977	500*	141 to 200	2.4	39	45	11	<1	3.7

*Average summer pumping rate.

Public-Supply-Well Vulnerability Primer

The vulnerability of a public-supply well to contamination depends on the vulnerability of the groundwater in different parts of the aquifer and the specific mixture of that groundwater drawn into the well.

Public-supply-well vulnerability to contamination is not the same as groundwater vulnerability, although the two are closely related. They are different because groundwater vulnerability is not uniform throughout an aquifer, and every public-supply well draws in water from only a part of an aquifer. The vulnerability of groundwater is affected by the presence of contaminant sources (contaminant input), the ability of released contaminants to move with and persist in the groundwater (contaminant mobility and persistence), and the overall ease of groundwater movement in the subsurface (intrinsic susceptibility). (See box below.) The vulnerability of a public-supply well reflects a combination of these three factors—each of which can be influenced by the presence of preferential flow pathways—for the specific mixture of water produced by the well. Therefore, understanding the interaction between a public-supply well and an aquifer is central to understanding the vulnerability of the well to contamination. This primer introduces various aspects of groundwater and public-supply-well vulnerability, which are then detailed throughout the remainder of the circular for the purpose of understanding water quality in public-supply wells.

How hydrologists define public-supply-well vulnerability to contamination

Public-supply-well vulnerability to contamination (PSWV) can be defined as a function of groundwater vulnerability (GWV) and the interaction of a well and the aquifer (Frind and others, 2006), which depends on the location, design, construction, operation, and maintenance of the well (WELL).

$$\text{PSWV} = f(\text{GWV}, \text{WELL}) \quad (1)$$

Definitions of “groundwater vulnerability” are somewhat varied in the technical literature (National Research Council, 1993; Rao and Alley, 1993; Vowinkel and others, 1996; Focazio and others, 2002; Frind and others, 2006; Kauffman and Chapelle, 2010). In general, however, groundwater vulnerability is defined as a function of contaminant input (CI) to the groundwater, contaminant mobility and persistence (CMP) once in the groundwater, and intrinsic susceptibility (IS) of the groundwater:

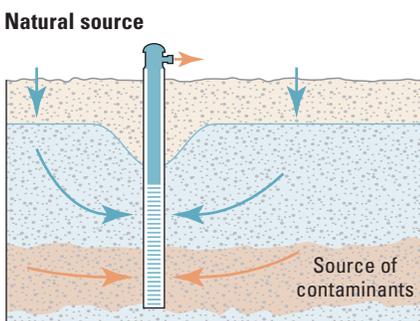
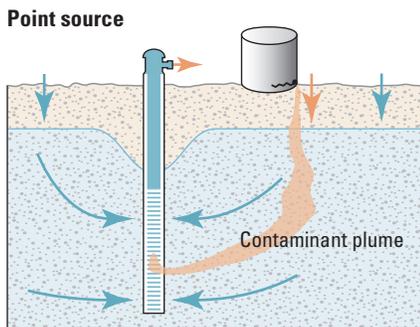
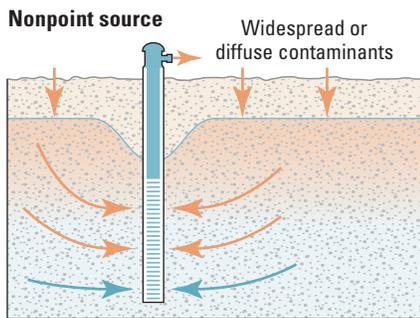
$$\text{GWV} = f(\text{CI}, \text{CMP}, \text{IS}) \quad (2)$$

The contaminant mobility and persistence term accounts for the effects of chemical processes (such as sorption, dissolution/precipitation reactions, and biodegradation) and physical processes (such as advection and dispersion) on contaminant concentrations (Focazio and others, 2002).

Intrinsic susceptibility, as used here, is not synonymous with vulnerability. Rather, it is the aspect of vulnerability that characterizes the ease with which water enters and moves through an aquifer. It depends on aquifer stresses (rates of recharge, including travel through the unsaturated zone and interactions with surface water, and well discharge) and aquifer properties (permeability, porosity, and hydraulic gradients) (Focazio and others, 2002).

Preferential flow pathways (pathways that provide little resistance to flow) are an additional factor affecting the vulnerability of groundwater and water from public-supply wells to contamination because such pathways influence the relative importance of each of the other factors.

Contaminant Input to the Groundwater



Activities near the land surface frequently release drinking-water contaminants into groundwater. If the contaminants are from many diffuse sources or a widespread, difficult-to-trace source, the source of contamination is a *nonpoint source*. (See figure at left.) Nonpoint-source contamination occurs when rainfall or snowmelt flowing over the land picks up contaminants.

Examples of nonpoint-source contamination are excess fertilizers, herbicides, and insecticides in runoff from agricultural land or residential areas; oil, grease, and toxic chemicals in runoff from urban land; and bacteria and nutrients from livestock, pet wastes, and faulty *septic systems*. Although concentrations of contaminants in groundwater near nonpoint sources can be relatively low, such sources might affect a large volume of water.

If the contaminants are from a discrete and identifiable location, the source of contamination is a *point source*. (See figure at left.) Point-source contamination occurs when a chemical, biological, or radiological substance is released into the environment from a localized area. Examples of point-source contamination are industrial solvent spills and leaky underground petroleum storage tanks. Concentrations of contaminants near point sources are commonly high, but such sources might affect only a small volume of water. Concentrations generally decrease away from the source; the pattern of contaminated groundwater emanating from a point source is referred to as a “contaminant plume.”

Geologic materials that make up aquifer sediments and rocks also can be a source of drinking-water contaminants. Under certain geochemical conditions, minerals in the geologic materials will be released into the flowing groundwater. Some chemical elements that compose the minerals can be harmful to humans if ingested in high enough quantities. Most of these harmful elements are regulated in water from public-supply wells. Examples of naturally occurring elements that can affect the quality of groundwater used for drinking are arsenic, uranium, and radium. Geologic materials that release natural contaminants into groundwater can be either localized or widespread.



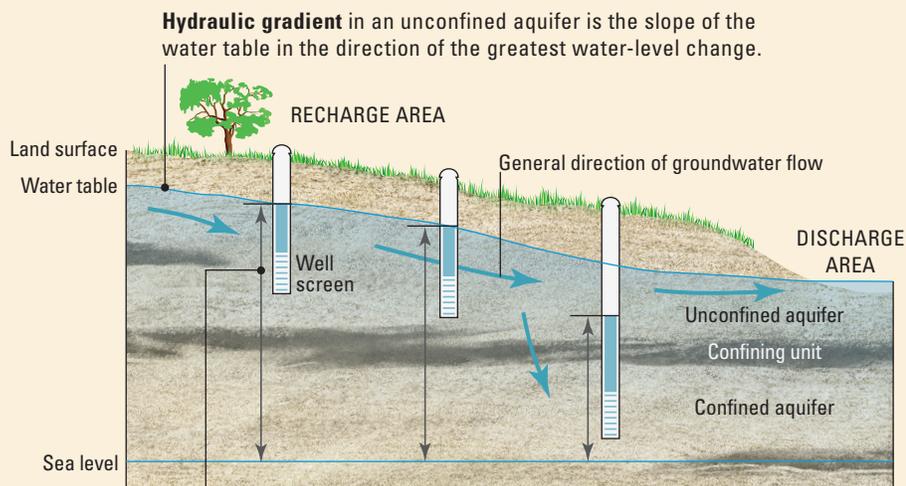
Water that infiltrates the ground beneath different types of land use can carry with it different contaminants that reflect the contrasting activities taking place at the land surface. Here, water infiltrating underneath agricultural land (orchards left), next to roads (center), and below residential development (right) carries with it contaminants typical of each type of land use.

Which way does the groundwater flow? That depends on the hydraulic heads and gradients in the aquifer system

Hydraulic head is an indicator of the total energy available to move groundwater through an aquifer. Recharge areas have higher hydraulic heads than discharge areas.

Hydraulic gradient is the change in hydraulic head with change in distance in a given direction. Groundwater and dissolved contaminants flow in the direction of the greatest decrease in hydraulic head. The slope of the water table is a measure of the horizontal hydraulic gradient in an unconfined aquifer. The slope of a potentiometric surface is a similar measure for a confined aquifer. The direction of groundwater movement between an unconfined and a confined aquifer is governed by the vertical hydraulic gradient between the aquifers, which can be upward or downward.

When a well begins pumping water from an aquifer, the water level in the well falls below the hydraulic head in the surrounding aquifer, changing the hydraulic gradient and causing water to move from the aquifer into the well.



Hydraulic head at the position of a well screen is the vertical distance between the water level in the well—when it is not pumping—and sea level.

Here, a USGS scientist uses a water-level tape to measure the elevation of the standing water in a nonpumping well to determine the hydraulic head in the aquifer at the depth of the well screen. This water-level measurement can be combined with other similar measurements for the aquifer so that hydraulic gradients and directions of groundwater flow within the aquifer can be determined.



Contaminant Mobility and Persistence in the Groundwater



Core samples (aquifer sediments and rocks removed from a borehole during well drilling) can be collected, boxed, and sent to a laboratory to determine whether naturally occurring toxic elements are present in the geologic materials that comprise the aquifer. If such drinking-water contaminants are present in the subsurface, the flowing groundwater can mobilize them and transport them to a public-supply well, depending on the geochemical conditions in the subsurface.

Once in an aquifer, contaminants that dissolve in water will travel with the flowing groundwater. The chemical properties of a contaminant and the geochemical conditions encountered by the contaminant will affect the contaminant's mobility and persistence in the groundwater; more specifically, contaminant properties combined with geochemical conditions control reaction processes such as *sorption/desorption*, *dissolution/precipitation*, *ion exchange*, or *biodegradation* that affect contaminant concentrations in groundwater. When these reactions occur at rates that are rapid in comparison with groundwater-flow rates, the concentration of a contaminant can be substantially reduced (or increased) before the contaminant reaches a well. The final concentration of a contaminant entering a well from a particular flow pathway will depend on the initial concentration of the contaminant and the reactions that took place along the pathway. A particularly important reaction involves the degradation of nitrate—one of the most widespread anthropogenic contaminants in groundwater. Dissolved nitrate is converted to harmless nitrogen gas in a process known as denitrification when dissolved oxygen is absent from the groundwater. Consequently, the presence or absence of dissolved oxygen in groundwater greatly influences whether nitrate released to the groundwater will degrade before reaching a public-supply well.

The physical properties of aquifer materials can affect contaminant concentrations. For example, aquifers composed of an assortment of sediments (silt, silty sand, sand, gravel) tend to disperse dissolved contaminants because water and contaminants preferentially travel along pathways that provide the least resistance to flow, such as interconnected lenses of relatively coarse aquifer material. This dispersion of contaminants can reduce contaminant concentrations at a given location within an aquifer. However, dispersion will increase the overall size of the contaminated area because, once dispersed, the contaminant mass will tend to occupy a larger part of an aquifer. The size of the pores or open spaces within an aquifer also can affect contaminants in the groundwater. For example, pore size influences whether pathogenic microorganisms will be removed from the water through contact with and attachment to the solid aquifer material.

Intrinsic Susceptibility of the Groundwater

Intrinsic susceptibility is characterized by the physical properties that influence how easy it is for water to move through the unsaturated zone and, subsequently, through the *saturated zone*. Intrinsic susceptibility is an important aspect of vulnerability because infiltrating water can contain contaminants, and subsurface travel times can influence whether reactions affecting contaminant concentrations can take place before the water is discharged from the aquifer.

Intrinsic susceptibility depends on the thickness and hydraulic properties of the unsaturated zone, which affect recharge rates to the aquifer. It also depends on aquifer hydraulic properties (permeability, *porosity*, and *hydraulic gradients*), which affect flow rates within the aquifer and

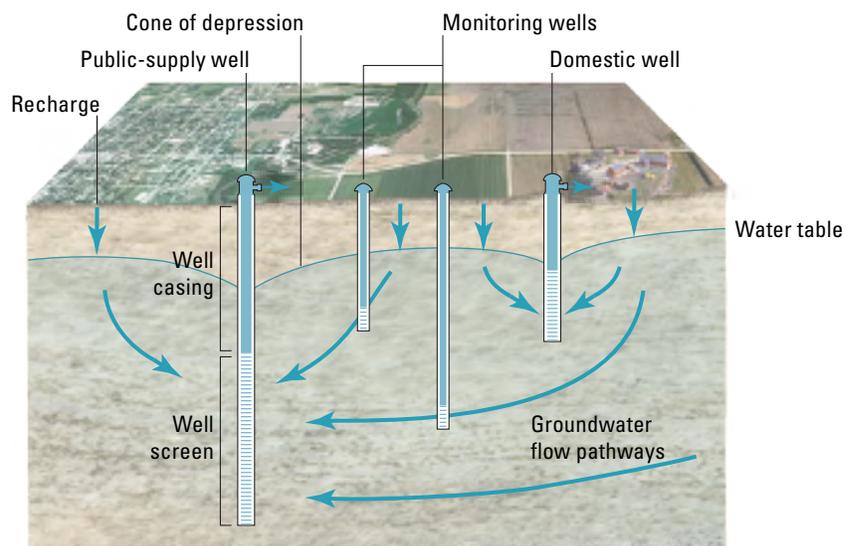
discharge rates from the aquifer. For example, the presence of a confining unit can substantially decrease groundwater-flow rates (groundwater velocity) and increase traveltimes. Consequently, a confining unit can decrease the intrinsic susceptibility of the groundwater in that part of an aquifer system underlying the confining unit. On the other hand, the presence of preferential flow pathways can cause water to travel rapidly through the subsurface. This is particularly true near a pumping well where hydraulic gradients may steepen, allowing water to move more rapidly toward the well than if the well were not pumping. Preferential flow pathways can allow water (and contaminants) to actually bypass parts of an aquifer system—including confining units—that they would otherwise flow through. As a result, preferential flow pathways can increase the intrinsic susceptibility of groundwater by substantially increasing groundwater-flow rates and decreasing traveltimes.

Collectively, recharge rates, discharge rates, the ability of the aquifer material to transmit water, and the size and shape of an aquifer contribute to the length of time groundwater will spend in an aquifer. Thus, groundwater age—the time elapsed since water entered an aquifer system—is a measure of intrinsic susceptibility. In general, young groundwater is more susceptible to anthropogenic contamination than older groundwater, particularly if the older groundwater recharged the aquifer before the widespread use of manmade chemicals. In this circular, “young” groundwater is considered to have been recharged after the 1940s.

Aquifer/Well Interaction

Every well collects water from a distinct combination of flow pathways. (See figure below.) The pathways that converge on a specific well can be attributed to the location, design (for example, screen placement and well capacity), construction, and operation and maintenance of the well.

The vulnerability of every well is unique to itself. Thus, the quality of water from a public-supply well will be different from the quality of water from nearby wells, including other public-supply wells. In this figure, the public-supply well draws in water (and associated contaminants) that entered the aquifer beneath both residential and agricultural areas, whereas the monitoring and domestic wells draw in water that entered the aquifer solely beneath the agricultural area. In addition, the flow pathways that converge on the public-supply well represent a wider range of travel distances (and traveltimes) than the other wells. Pathways associated with long traveltimes have the potential to allow contaminant reactions to progress further than pathways associated with short traveltimes. Differences such as these can lead to differences in the quality of water produced by different wells.



Consequently, these varied well characteristics together control whether the contributing area of the well intersects a particular contaminant source, whether the well draws groundwater from parts of the aquifer favoring contaminant mobility and persistence, whether the well pumps water that entered the aquifer in recent years, and whether the well intercepts water moving along preferential flow pathways. In other words, a well affects its own vulnerability by drawing water from an aquifer in a way that uniquely combines the different aspects of groundwater vulnerability. Thus, the vulnerability of every well is unique to itself. This is true even for wells within the same aquifer and well field.

Combined Factors

When contaminants do occur in water from a public-supply well, it is the result of complex interactions between contaminant inputs, recharge rates, contaminant reaction rates, groundwater velocities and travel times, flow pathways, and the mixing of water and contaminants in the aquifer and in the well. The presence of a contaminant source is but one piece of the puzzle. Still, preventing groundwater contamination in the first place remains important.

USGS scientists, such as the hydrologist in this photo, collect water samples from public-supply wells to better understand why contaminants occur at detectable levels in water from such deep, high-capacity wells. Regardless of the combined factors that affect public-supply-well vulnerability to contamination, a contaminant source must be present for a chemical or microbial contaminant to show up in water from a well. In a prior USGS study, the probability of detecting VOCs in water from public- or domestic-supply wells was strongly associated with the amount of developed land within 3,000 feet of the wells—a simple measure of contaminant input (Rowe and others, 2010). Thus, preventing contaminants from being released to the groundwater in the first place remains important for the prevention of contaminated drinking water.





USGS scientists collect water samples from public-supply wells before the water is treated for use as drinking water. This enables the raw (untreated) water from a well to be analyzed for different measures of vulnerability. Information on the vulnerability of the water from a public-supply well to contamination can be used to help explain and forecast water quality.



Groundwater vulnerability expresses the tendency or likelihood for contaminants to reach a specified location within an aquifer. This likelihood must be estimated from information that can be obtained from measurement or modeling (National Research Council, 1993). Similarly, public-supply-well vulnerability expresses the likelihood for contaminants to affect the quality of water from a public-supply well and must be inferred from information that is measurable. Measures of vulnerability can be as simple as a single parameter, such as depth to groundwater, or as complex as the output from a highly sophisticated groundwater-flow model that has been calibrated to many types of data. Vulnerability measures can provide insight into a single aspect of vulnerability (for example, contaminant input) or multiple aspects of vulnerability (contaminant input, contaminant mobility and persistence, and intrinsic susceptibility).

The choice of which vulnerability measures to use in a given assessment should be based on the knowledge that is desired and the scale of the assessment. Complex measures are more practical for assessments involving individual wells than for assessments involving many wells over a broad area. For example, groundwater age can serve as a measure of intrinsic susceptibility, but it might not be feasible to estimate groundwater age for the large number of wells that would be necessary to assess vulnerability at the aquifer scale. In contrast, the percentage of well-drained soils—which does not account for as many underlying processes as groundwater age—might be a suitable measure of intrinsic susceptibility for an aquifer-wide assessment.

Each vulnerability measure contributes to the uncertainty in a public-supply-well vulnerability assessment. Trading one measure for another might increase the amount of uncertainty in an assessment, but the trade-off might be necessary to understand vulnerability at the desired scale. Regardless of scale, evaluating information related to contaminant input, contaminant mobility and persistence, and intrinsic susceptibility for a well (or wells) will provide insight into the vulnerability of the water from the well(s) to contamination. This insight can be used to help explain observed water quality and forecast future water quality in the well(s).

Much can be learned by analyzing water samples from a public-supply well for a variety of chemical constituents. For example, chloride and bromide can be used to help determine where the water from the well came from; dissolved oxygen, nitrate, manganese, iron, and sulfate can be used to determine redox conditions and, thus, which contaminants might be persistent in the groundwater; and age tracers, such as tritium and sulfur hexafluoride, can be used to help determine how long it might take contaminated groundwater to reach the well.

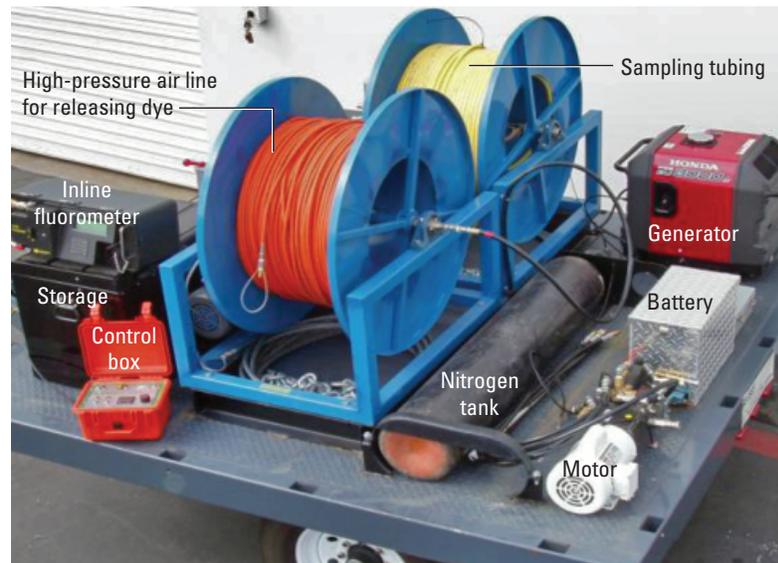


Results of this study call attention to three measures of vulnerability that are particularly useful for understanding the quality of water from individual public-supply wells. Taken together, the three measures can help answer the question, “Which contaminants in an aquifer might reach a public-supply well, and when, how, and at what concentration might they arrive?”

1. **Sources of recharge** that contribute water (and associated contaminants) to a well—a measure of contaminant input.
2. **Geochemical conditions** encountered by water pumped from a well—a measure of contaminant mobility and persistence.
3. **Groundwater-age mixture** of different waters that blend (or mix) in a well—a measure of intrinsic susceptibility.

These three measures, how they were determined for this study, and what they communicate about public-supply-well vulnerability to contamination are the subject of this chapter. Although these measures can account for the effects of preferential flow pathways on contaminant input, contaminant mobility and persistence, and intrinsic susceptibility of water from a public-supply well, additional information on preferential flow pathways is presented in chapter 4 because of the importance of the topic.

Groundwater samples from public-supply wells represent a greater range of conditions, both in space and time, than samples from monitoring or domestic wells do. As a result, they are particularly useful for gaining insight into the contaminant history of an aquifer system. Yet, samples from public-supply wells can be challenging to interpret. The more information that is available to aid in the interpretation of public-supply-well water samples, the better.



A combined wellbore-flow and depth-dependent sample collection tool was constructed for this study to enable downhole data to be collected from actively pumping public-supply wells. In this way, information could be obtained on where along the well screen contaminants actually entered a well, in addition to information on the range of geochemical conditions and groundwater ages represented by the water from the well.

Sources of Recharge

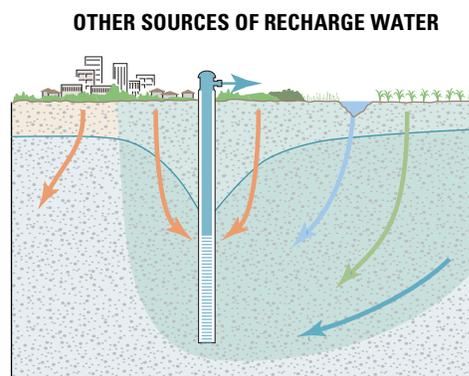
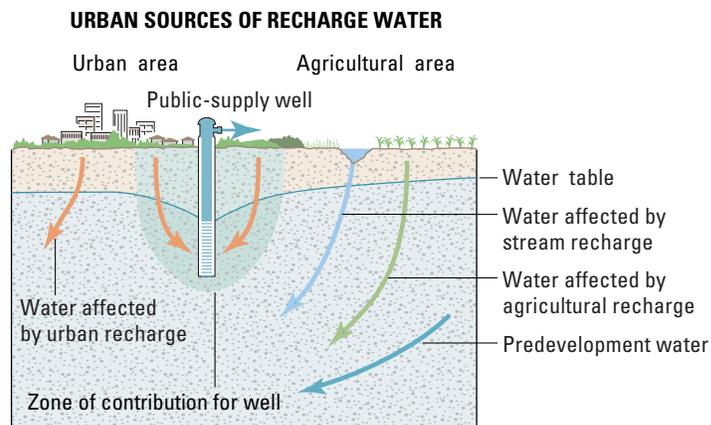
Compared to nearby monitoring or domestic wells, public-supply wells often produce water with a wider range of contaminants because they integrate more sources of recharge.

Public-supply wells commonly integrate water from multiple sources of recharge that contain different drinking-water contaminants. For example, water that is recharged beneath urban land is likely to contain more VOCs than water that is recharged beneath agricultural land (Zogorski and others, 2006). On the other hand, agricultural recharge is likely to have higher concentrations of nitrate than urban recharge (Dubrovsky and others, 2010). Both urban and agricultural recharge might contain pesticides, but not necessarily the same ones: simazine and prometon are more commonly associated with urban recharge, and atrazine and metolachlor are more commonly associated with agricultural recharge (Gilliom and others, 2006). Information on the sources of recharge for a public-supply well provides insight into which contaminants might be in the water that will eventually reach the well. For this reason, an estimate of the sources of recharge for a well is a useful measure of the vulnerability of the water from the well to contamination.

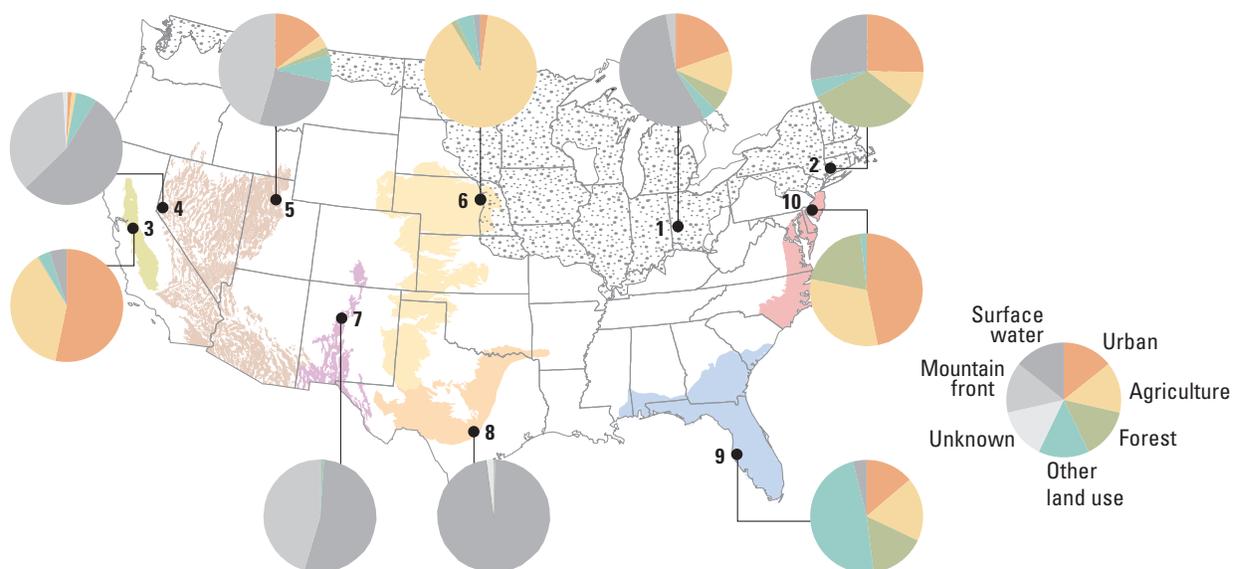
The sources of recharge water for a well, the relative contribution from each source of water, and the contaminants associated with the different water sources can affect the quality of water from a well. This figure illustrates how the quality of the water from a well can be influenced by multiple and different recharge sources.

The well in the upper diagram draws in water that was recharged in an urban area (orange arrows). Some contaminants associated with shallow groundwater in urban areas are VOCs, nitrate, and urban-use pesticides.

The well in the lower diagram draws in water from three additional sources: (1) water recharged in an agricultural area (green arrow), which might include nitrate and agricultural-use pesticides; (2) infiltration of water from a stream (light-blue arrow), which might include nitrate, pesticides, and wastewater contaminants; and (3) water unaffected by recent land use (dark-blue arrow), which probably does not include anthropogenic contaminants but might include naturally occurring drinking-water contaminants.



Regional differences in the sources of recharge for public-supply wells



Sources of recharge for public-supply wells in multiple study areas were identified by using regional-scale groundwater-flow and particle-tracking models combined with land-use data. The pie charts in the figure above are based on results from the models, which were aggregated for the network of public-supply wells in each study area. (The percentages represent only the small parts of the aquifers simulated by the models.)

Public-supply wells in the Nevada (4), Utah (5), New Mexico (7), Texas (8) and Ohio (1) study areas primarily produced water that recharged the aquifers in localized areas—near the edge of a mountain or beneath a surface-water body. On the other hand, public-supply wells in the California (3), Nebraska (6) and New Jersey (10) study areas primarily produced water that recharged beneath urban or agricultural lands. Wetlands, which are included in the "Other land use" category in the figure above, were an important source of recharge for public-supply wells in the Florida (9) study area. These differences can influence which contaminants are detected in water from public-supply wells in different parts of the Nation.

(See page 19 for names of aquifers and study areas.)



Identifying Sources of Recharge for a Public-Supply Well

There are a number of ways to estimate the area contributing recharge to a public-supply well. The best way to estimate recharge areas is through simulation of groundwater flow by using computer models (Franke and others, 1998). Even estimates obtained in this way, however, are prone to uncertainty. As a result, study-team scientists developed several computer programs to help quantify the uncertainty associated with model-derived estimates for recharge areas (Starn and Bagtzoglou, 2011). (See Appendix, pages 108, 110.)

Groundwater chemistry data also can provide insight into the origins of water, and thus dissolved contaminants, entering a well and can be easier to obtain than model-derived estimates. Conservative chemical constituents in groundwater (for example, chloride and bromide, and the stable isotopes

deuterium and oxygen-18) were especially useful for identifying the sources of recharge water for study wells. This is because conservative constituents are not easily removed from groundwater by reactions with aquifer materials—concentrations remain constant during transport from a recharge area to a well. In study areas where different sources of recharge had distinctly different concentrations (or ratios) of conservative constituents, it was possible to use mixing equations to determine whether water from the study well was a mixture of the different recharge waters. The proportion of the produced water from each recharge source also could be estimated. A sample calculation for resolving a two-component mixture by using conservative constituents is given in the Appendix (page 111). Computer programs such as PHREEQC (Parkhurst and Appelo, 1999) can be used to resolve more complex mixtures (for example, Bexfield and others, 2011).

Additional insight into the sources of recharge for several study wells was gained by sampling the wells at several depths within their screened intervals. This method of sampling (Appendix, page 108) provided information on where different waters and contaminants actually entered the wells along their well screens.

The case study on the following pages illustrates how conservative chemical constituents, mixing equations, and depth-dependent sampling helped reveal the sources of recharge water and associated contaminants for a public-supply well in this study.

There are many sources of recharge for an aquifer and the public-supply wells that tap them. Two of the more common sources are (1) water that infiltrates beneath urban or agricultural land and (2) infiltrating surface water.

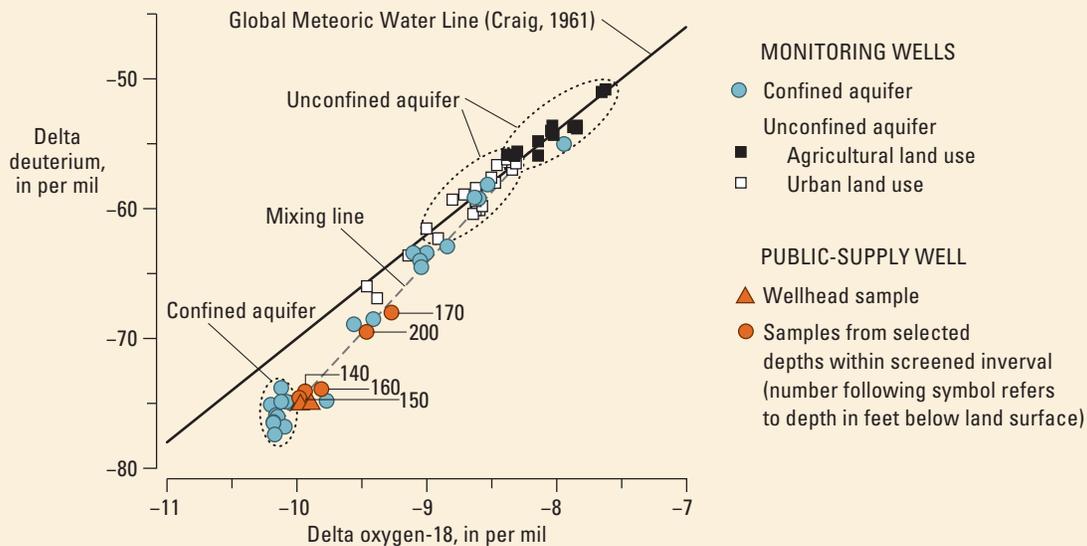
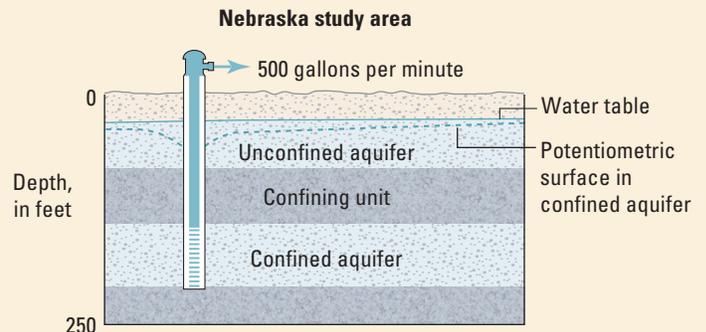


CASE STUDY

Geochemical methods for identifying sources of recharge water helped explain contaminant occurrence in the Nebraska study well

Water from the Nebraska study well had detectable concentrations of VOCs and uranium. Although shallow groundwater in the study area contained elevated concentrations of nitrate, VOCs, pesticides, pesticide degradation products, uranium, and arsenic, the detection of anthropogenic contaminants in water from the study well was confounding. This is because a clay confining unit separates the contaminated, unconfined aquifer and the aquifer tapped by the well; the well is screened in the confined aquifer between 140 and 200 feet (ft) below land surface (bls).

Deuterium (^2H) and oxygen-18 (^{18}O) data for the public-supply well and nearby monitoring wells provided insight into the sources of recharge for the public-supply well, the relative contribution of each water source, and the associated contaminants in the water entering the well. The ability to distinguish recharge sources for the study well was made possible by the presence of isotopically distinct water in different parts of the aquifer system; ^2H and ^{18}O



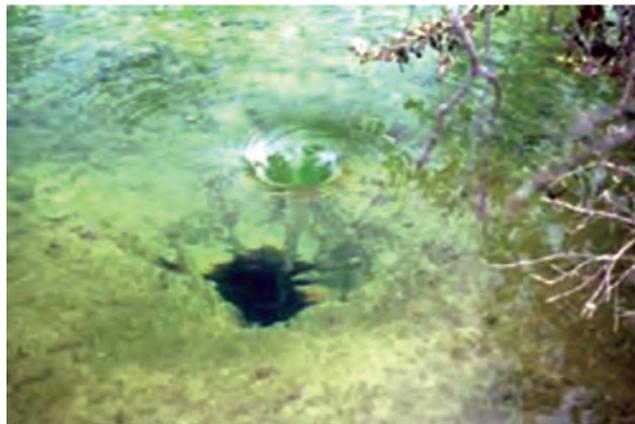
The distinct geochemical characteristics of different sources of recharge for the Nebraska study well enabled study-team scientists to “unmix” the water from the well. Samples from unconfined-aquifer monitoring wells had ^2H and ^{18}O values that plotted close to the Global Meteoric Water Line (Craig, 1961) (see figure above), which suggests that recharge to the unconfined aquifer was primarily from precipitation. Samples from the confined aquifer generally plotted in a small area to the right of the Global Meteoric Water Line, suggesting that the ^2H and ^{18}O values for confined-aquifer waters were modified by evaporation sometime after precipitation. Samples from the public-supply well and some confined-aquifer monitoring wells plotted along a line between samples from the unconfined and confined aquifers, indicating that the water from these wells was a mixture of waters from both aquifers. On the basis of a relatively simple two-component mixing equation, it was estimated that 12 percent of the water from the public-supply well was from the unconfined aquifer.

Cyclic water-quality variations can indicate changes in the sources of recharge for a well

The relative contribution of different sources of recharge for a well can change in response to cyclic or long-term variations in hydrologic conditions (Reilly and Pollock, 1995). Changing recharge sources can lead to changes in the vulnerability of the water from a well to contamination.

In an area near San Antonio, Texas, atrazine concentrations in water from a monitoring well in the karstic Edwards aquifer varied in response to changes in hydrologic conditions—concentrations were higher during wetter periods and lower during drier periods. The variation in water quality occurred because the well produced a mixture of water from two sources that had very different atrazine concentrations. The amount of recently recharged surface water from losing streams varied with hydrologic conditions. The atrazine concentrations were 10 times higher in the recharging surface water than in the groundwater. During wet periods, stream infiltration contributed a greater proportion of recharge to the well compared with dry periods, bringing with it a greater amount of atrazine.

In the same study area, nitrate showed the opposite pattern—concentrations in the groundwater were generally higher than in the surface water. Nitrate concentrations in the monitoring well were lower during wetter conditions because high nitrate concentrations in the shallow groundwater were diluted by a greater proportion of stream infiltration, which had lower concentrations of nitrate.



David Johns, City of Austin, used with permission

The vortex in this stream is caused by rapid drainage of water through a 2-foot-diameter karst feature in the streambed. Streams crossing the recharge zone of the Edwards aquifer lose much of their flow as water infiltrates to the water table along such features. Changes in hydrologic conditions rapidly affect the quantity of infiltrating stream water, which in turn affects the quality of the groundwater resource.

MORE INFORMATION

Musgrove and others, 2010

Geochemical Conditions

“... information on using groundwater-chemistry data to help assess well vulnerability is a good addition to the wellhead protection concepts published by the USEPA in the early 1990s.”

Mike Wireman,
U.S. Environmental Protection Agency,
National Groundwater Expert, 2011

Geochemical conditions—especially redox conditions, pH, and alkalinity—strongly affect the mobility and persistence of many chemical constituents in groundwater, including those that are regulated in drinking water. After a chemical is released into groundwater, the geochemical conditions encountered will affect whether the chemical constituent travels with the groundwater, reacts with the aquifer material, or degrades before it reaches a well. For example, nitrate, tetrachloroethene (PCE) and trichloroethene (TCE), and uranium are chemically stable and can be transported for long distances in oxic groundwater. Thus, information on aquifer geochemical conditions provides insight into which contaminants in an aquifer will be stable in the groundwater and could be transported all the way to a public-supply well. For this reason, an estimate for the geochemical conditions associated with the groundwater entering a well is a useful measure of the vulnerability of the water from the well to contamination.

Redox Conditions of Groundwater and Water from Wells

Methods for determining redox conditions in water from wells are not as straightforward as methods for determining other geochemical conditions (for example, pH and alkalinity) (U.S. Geological Survey, variously dated). As a result, this section focuses on redox conditions, why they matter, and how they can be assessed.



Andrew Young, Brigham Young University

Trace elements in groundwater originate primarily from the dissolution and weathering of rocks and minerals that make up the aquifer solids and the overlying soils. The arsenopyrite shown in this photo is a sulfide mineral containing arsenic, which can dissolve into the groundwater under oxic geochemical conditions.

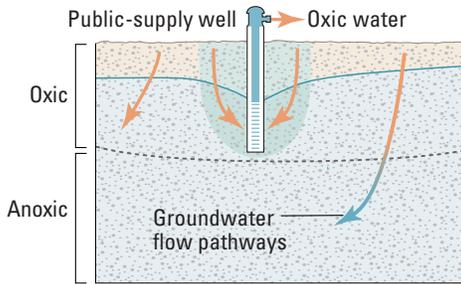
The redox condition of a groundwater sample is defined by the dominant type of redox reaction (redox process) occurring in the sample. Redox reactions involve the exchange of one or more electrons between chemical constituents that are either electron donors or electron acceptors. In groundwater, organic carbon is a common electron donor, and there are often multiple potential electron acceptors. Dissolved oxygen is the preferred electron acceptor. When dissolved oxygen is present to participate in redox reactions, the water is “oxic”; when it is not present (dissolved oxygen <0.5 milligrams per liter (mg/L)), the water is “anoxic.”

Redox reactions are catalyzed by microorganisms that derive their energy from the reactions. Therefore, electron acceptors are used in a sequential manner on the basis of the amount of energy produced by each reaction. The order in which some common electron acceptors are used is as follows:

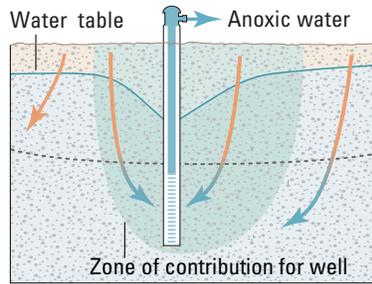
dissolved oxygen > nitrate > manganese(IV) > iron(III) > sulfate > carbon dioxide

Once one electron acceptor is consumed, the next most favorable electron acceptor will be used and the redox condition of the groundwater will become more “reducing.”

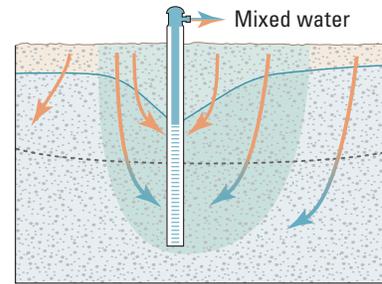
The sequential use of electron acceptors causes zones of different redox conditions to exist within aquifers, resulting in some spatial variation in contaminant occurrence in the groundwater. Redox zonation, combined with well location and design, influences which contaminants released to the groundwater will show up in which wells in an aquifer. (See figures on the following page.) Because public-supply wells commonly draw in water with a wider range of redox conditions than nearby monitoring wells, including those completed at a similar depth in the same aquifer, it is not sufficient



The well in this figure is screened in the shallow part of an aquifer and produces water that is oxic. Under these conditions, nitrate entering the aquifer at the water table would persist as it travels to the well. However, naturally occurring elements that are attached to the solid aquifer material under oxic conditions (for example, iron, manganese, and arsenic) would not be released to the groundwater and become a water-quality issue.



The well in this figure is screened in the deep part of the aquifer and produces water that is anoxic. Under these conditions, nitrate entering the aquifer at the water table might not reach the well; it will travel with the groundwater until it reaches the anoxic zone, where it will start to transform into nitrogen gas. However, reactions between the groundwater and aquifer material in the anoxic zone might release naturally occurring elements that are attached to aquifer material under oxic conditions.



The well in this figure is screened in both shallow and deep parts of the aquifer and produces a mixture of oxic and anoxic waters. Wells with open intervals that cross redox boundaries can be vulnerable to contamination from a wide range of chemicals. In addition, redox boundaries provide an ideal habitat for bacteria that cause biofouling (Cullimore, 2008) because such environments commonly contain a diversity of electron donors and acceptors.

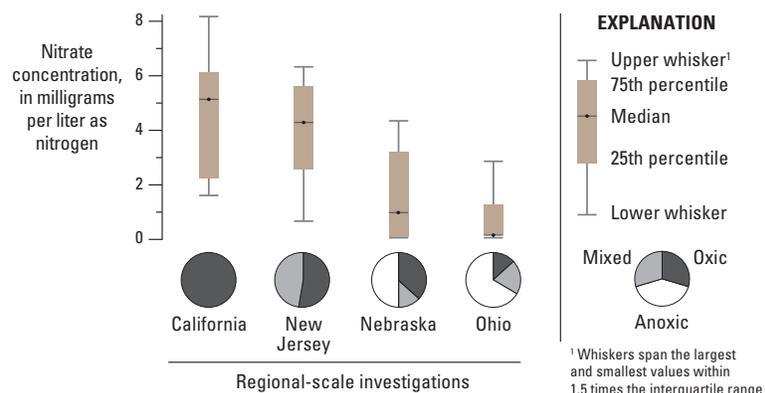
to sample and analyze water from monitoring wells to determine the redox condition of the groundwater entering a public-supply well. Rather, water from the public-supply well itself needs to be analyzed.

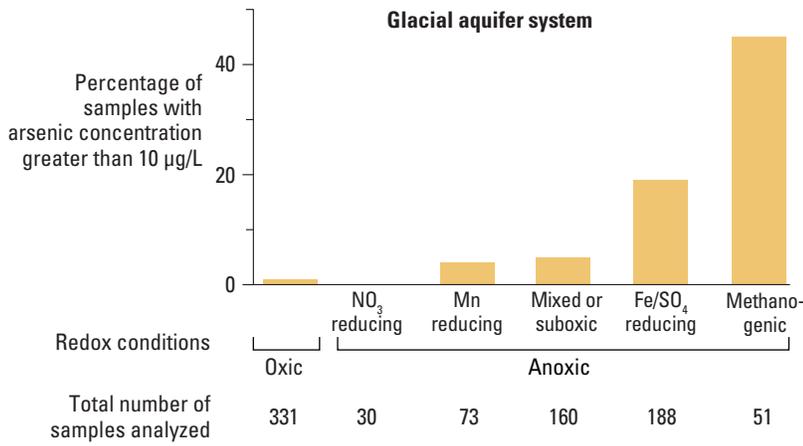
Why Redox Conditions Matter

Water managers who understand how redox conditions are distributed within an aquifer system are in a position to anticipate which chemical constituents in the groundwater (for example, nitrate, arsenic, iron, manganese, and certain VOCs or pesticides) would (or would not) be expected to occur in water from a particular well. In addition, knowledge about redox conditions in an aquifer system can help water managers select the most suitable water-treatment methods for the water from their wells.

Redox conditions of groundwater also are important because the oxidation state of some elements affects their toxicity. For example, the oxidized form of chromium (Cr^{6+}) is more toxic than the reduced form (Cr^{3+}).

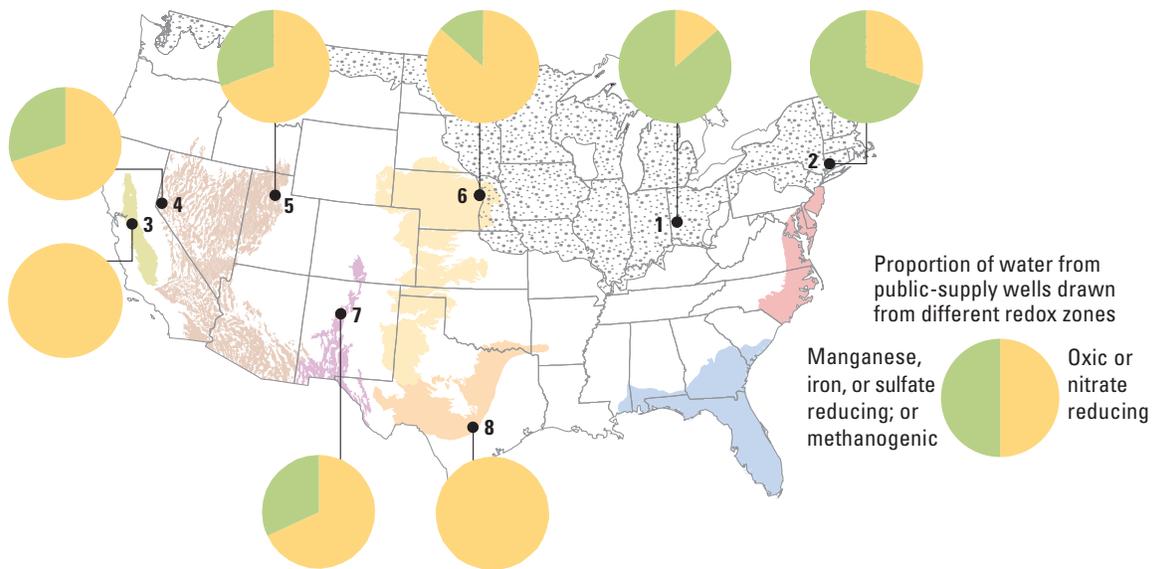
Nitrate concentrations in networks of public-supply wells in four study areas reflect regional differences in redox conditions. In each area, the land use was more than 25 percent agricultural, and the public-supply wells tapped highly productive sand and gravel aquifers. Aggregated water-quality data indicate that nitrate concentrations in the public-supply wells increased as the percentage of oxic conditions increased and the percentage of anoxic conditions decreased (L.J. Kauffman, U.S. Geological Survey, written commun., 2010).





In the glacial aquifer system, redox conditions are a relatively good indicator of the likelihood of detecting elevated arsenic concentrations. The glacial aquifer system is a heterogeneous mix of unconsolidated sediment that extends across parts of 26 states. About 9 percent of water samples from this aquifer system had elevated arsenic concentrations (greater than the drinking-water standard of 10 micrograms per liter (µg/L)). Most of the samples with elevated arsenic concentrations had redox conditions that were highly reducing (see page 42); almost 20 percent were iron or sulfate reducing, and 45 percent were methanogenic. The majority of waters sampled were oxidic, but less than 1 percent of the oxidic samples had elevated arsenic concentrations.

Regional differences in redox conditions of groundwater from public-supply wells



A redox framework (see page 42) was used to assess redox conditions of groundwater from public-supply wells in the regional-scale investigations of this study. Pie charts in the figure above depict the percentage of water from all wells in each study area that was characterized as being in one of two redox groups. Oxidic and nitrate-reducing conditions were prevalent in aquifers in the Western United States, whereas more reducing conditions were prevalent in the glacial aquifer system in the Midwest and East.

A similar regional trend was identified in a study of more than 5,000 domestic wells in principal aquifers of the Nation (McMahon and Chapelle, 2007; McMahon and others, 2009). The spatial distribution of redox processes in groundwater and in water from the domestic wells was related to differences in geology, climate, hydrology, and other factors. The predominantly oxidic conditions in the western aquifers are the result of low concentrations of organic carbon—an important electron donor. Where little organic carbon is present, dissolved oxygen is not consumed in redox reactions. In contrast, the glacial aquifer system contains abundant electron donors in the form of organic carbon and pyrite, which enable redox reactions to progress until conditions are more strongly reducing (McMahon and Chapelle, 2007; McMahon and others, 2009). These differences in redox conditions influence contaminant detections in water from wells in different parts of the Nation.

(See page 19 for names of aquifers and study areas. Only the study areas that were included in this analysis are shown here.)

CASE STUDY

Nitrate transport differs among study areas because of differences in redox conditions

Nitrate is one of the most common anthropogenic contaminants in groundwater. The source, fate, and transport of nitrate were investigated for the public-supply wells studied at the local scale by using chemical, isotopic, and groundwater age-tracer data collected from the wells and from associated networks of monitoring wells.

Redox conditions control whether nitrate persists or degrades as it travels from recharge areas to public-supply wells. Under oxic conditions, nitrate is stable and can be transported with the groundwater. Under anoxic conditions, nitrate is degraded by denitrification—the microbial reduction of nitrate to nitrogen gas. In general, denitrification occurs where nitrate-bearing water comes into contact with aquifer materials such as organic matter, or reduced iron or sulfur minerals, that can be oxidized by reaction with the nitrate. This can occur near contacts between fine-grained and coarse-grained sediment or in other locations where geologic and mineralogic conditions change along groundwater flow pathways (McMahon, 2001; Böhlke and others, 2002).

Two of the study areas—California and Nebraska—had similar sources of anthropogenic contaminants and similar proportions of agricultural and urban land. In both areas, agricultural irrigation was widespread, and irrigation return flow was a significant component of groundwater recharge. Agricultural fertilizer was the predominant source of nitrate, but septic systems also contributed nitrate. In both study areas, nitrate concentrations above the drinking-water standard of 10 mg/L were detected in some samples of shallow groundwater.

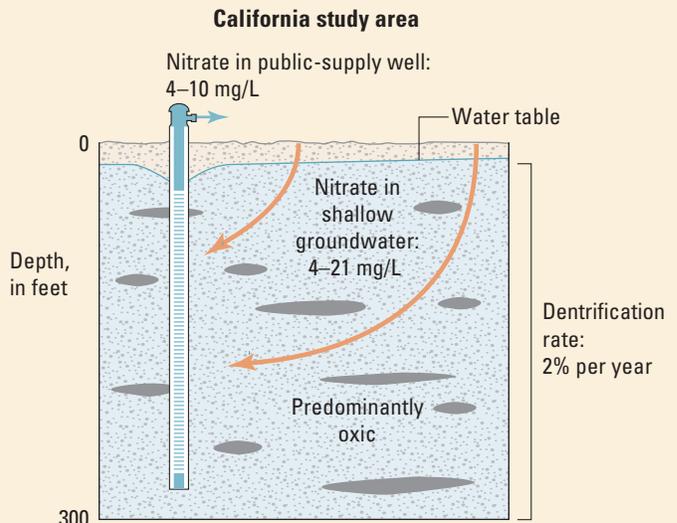
Denitrification occurred gradually across a thick zone (300 ft) of aquifer sediments at a rate equivalent to about 2 percent per year in the California study area. About 95 percent of the original nitrate was able to persist along flow pathways to the study well. This occurred because redox conditions were predominantly oxic despite the sizable amount of silt and clay within the aquifer sediments (50 percent). The fine-grained sediments exist as lenses within the sands and gravels, resulting in very localized anoxic conditions (near the contacts between the fine- and coarse-grained sediments) that limit the amount of denitrification that can occur.

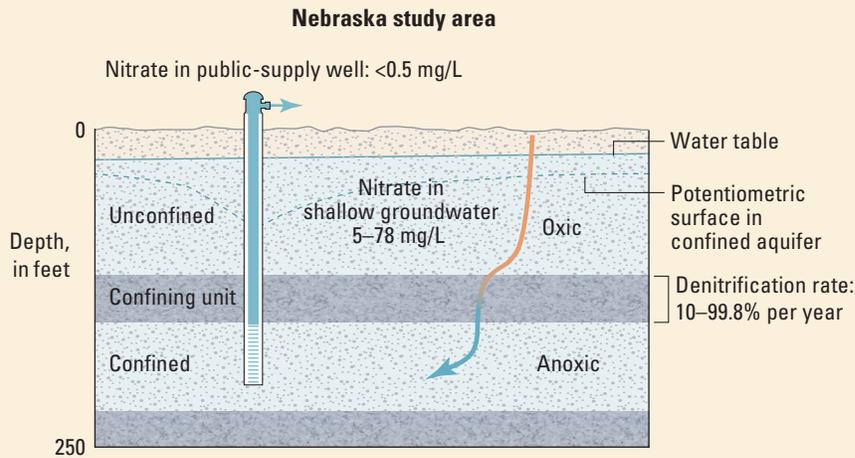
Despite similarities in nitrate sources and fluxes, water from the California public-supply well had substantial concentrations of nitrate (4–10 mg/L), whereas water from the Nebraska public-supply well had very low concentrations (<0.5 mg/L).

One important difference between the study areas was the distribution of redox conditions within the aquifer systems. Concentrations of nitrate in the California study well were similar to those in the shallow groundwater because redox conditions throughout the aquifer were predominantly oxic. In the Nebraska study well, concentrations of nitrate were significantly less than those in the shallow groundwater because anoxic conditions prevailed in the confined aquifer tapped by the well.

Overall, the aquifer systems in the Nebraska and California study areas have similar percentages of fine-grained material. However, for Nebraska, the fine-grained material is predominantly in the form of a continuous layer above the water-producing zone, which is a more effective reactive barrier to nitrate than the isolated fine-grained material in the California study area.

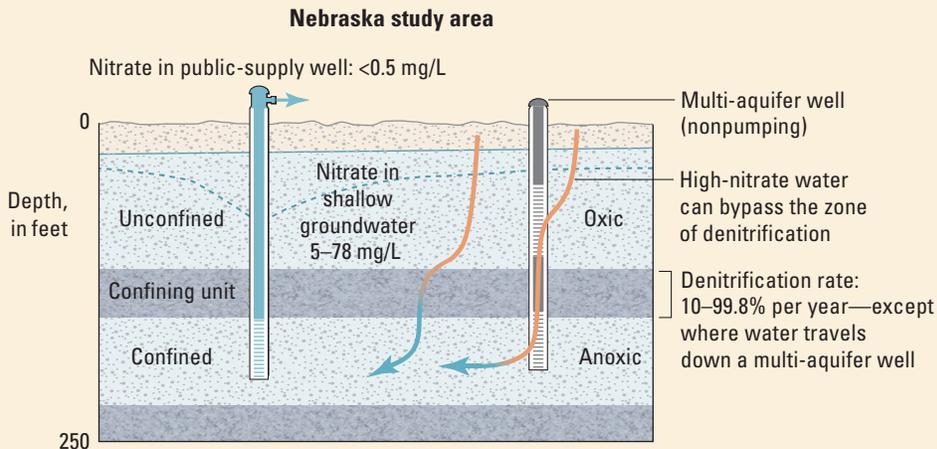
Although the Nebraska well was screened in the confined aquifer, at least 12 percent of the water captured by the well was from the unconfined aquifer, where nitrate concentrations were elevated. Multiple lines of evidence indicate that nitrate in shallow groundwater reached the confined aquifer by moving down multi-aquifer wells. Anoxic conditions in the confined aquifer prevented the nitrate from reaching the study well.





Denitrification occurred rapidly at the top of the fine-grained confining unit (just below the unconfined aquifer) at an estimated rate equivalent to 10–99.8 percent per year in the Nebraska study area. This denitrification rate was sufficient to degrade all nitrate in the time it took the groundwater to travel through the first 10–13 feet of the confining unit.

The absence of nitrate does not equate with the absence of vulnerability to other anthropogenic contaminants.



Elevated concentrations of nitrate from the unconfined aquifer leaked into the confined aquifer along multi-aquifer wellbores. However, the nitrate did not persist in the anoxic conditions of the confined aquifer; about 95 percent of the original nitrate degraded by the time the affected groundwater reached the public-supply well. PCE and TCE were detected at low concentrations in the public-supply well, even though these contaminants also degrade in anoxic conditions. The PCE and TCE might have persisted because they commonly are released to groundwater from point sources, which can have very high source concentrations. High initial concentrations can result in a need for a greater degree of degradation before a chemical constituent disappears from the groundwater. PCE and TCE also need geochemical conditions that are more reducing (methanogenic) than the conditions needed for nitrate to degrade (nitrate reducing).

MORE INFORMATION

Denitrification in four study areas
McMahon and others, 2008a

California study area
Burow and others, 2008
Jurgens and others, 2008

Nebraska study area
Clark and others, 2008
Landon and others, 2008

“Redox reactions are something that all professionals should consider when designing, installing and sampling wells.”

Frederick Bloetscher, Associate Professor,
Florida Atlantic University,
and American Water Works Association,
Water Resources Division Trustee, 2011

Assessing Redox Conditions of Water from Wells

Determining the redox condition of the water from a well is an important and practical tool for assessing the vulnerability of the well to contamination from a variety of chemicals. The most reliable method for assessing redox conditions is to document consumption and production of reactants and products of the redox reactions that occur along groundwater flow pathways (Chapelle and others, 1995). Unfortunately, flow pathways are not always known and (or) some redox reactants and products are not commonly measured in water-quality studies. Further complicating matters, public-supply wells often integrate water from multiple flow pathways that are associated with different redox conditions. To overcome these challenges, a redox framework for identifying the redox conditions of water from a well was developed by study-team scientists.

The framework is based on threshold concentrations of six water-quality constituents that are relatively inexpensive and easy to measure—dissolved oxygen, nitrate, manganese, iron, sulfate, and hydrogen sulfide. The

Framework for identifying redox conditions of groundwater from a well

[O₂, dissolved oxygen; NO₃-N dissolved nitrate as nitrogen; Mn, dissolved manganese; Fe, dissolved iron; SO₄, dissolved sulfate; H₂S, hydrogen sulfide; Mn(IV), oxidized manganese; Fe(III), ferric iron; mg/L, milligrams per liter; -, not applicable; >, greater than or equal to; <, less than]

General redox category	Predominant redox process	Threshold concentration (mg/L)					Fe/H ₂ S mass ratio
		O ₂	NO ₃ -N	Mn	Fe	SO ₄	
Oxic	O ₂ reduction	≥0.5	-	<0.05	<0.1	-	-
Suboxic ¹		<0.5	<0.5	<0.05	<0.1	-	-
Anoxic	NO ₃ reduction	<0.5	≥0.5	<0.05	<0.1	-	-
	Mn(IV) reduction	<0.5	<0.5	≥0.05	<0.1	-	-
	Fe(III) or SO ₄ reduction	<0.5	<0.5	-	≥0.1	≥0.5	-
	Fe(III) reduction	<0.5	<0.5	-	≥0.1	≥0.5	>10
	Mix Fe(III) and SO ₄ reduction	<0.5	<0.5	-	≥0.1	≥0.5	≥0.3 and ≤10
	SO ₄ reduction	<0.5	<0.5	-	≥0.1	≥0.5	<0.3
	Methanogenesis	<0.5	<0.5	-	≥0.1	<0.5	-
Mixed	Criteria for more than one redox process are met						

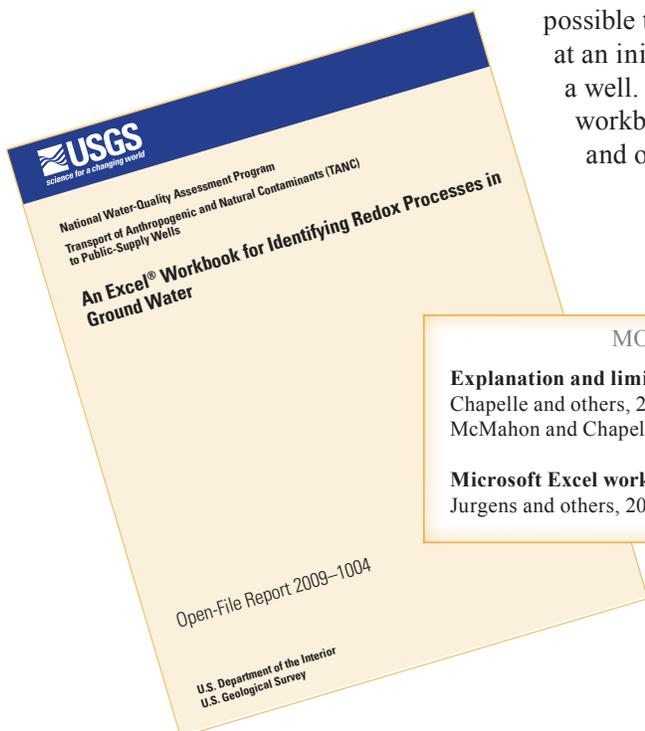
¹ Further definition of redox processes is not feasible.

Accurate data for the concentration of dissolved oxygen in groundwater is important for understanding redox conditions in the groundwater. Portable water-quality instruments, such as the one depicted in this photo, can be used at a field site to measure dissolved oxygen in groundwater as it is pumped from a well.



threshold concentrations were determined on the basis of microbial physiology, results of multiple field studies, and analytical reporting limits. One limitation of the method is that dissolved iron and manganese can precipitate out of solution, so measured concentrations might underestimate the extent of iron or manganese reduction. Nonetheless, this is a systematic and generalized approach that can be applied to water from wells in diverse aquifer settings.

The redox framework is useful even if the input dataset does not include all six recommended constituents. If dissolved oxygen data are not available, qualified redox codes will be assigned. If dissolved sulfide data are not available, the processes of iron reduction and sulfate reduction will be combined into a single classification. As a result, it might be possible to use existing data and the redox framework to arrive at an initial estimate for the redox conditions of the water from a well. The redox framework is available as a Microsoft Excel workbook to make it easy to analyze large datasets (Jurgens and others, 2009b). (See Appendix, page 108.)



MORE INFORMATION

Explanation and limitations of the redox framework

Chapelle and others, 2009
McMahon and Chapelle, 2007

Microsoft Excel workbook for applying the redox framework

Jurgens and others, 2009b



Core (sediment or rock) samples were collected during drilling for determination of physical and chemical properties of the solid aquifer material. Where anoxic conditions existed in an aquifer, USGS scientists processed the samples in a glove bag that was continually purged with ultrapure nitrogen gas (see photo). This was done so that the sampling process itself did not alter the geochemical conditions of the samples before they were shipped to and analyzed at a laboratory.

Human Activities Can Alter Geochemical Conditions and Affect Contaminant Concentrations

In domestic and public-supply wells, naturally occurring drinking-water contaminants (also referred to herein as “natural contaminants”), such as radon, arsenic, and uranium, are detected more frequently at concentrations of potential concern than are anthropogenic contaminants, such as nitrate, VOCs, and pesticides (DeSimone, 2009; Toccalino and others, 2010). Natural contaminants are a component of the minerals that make up the solid aquifer material, and can be mobilized—that is, released from sediments and rocks to groundwater—under certain geochemical conditions.

Human activities can cause local- and regional-scale changes in aquifer geochemical conditions and indirectly increase (or decrease) concentrations of natural contaminants in groundwater and in water from public-supply wells. For example, groundwater in the vicinity of a landfill can have elevated concentrations of arsenic, yet the source of the arsenic is not the contents of the landfill. Rather, the source is geologic—part of the solid aquifer material (DeLemos and others, 2006). This type of situation occurs because microorganisms degrade large amounts of organic carbon derived from the waste within the landfills, creating anoxic conditions in the groundwater. Arsenic is then released from the solid aquifer material to the groundwater under the newly anoxic conditions, thus increasing arsenic concentrations in groundwater downgradient from the landfill.

Another way that human activities can affect concentrations of natural contaminants in groundwater is by altering groundwater flow so that waters with different chemical characteristics mix. For example, in the Florida

Detections of naturally occurring arsenic or uranium in water from public-supply wells in this study were linked to human activities that altered the geochemical conditions of the groundwater.

Irrigation can increase concentrations of naturally occurring drinking-water contaminants in shallow groundwater if excess irrigation water infiltrates to the water table and is chemically distinct from the native groundwater. This is because even slight changes in subsurface geochemical conditions (for example, redox, pH, or alkalinity) can move toxic elements off the solid aquifer material and into the groundwater.



California Department of Water Resources

study area, much of the downward movement of groundwater is along flow pathways that follow natural conduits in the limestone bedrock. High-volume pumping from the study well pulls shallow, oxic and low-pH water, which is capable of dissolving arsenic-bearing minerals, into deeper, anoxic and high-pH parts of the aquifer system where arsenic can remain in solution. This accelerated mixing of dissimilar waters both mobilizes arsenic from the rocks and allows it to remain dissolved in the newly mixed water.

In the Nebraska study area, mixing of shallow oxic water with deeper anoxic water is linked to elevated uranium concentrations in the study well. Human activities cause mixing in this study area in two ways: (1) extensive pumping of deep water for irrigation produces a strong, downward regional hydraulic gradient, and (2) multi-aquifer wells act as artificial conduits for shallow water to migrate to deeper parts of the aquifer system in response to the downward hydraulic gradient.

In the California study area, human activities have altered recharge and discharge rates, groundwater flow patterns, and geochemical conditions in the shallow parts of the aquifer system. The result has been the release of uranium from the solid aquifer material to the groundwater. Uranium concentrations in water from public-supply wells in the area have increased over time and are predicted to continue increasing as a result of these changes. (See case study on the following pages.)

MORE INFORMATION

Effects of human-induced alteration of groundwater on natural contaminants in water from wells

Ayotte and others, 2011

Individual study area findings

Burow and others, 2008

Jurgens and others, 2008

Katz and others, 2007

Landon and others, 2008

CASE STUDY

Widespread, long-term pumping and irrigation linked to increased uranium concentrations in California study well

Concentrations of uranium in water from the California study well have approached the Maximum Contaminant Level (MCL) of 30 micrograms per liter ($\mu\text{g/L}$). Uranium concentrations greater than the MCL have been detected in several nearby public-supply wells, so the wells are no longer used as a source of drinking water. Uranium occurs naturally; it is attached to the aquifer sediments. However, elevated concentrations of uranium in groundwater are linked to human activities that have altered the geochemical conditions, flow pathways, and groundwater velocities in the aquifer system.

The California study area is within one of the most productive agricultural areas in the world. In 2000, agricultural irrigation accounted for about 95 percent of the total water use, although urban development has expanded into agricultural areas and constitutes about one-half of the study area. Groundwater for irrigation and public supply is from a thick sequence of alluvial sand and gravel interbedded with lenses of silt and clay. Contaminants in the shallow groundwater (less than about 165 ft below land surface) are linked to human activities: VOC detections in urban areas, and pesticide detections and elevated nitrate concentrations in urban and agricultural areas. The deep zone (more than 230 ft below land surface) contains old water unaffected by human activities. At intermediate depths, the groundwater has some characteristics of both the deep and shallow zones.

The alkalinity of shallow groundwater in the study area, primarily in the form of the bicarbonate ion, has increased substantially since irrigation began. In arid and semi-arid areas, such as the California study area, low soil moisture limits plant growth and soil microbial activity. This leads to naturally low levels of soil carbon dioxide. However, irrigation has increased both plant growth (in the form of crops and landscaping) and soil microbial activity, which have increased the amount of carbon dioxide in the soil. This increase in soil carbon dioxide has accelerated the dissolution of carbonate minerals into infiltrating recharge water, which has increased the alkalinity of the shallow, oxic groundwater. Such conditions favor uranium mobility.

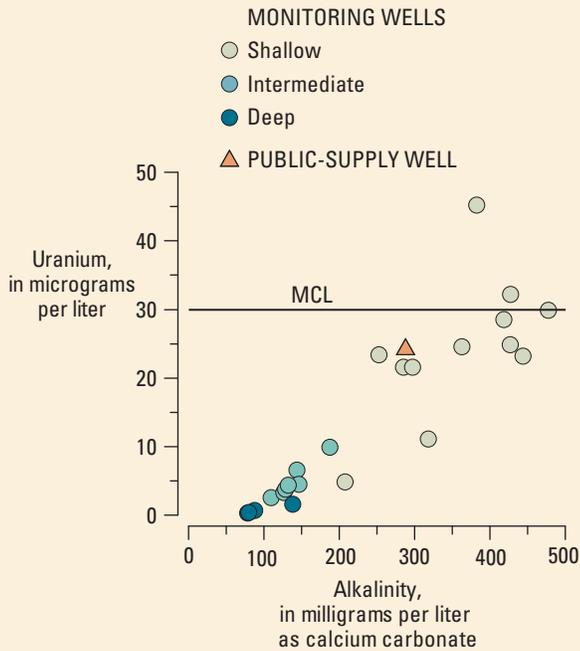


California Department of Water Resources

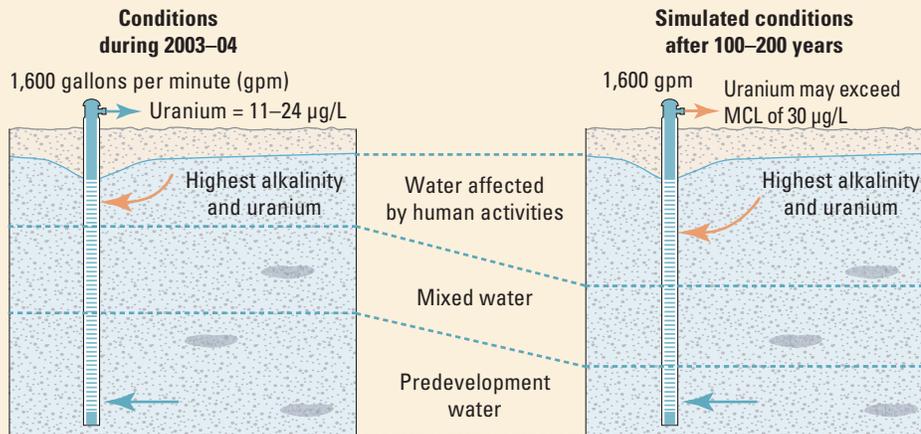
Long-term pumping and irrigation also have increased the vertical hydraulic gradients in the aquifer, causing high-alkalinity water to move deeper into the aquifer than it would have under natural flow conditions. Consequently, alkalinity and uranium concentrations in water from the public-supply well will likely increase in the future. (See lower figure, opposite page.)

MORE INFORMATION

Burow and others, 2008
Jurgens and others, 2008
Jurgens and others, 2009a



Uranium is strongly sorbed to aquifer sediments in oxic groundwater with low alkalinity. However, where bicarbonate (the most common ion making up alkalinity) is available, it reacts with uranium attached to aquifer sediments to form calcium-uranyl-carbonate complexes. These complexes dissolve into the groundwater, resulting in higher uranium concentrations in the water. In the California study area, the highest concentrations of both alkalinity and uranium were detected in shallow groundwater, which had been altered geochemically by agricultural activities. In deeper parts of the aquifer system, alkalinity is relatively low, so geochemical conditions are favorable for uranium to remain attached to aquifer sediments. Because the public-supply well draws in some shallow groundwater, the inadvertent increase in dissolved uranium in the shallow groundwater has led to an increase in uranium concentrations in water from this (and other) public-supply well(s).



About 20 percent of the water produced by the public-supply well is from the shallow part of the aquifer containing high concentrations of alkalinity and uranium. Because this is a relatively small proportion of the total water from the well, the produced water has uranium concentrations below the MCL of 30 µg/L.

In the future, uranium concentrations in the public-supply well are likely to increase. This is because uranium that is present throughout the solid aquifer material will continue to be mobilized as high-alkalinity water is transported deeper into the aquifer in response to strong vertical hydraulic gradients caused by pumping and irrigation. Over the next 100–200 years, uranium concentrations in the public-supply well could reach the MCL if the proportion of water containing high alkalinity and uranium becomes sufficiently large. More importantly, uranium concentrations could reach levels of concern in shallower public-supply wells within a few decades.

Groundwater-Age Mixtures

A single value for the age of the groundwater pumped from a public-supply well (for example, average groundwater age) will not correspond to the length of time it will take shallow contaminated groundwater to reach the well because some of the water will be younger and some of it older than the single-age estimate.

The water pumped from a public-supply well is a mixture of groundwater that entered the surrounding aquifer at different times in the past because public-supply wells draw in water from relatively large parts of an aquifer. The number of years since water entered an aquifer system at the water table (traveltime since recharge) is referred to as the age of the groundwater and can influence which contaminants might be present in the water. Groundwater that was recharged hundreds of years ago is less likely to be contaminated with manmade chemicals than groundwater that was recharged years or decades ago. This is because many chemicals that are currently found in groundwater were not widely used before the 1950s. However, water that recharged an aquifer hundreds of years ago might contain high concentrations of naturally occurring drinking-water contaminants because the groundwater would have been in contact with the solid aquifer material—the source of the contaminants—for a very long time. For example, in the glacial aquifer system, arsenic concentrations above the drinking water standard (10 micrograms per liter ($\mu\text{g/L}$)) were most often associated with groundwater that recharged the aquifer system prior to the 1950s. Similarly, arsenic concentrations in water from public-supply wells in study areas in California, Connecticut, Ohio, Nebraska, Nevada, and Utah increased with increasing traveltimes to the wells (increasing groundwater age). The groundwater-age mixture for a well characterizes the complete range of time that it might take contaminants that are released to the groundwater to reach a well. For this reason, an estimate for the groundwater-age mixture for a well is a useful measure of the intrinsic susceptibility—and thus vulnerability—of the water from the well.

The groundwater-age mixture for water from different public-supply wells can be highly varied. This is partially because the age of the groundwater in different aquifer systems is not the same. The age of the water in any

MORE INFORMATION

Arsenic in the glacial aquifer system
Thomas, 2007

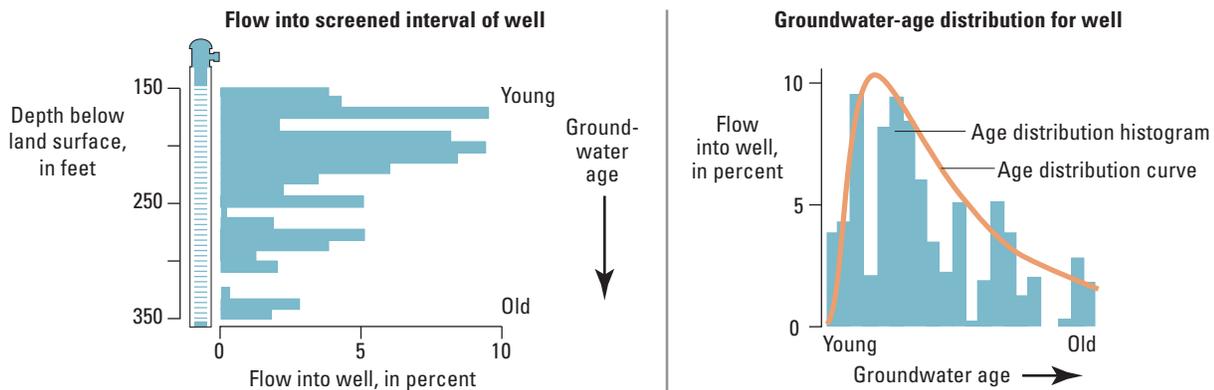
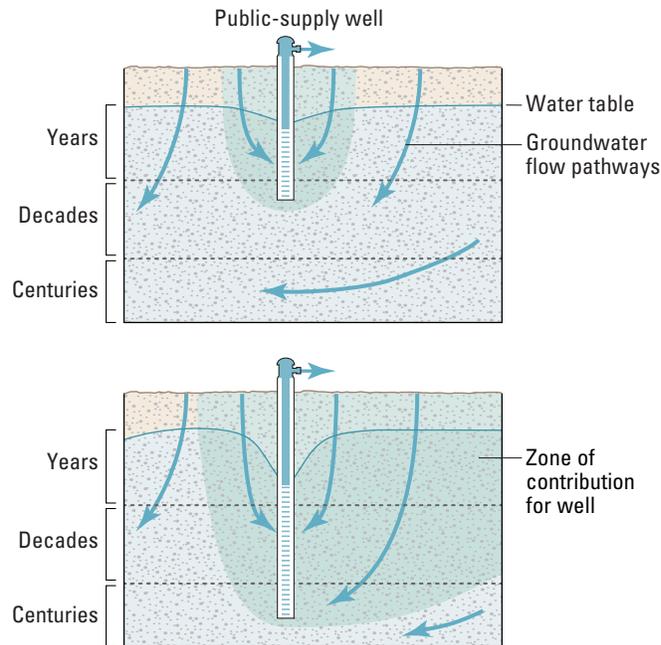
Public-supply well vulnerability to arsenic and uranium
Hinkle and others, 2009



Public well used to supply water to a community in southwestern Ohio.

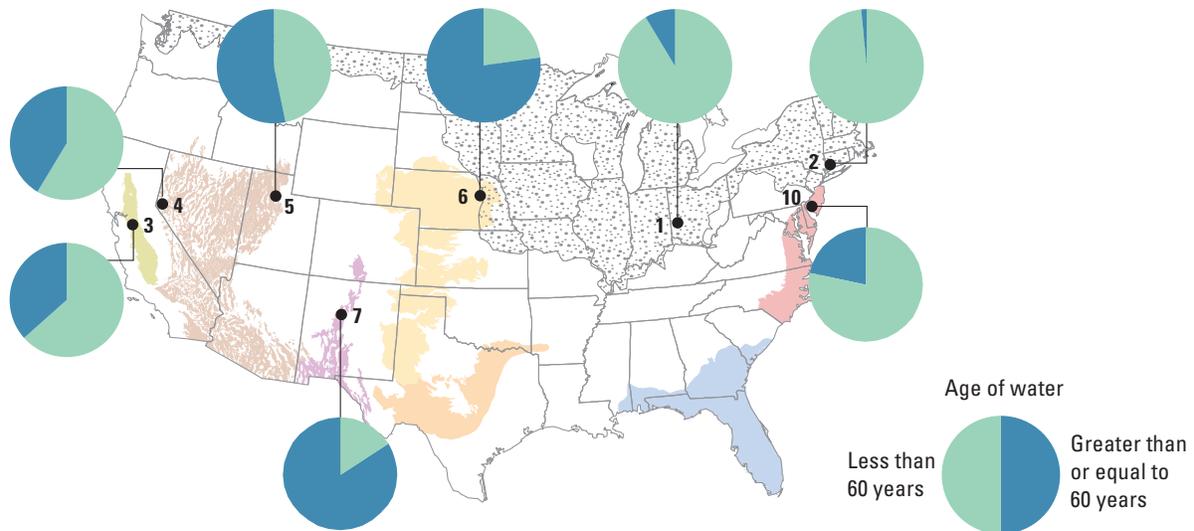
aquifer system depends foremost on the amount and rate of recharge entering the aquifer system at the water table. The size and shape of an aquifer system, the ability of the aquifer material to transmit water, and the amount of groundwater pumping also influence groundwater age (Vogel, 1967; Solomon and others, 2006). In addition, public-supply-well construction and operation (screen placement, pumping rates and schedules) can lead to differences in the age mixture of the groundwater pumped from different wells, including wells within the same aquifer.

Public-supply wells commonly produce groundwater with a mix of ages that span decades to hundreds or even thousands of years. This is because groundwater age generally increases with depth in an aquifer, and public-supply wells draw in water from multiple depths. The groundwater-age mixture for any well is simply the mix of ages for the groundwater in the surrounding aquifer that enters the well. In this figure, two wells in the same aquifer draw in water with a different range of groundwater ages because they are completed at different depths. As a result, they are likely to produce water containing different types and amounts of drinking-water contaminants.



Groundwater of different ages is not necessarily drawn into a public-supply well in equal proportions. This is because some aquifer units transmit water more readily than others. For example, in this figure (left-hand side), a greater percentage of young, shallow water enters the well compared with older, deeper water, presumably because the shallower part of the aquifer transmits water more readily than the deeper part. The groundwater-age mixture for the well in this figure is illustrated in graphical form on the right-hand side of the figure. Such groundwater-age distribution histograms or curves were used in this study to help explain the quality of water from public-supply wells.

Regional differences in the groundwater-age mixtures in public-supply wells

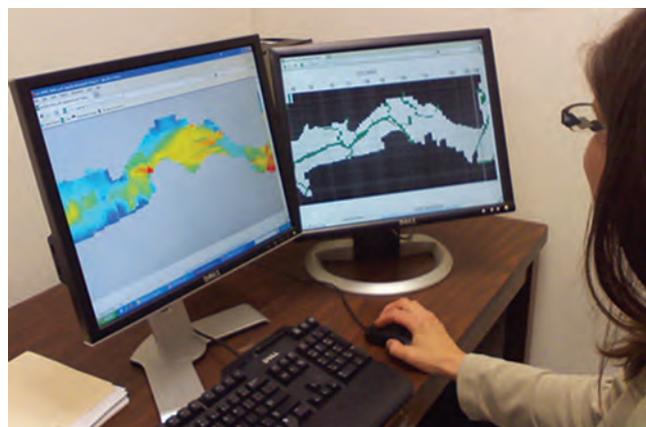


Groundwater-age mixtures for hundreds of public-supply wells were computed by using regional-scale groundwater flow models constructed for this study. Pie charts based on results from the models illustrate the overall proportion of water in each study area with travel times from the water table to a supply well of less than 60 years, or greater than or equal to 60 years. (These percentages represent only the small parts of the aquifers simulated by the models.)

The public-supply wells in the western aquifers collectively produced a higher percentage of relatively old water than did the eastern-aquifer wells. Because many potential drinking-water contaminants, including VOCs, pesticides, and fertilizers, were not widely used until recent decades, these differences in groundwater age can influence the detection of contaminants in water from public-supply wells in different parts of the Nation.

(See page 19 for names of aquifers and study areas. Only the study areas that were included in this analysis are shown here.)

USGS scientists use computer programs to create models of groundwater flow that can be used to help estimate the groundwater-age mixture of the water entering and being discharged from a well.



Estimates of groundwater-age mixtures can help answer questions about public-supply-well vulnerability to contamination that cannot be answered with a single value for the age of the produced water.

Why Groundwater-Age Mixtures Matter

An estimate of the complete groundwater-age mixture for a well can address many questions related to water quality that cannot be addressed with a single value for the age of the groundwater, such as the average age; for example,

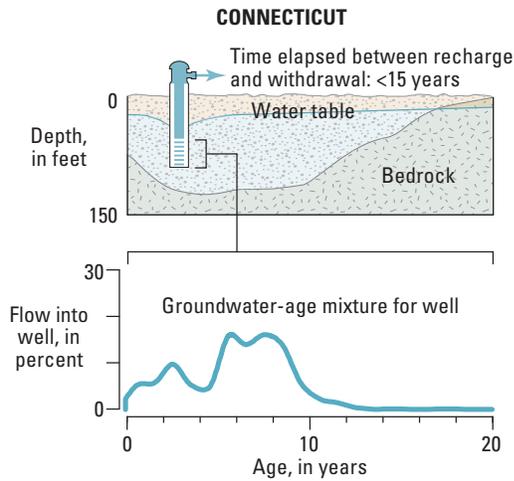
- What is the potential for in-well dilution of anthropogenic contaminants in relatively young water entering a well by old, uncontaminated groundwater simultaneously entering the well?
- What are the shortest traveltimes from the water table to a well?
- How readily will the quality of the water pumped from a well respond to source water protection efforts?
- How might the quality of the water pumped from a well respond to widespread contaminant input at the water table (nonpoint-source contamination)?



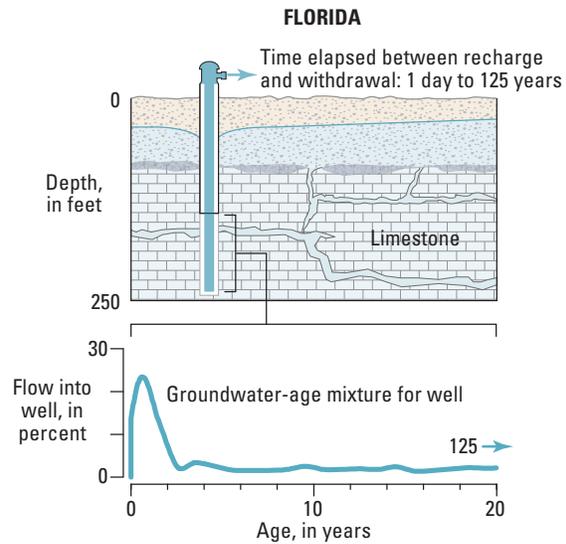
Land use in the vicinity of shallow wells can frequently explain the quality of water from such wells, but the relation between land use and water quality in public-supply wells is not as straightforward. This is because a substantial time lag exists between contaminant input at the water table and contaminant arrival at public-supply wells. An investigation into the influence of septic systems on the quality of water from different types of wells (monitoring, domestic, and public supply) demonstrates the importance of traveltime for explaining water quality in public-supply wells. The number of nearby houses served by septic systems, such as the ones in this photo, helped explain septage-influenced water detected in shallow monitoring and domestic wells. In contrast, minimum traveltimes from the water table to the wells best explained septage-influenced water detected in public-supply wells (Katz and others, 2011).

Groundwater-Age Mixtures Are Linked To In-Well Dilution Potential

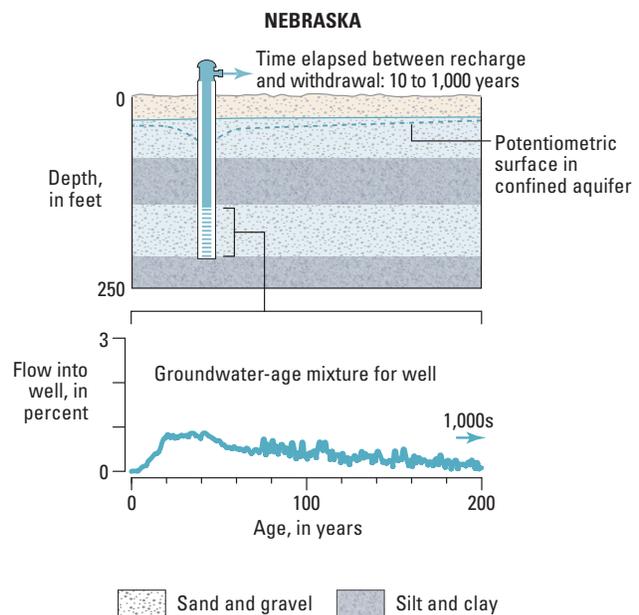
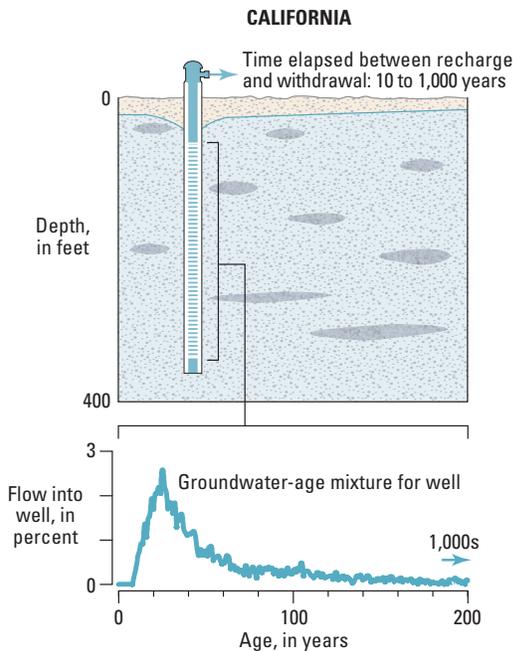
Uncontaminated water (of any age) that enters a well can dilute contaminants entering the well. Although some young groundwater (recharged after the 1940s) entering a well might not be contaminated, it is reasonable to expect that most or all old groundwater (recharged before the 1950s) will be free of anthropogenic contaminants. Therefore, the proportion of old water entering a well can be used as a “lower limit” for the amount of in-well dilution that could occur if the shallow groundwater were contaminated. Such information on dilution potential is useful for comparing the vulnerability of different wells to contamination from anthropogenic sources. Examples of groundwater age distributions and in-well-dilution potential from this study are presented on the following page.



In the Connecticut study area, the aquifer is relatively shallow, and nearly all of the water produced by the study well was recharged during the past 15 years. As a result, the vulnerability of the water from the well to contamination from manmade chemicals is relatively high, and the potential for in-well dilution of such chemical contaminants by old water is low.



The well in the Florida study area produces water with a wide range of ages, from less than 1 day old to about 125 years old. The very young water travels to the well through dissolution features such as sinkholes and conduits that connect shallow groundwater and the well. This fraction of water is highly vulnerable to contamination from anthropogenic sources—both chemical and microbial. The well also produces old water from the limestone matrix, so there is some potential for in-well dilution of manmade chemicals.



Wells in the California and Nebraska study areas produce water with a wide range of ages—10 years to thousands of years. (Note that the scales for the axes on these graphs are different from the ones on the Connecticut and Florida graphs.) No single recharge year contributes more than a few percent of the total volume of water from either of these wells. Because a large fraction of water from the wells entered the aquifers prior to the widespread use of manmade chemicals, these wells have a substantial potential for in-well dilution of such chemicals by the old groundwater entering the wells.

Differences in groundwater-age mixtures among wells can be substantial, resulting in notable differences in the potential for in-well dilution of anthropogenic contaminants by old, unaffected water.

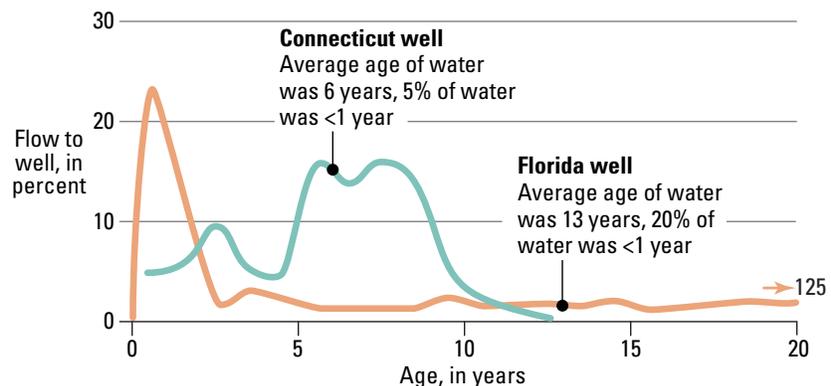
Whether or not in-well dilution can prevent concentrations of contaminants from exceeding an MCL ultimately depends on the proportion of the contaminated and uncontaminated waters entering the well, along with the contaminant concentrations. For example, if water with a contaminant concentration 10 times higher than an MCL mixes with old, uncontaminated water in a well, the final concentration will remain above the MCL unless the old fraction makes up more than 90 percent of the produced water. However, if the concentration of the contaminated fraction equals the MCL, the concentration in the produced water will remain below the MCL if even a modest amount of uncontaminated water also enters the well.

Groundwater-Age Mixtures Include the Shortest Traveltimes to a Well

An estimate of the complete groundwater-age mixture for a well can provide insight into the shortest traveltimes to the well, potentially revealing a hidden vulnerability to contamination from anthropogenic sources. This point is illustrated with results from the local-scale investigations in Connecticut and Florida. The groundwater-age mixtures for the study wells in each area were derived by using groundwater-flow and particle-tracking models. The average groundwater age for the water from each well also was computed by using the models.

A comparison of the average ages for the two wells suggests that the Connecticut well produces younger water than the Florida well and is potentially more vulnerable to contamination than the Florida well. (See figure below.) However, the complete groundwater-age mixtures estimated for the wells (curves on graph) reveal a different story. The Florida well actually produces a higher percentage of water that is less than 1 year old compared with the Connecticut well. Therefore, the Florida well is likely to have a greater vulnerability to contamination from pathogenic microorganisms (such as bacteria that have limited survival times in aquifers) compared with the Connecticut well.

Average groundwater age does not provide enough information on public-supply-well vulnerability to contamination. Rather, it is the age and proportion of the very youngest water entering the well that provides the most insight into vulnerability to pathogens and anthropogenic contaminants. For example, on the basis of groundwater-flow models, the average groundwater age for the Florida study well was 13 years, whereas the average groundwater age for the Connecticut study well was 6 years. However, more than 20 percent of the water from the Florida study well recharged the aquifer during the past year, whereas only 5 percent of the water entering the Connecticut study well was this young.



MORE INFORMATION

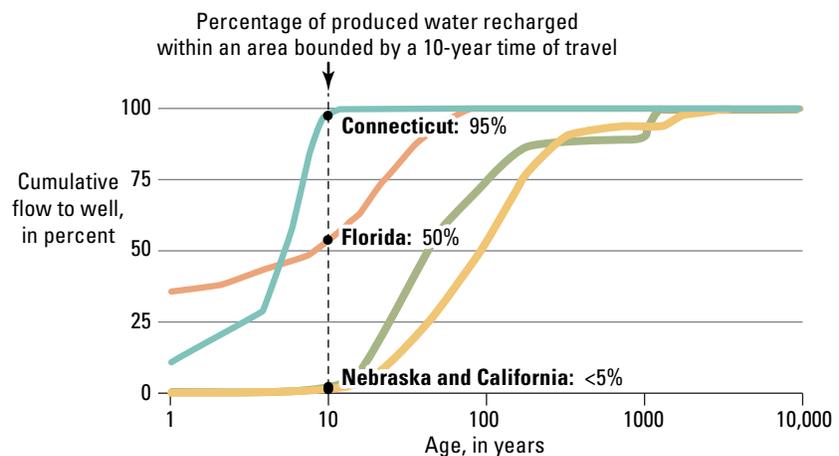
Connecticut study area	Florida study area
Brown and others, 2009	Crandall and others, 2009
Jagucki and others, 2010	Jagucki and others, 2009b
Starn and Brown, 2007	Katz and others, 2007

Groundwater-Age Mixtures Can Influence Source Water Protection Outcomes

The effectiveness of management actions can be tied to the groundwater-age mixture of the water from a well.

Time of travel (synonymous with groundwater age when time zero is at the water table) is one criterion used to define the area around a well within which to implement source water protection. However, source water protection based on similar times of travel (for example, 10-year time of travel) can result in dissimilar amounts of protection of different wells with vastly different groundwater-age mixtures. For example, almost all of the water from the Connecticut study well travels from the water table to the well within 10 years. (See figure below.) As a result, source water protection within a zone of transport bounded by a 10-year time of travel could influence nearly all of the water from this well. In contrast, less than 5 percent of the water from the Nebraska and California wells is recharged within 10 years of travel from the wells. Land-use changes or protection measures within a similar zone of transport would have comparatively little effect on the quality of water from these wells—more than 95 percent of the water would not be influenced by the protection efforts.

A one-size-fits-all source water protection strategy can protect very different percentages of water pumped from different wells. The percentage of water that could be affected by source water protection within a zone defined by a 10-year time of travel is substantially different for several study wells, as shown in this figure. If it were necessary to prioritize protection activities, wells that produce predominantly young water might receive the greatest benefit from such activities.

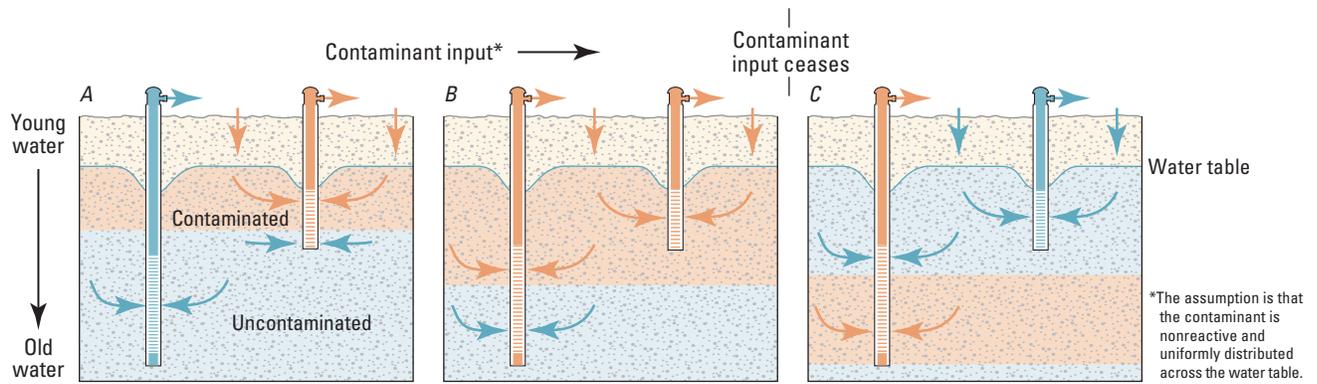


Estimates of Groundwater-Age Mixtures are Useful for Forecasting Water Quality

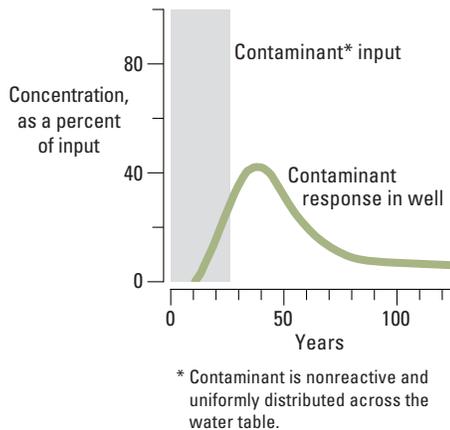
Some human activities (for example, septic-system use, some agricultural practices, lawn care, and stormwater capture by *dry wells*) can result in widespread contamination of shallow groundwater. A persistent nonpoint source of contamination will affect greater and greater depths within an aquifer over time, unless the contaminant degrades in the subsurface. Because groundwater age increases with depth, the change in water quality at a well resulting from nonpoint-source contamination will be related to the age mixture of the water pumped from the well.

If the groundwater-age mixture for a well has been estimated, it can be used to help forecast future water quality. (See Appendix, pages 109, 117.) As an example, a water-quality response curve for a public-supply well that produces water with groundwater ages ranging from ten to hundreds





Wells that produce water with different groundwater-age mixtures respond differently to the same input of nonpoint-source contamination, as illustrated above. (A) Contaminated water appears in the shallow well. (B) All flow pathways bring contaminated water to the shallow well, and the concentration in the well equals that of the contaminated recharge water. The contaminant appears in the deep well, but the concentration is relatively low because a large fraction of old, uncontaminated water enters the well. (C) The contaminant disappears from the shallow well because contaminant input has ceased and clean water now recharges the aquifer. Contaminants are still detected in the deep well, but they are associated with past land use as opposed to present land use. Contaminant concentrations in the deep well never reach the concentration in the recharge water in (A) and (B) because the period of contaminant input is not as long as the period of recharge for the water entering the well—uncontaminated water always enters the well somewhere along the well screen. However, contaminants will continue to be detected in water from the deep well long after recharge with contaminated water ceases.



A water-quality response curve illustrates changes in contaminant concentrations in a well over time that occur because of changes in recharge quality. A tool that can be used to generate water-quality response curves by combining contaminant input data and estimated age distributions (TracerLPM) was developed for this study. (See Appendix, pages 109, 117).

of years is shown on the left. The contaminant input in this example is 25 years of widespread, contaminated recharge at the water table (gray shaded area on graph). Contaminated water appears in the well after a delay of 10 years—the shortest traveltime from the water table to the well (green curve). (Transport across the unsaturated zone is not depicted.) The initial contaminant concentration in the well is a fraction of the input concentration because most flow pathways continue to bring uncontaminated water to the well, diluting the contaminated water from the faster pathways. Over time, more and more flow pathways bring contaminated water to the well and the concentration in the well increases. In this example, the concentration continues to increase even after contamination of the shallow groundwater ceases 25 years after it began. This is because a substantial amount of contaminant mass in the aquifer system has yet to reach the well, owing to the many flow pathways with traveltimes greater than 25 years. Although contaminant concentrations continue to increase after cessation of contaminant input, the concentration in the well will never reach the concentration in the contaminated recharge. As long as the age range of the water drawn into a well is greater than the duration of contaminant input, some unaffected water will continuously dilute contaminants entering the well. The maximum concentration in the well in this example is 40 percent of the input concentration because of the very broad range of groundwater ages in the water from the well compared with the 25-year period of contaminant input.

MORE INFORMATION

Connecticut study area
Jagucki and others, 2010
Starn and Brown, 2007

Florida study area
Crandall and others, 2009
Jagucki and others, 2009b

California study area
Burow and others, 2008
Jagucki and others, 2009a

Nebraska study area
Clark and others, 2008
Jagucki and others, 2008

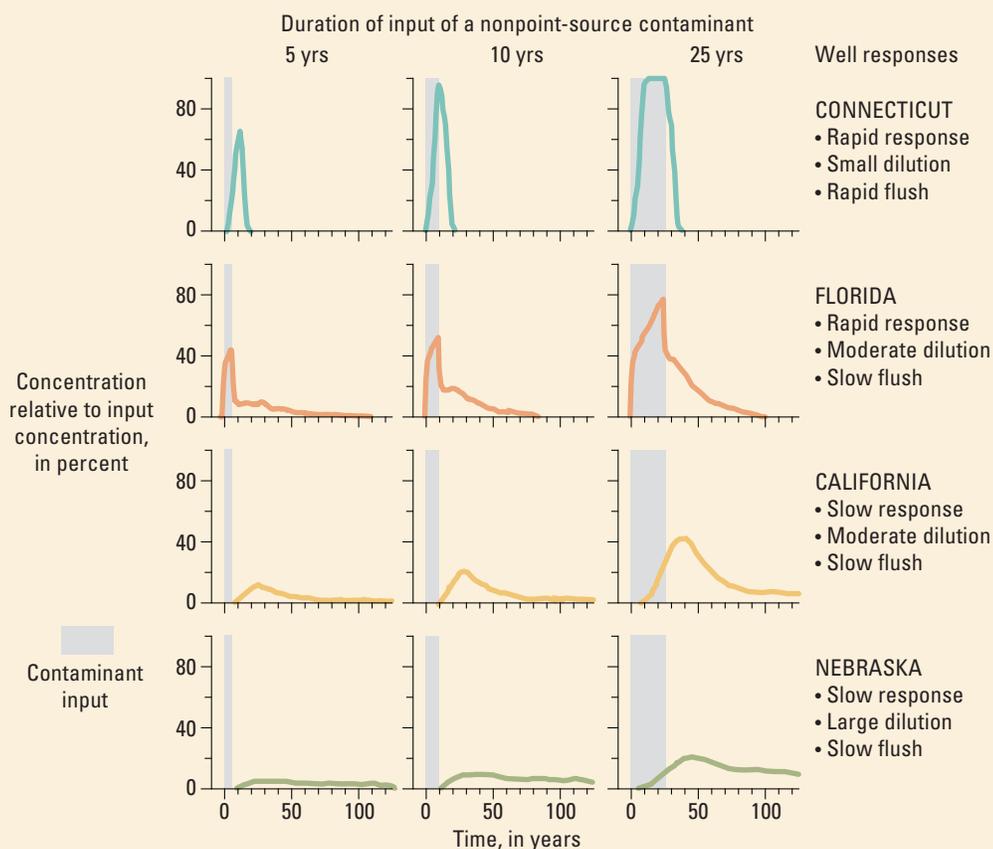
CASE STUDY

Differences in groundwater-age mixtures help explain why concentrations of nonpoint-source contaminants continue to increase in some wells while decreasing in others

How does water quality at different wells respond to similar contamination of the shallow groundwater? To investigate this, water-quality response curves for the study wells in Connecticut, Florida, California, and Nebraska were created for several hypothetical contaminant input-duration scenarios. The scenarios were 5 years of contaminated recharge followed by clean recharge (figure below, left column), 10 years of contaminated recharge followed by clean recharge

(middle column), and 25 years of contaminated recharge followed by clean recharge (right column).

The age mixtures for groundwater in the wells were obtained from groundwater-flow models. The contaminant was assumed to be nonreactive and uniformly distributed across the recharge area for each well. Another assumption was that the contaminant was released into the shallow groundwater near the water table; differences in



The groundwater-age mixture for a well can be used to help forecast the response of the well to widespread contaminant input at the water table. Comparison of water-quality response curves for multiple wells can help identify differences in the potential response of the wells to similar contaminant input scenarios. Model results show that wells with young water and narrow age ranges (for example, Connecticut study well) can respond rapidly to contaminant input and source removal, but do not benefit much from in-well dilution of contaminants. On the other hand, wells that produce groundwater with a wide range of ages can benefit from in-well dilution because no single recharge year contributes more than a few percentage of the water pumped from the well (for example, Nebraska). Concentrations can continue to go up after contaminant source removal if a substantial amount of the produced water is older than the number of years of contaminant input.

contaminant transport across the different unsaturated zones were not accounted for in the simulations. Given these assumptions, the differences in the graphs on the opposite page are solely the result of differences in traveltimes and, thus, groundwater-age mixtures among the wells.

The Connecticut well produces mostly young water. As a result, contaminant concentrations in these simulations increase rapidly in the Connecticut well after the start of contaminant input (rapid response) and decrease rapidly after contaminant input ceases (rapid flush). Concentrations in groundwater in the well almost reach the input concentration after only 10 years of contaminated recharge (figure on opposite page, top row).

The water quality in the Florida well responds more rapidly to the onset of contaminant input compared to the Connecticut well because much of the groundwater entering the Florida well travels from the water table to the well in a very short amount of time (more than 20 percent of the water from the Florida well is less than 1 year old). However, the Florida well also produces a substantial fraction of old water. So, in-well dilution causes the contaminant concentration in the well to be less than the input concentration. If contaminant input ceased after 25 years, concentrations in the Florida well would decrease rapidly because the well produces a high proportion of water less than 25 years old.

The California and Nebraska wells produce a large fraction of old water, resulting in simulated initial responses,

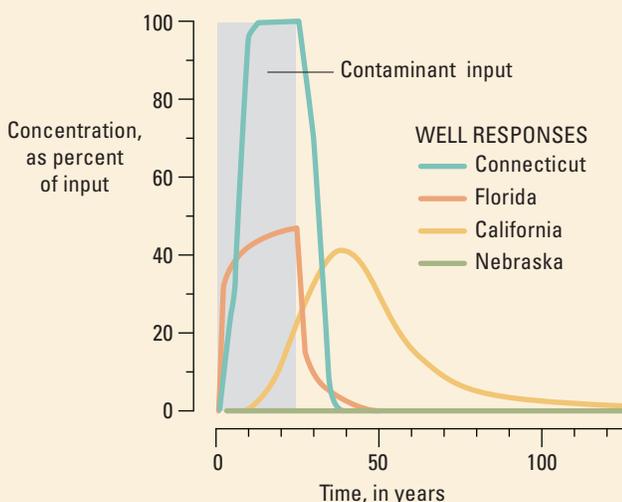
dilution, and flushing that are much different than those for the Connecticut and Florida wells. For the 25-year contaminant-input scenario, the time delay between the start of contaminant input and peak concentration in the wells is close to 4 decades. Concentrations in the wells would continue to increase for about 15 years after contaminant input ceases (figure on opposite page, bottom two rows) because much of the contaminated groundwater would still be traveling to the wells at the end of the period of input. In these scenarios, contaminant concentrations in the wells would never reach the input concentration because the wells draw in a large amount of water that is older than 25 years (the length of contaminant input), resulting in continuous dilution of contaminants in younger water.

Some contaminants (such as nitrate) can degrade within an aquifer. The response of the water quality in a well to this type of contamination depends on the traveltime to the well and the amount of degradation that occurs in the surrounding aquifer. Results for a scenario in which

Several years or even decades of monitoring will not be enough to determine long-term trends in many public-supply wells because of the wide range of groundwater ages in the wells. For these wells, a coupled monitoring and modeling approach is needed.

25 years of contaminant input was coupled with site-specific denitrification rates are shown in the figure at the lower left. Very little denitrification occurs in the aquifers surrounding the Connecticut and California wells. Therefore, the curves for these wells are similar to the curves shown on the opposite page for the 25-year scenario without denitrification. However, a

notable amount of denitrification takes place in the aquifers in the Florida and Nebraska study areas. As a result, the maximum predicted concentrations for these wells are less than those predicted on the basis of the age mixtures alone.



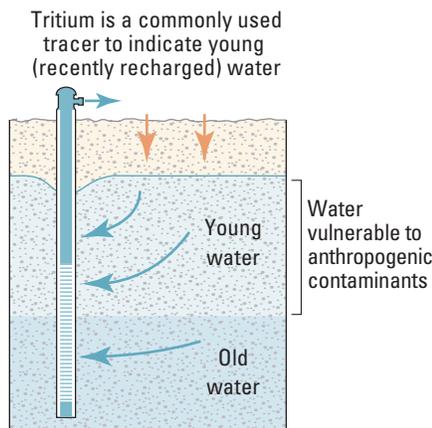
Differences in the response of wells to the same contaminant input may be particularly pronounced where differences exist in both the groundwater-age mixtures and the geochemical conditions that affect contaminant degradation rates.

MORE INFORMATION

Response of public-supply wells to land-use change
McMahon and others, 2008b

Groundwater-age distributions for evaluating public-supply well vulnerability
Eberts and others, 2012

Estimating Groundwater-Age Mixtures for Wells



One of the more commonly used indicators of young groundwater is tritium. Tritium (^3H) is a radioactive form of hydrogen that can be part of the water molecules that recharge an aquifer. Because it is short lived, tritium is most frequently detected in water samples that contain a component of relatively recent recharge. However, the amount of tritium in groundwater recharge has been declining since the end of aboveground nuclear weapons testing—a source of tritium in the atmosphere. As a result, tritium is becoming less useful for identifying recently recharged groundwater. Moreover, a single tritium measurement does not describe the mixture of groundwater ages in water pumped from a public-supply well and therefore cannot be used to forecast the response of the well to widespread contaminant input at the water table.

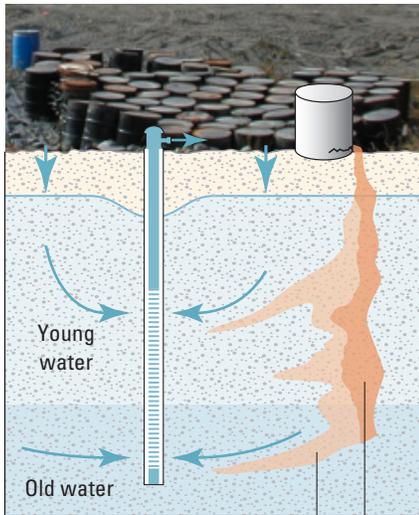
The link between groundwater age and public-supply-well vulnerability to contamination has been recognized for some time, particularly the relation between young groundwater and the potential for contamination by manmade chemicals (Kazemi and others, 2006, p. 68). Hence, some states and local communities estimate the age of the water produced by their public-supply wells to gage the vulnerability of their water source to contamination. Most often, water from a well is analyzed for a chemical indicator (tracer) of relatively young groundwater, and a single value for the age of the groundwater from the well is obtained. When groundwater age is estimated in this way, the age is an “apparent” groundwater age because a substantial amount of interpretation is involved. (For a summary of tracer-based methods for dating groundwater, see Plummer and others, 2003.) More importantly, a single value for groundwater age does not describe the full recharge history for a public-supply well—some of the water entering the well will be younger and some will be older than the estimated age. Lack of information on the younger and older water can lead to a misdiagnosis of the vulnerability of the well because contaminant input is likely to have changed over time. Therefore, it is useful to have tools for estimating the groundwater-age mixture in water from wells.



Water is analyzed for tritium in the laboratory by using (clockwise from upper left) distillation, electrolytic enrichment, secondary distillation, and scintillation counting.



The methods and tools that were used in this study to estimate the complete distribution of groundwater ages in water from public-supply wells are introduced here and discussed in more detail in the Appendix. (See pages 109, 113–116.) A widely used (and expensive) method combines groundwater-flow modeling with particle-tracking modeling. Data from many locations throughout the modeled area are needed for this method so that the models are calibrated to real-world conditions before being used for



Dissolved contaminant—travels with the flowing groundwater

Dense non-aqueous phase liquid (DNAPL) contaminant—does not necessarily travel with the flowing groundwater

Because of the release of dense non-aqueous phase liquids to the environment, old water sometimes contains contaminants from recent human activity, as depicted in the above figure. The photo in the figure shows a site in which such dense compounds from an old dry-cleaning facility were once stored and leaked.



age estimation. Ideally, the calibration data include concentrations of age tracers in the groundwater. A less resource-intensive method involves fitting a curve described by a mixing equation to tracer concentrations in groundwater from a well of interest. For this method, multiple tracer data (multiple tracers for a single sample or a single tracer for multiple samples collected over a period of years) are needed to narrow down the possible combinations of groundwater ages in the water. A computer program (TracerLPM; Jurgens and others, 2012) was developed for this study to simplify the curve-matching process. Finally, if no groundwater-flow model or age-tracer data are available for a well, it might be possible to obtain a rough estimate of the groundwater-age mixture for the well from basic aquifer properties and well characteristics (such as aquifer thickness, porosity, recharge rate, and well screen depth) and use of equations that solve for traveltime (Cook and Böhlke, 2000; Mendizabal and Stuyfzand, 2009).

Limitations of Groundwater-Age Estimates for Assessing Well Vulnerability

One limitation of relying on groundwater-age estimates for assessing public-supply-well vulnerability is that reliable estimates can be difficult to obtain and might require the services of a technical expert. In addition, the groundwater-age mixture of the water from a well might vary over time as a result of pumping (Masterson and others, 2002).

Another limitation is that some types of contaminants enter aquifers and move towards wells without being transported with the flowing groundwater. Consequently, the age of the water might not reflect the actual vulnerability of the water to contamination. For example, the solvents PCE and TCE are two of the most frequently detected groundwater contaminants in the United States (Zogorski and others, 2006). These VOCs are denser than water and can enter and move within aquifers by sinking through the unsaturated and saturated zones before dissolving and flowing with the groundwater. As a result, such compounds are sometimes detected in groundwater that recharged an aquifer hundreds of years ago.

A method for identifying wells with groundwater that is vulnerable to contamination from local sources of VOCs—regardless of the age of the water—was developed by using data from this study. The method is based on analysis of VOCs at extremely low concentrations (parts per quadrillion) using a gas chromatograph with an electron-capture detector; this method can provide water managers with an early warning that a well is vulnerable to contamination. (See Appendix, pages 109, 118.)

Finally, old water is not without its vulnerability to contamination. Naturally occurring drinking-water contaminants can occur in such water.

Tracers of young groundwater may not detect a vulnerability to contaminants that do not travel with the flowing groundwater or that occur naturally.



Karst features enable the Peace River in Florida to flow quickly into the subsurface.

“Preferential flow pathways are significant in many hydrogeologic settings and need to be taken into account by those involved in establishing source water protection areas for public-water-supply wells.”

Darcy Campbell,
U.S. Environmental Protection Agency,
Region 8, 2011

Preferential flow pathways are pathways that provide little resistance to groundwater flow, enabling water and associated contaminants to move relatively quickly in the subsurface. If a stress is added to an aquifer system (such as an increase in recharge from precipitation or an increase in discharge from pumping wells) the movement of the groundwater and contaminants along preferential flow pathways will be accelerated more so than along other flow pathways. Preferential flow pathways are important because they can affect every aspect of groundwater and public-supply-well vulnerability. For example, preferential flow pathways can influence whether a source of contaminants is linked to a well, whether chemical reactions can substantially alter contaminant concentrations before contaminated groundwater enters a well, and whether contaminated groundwater will reach a well within a time period of concern for the well owner. For these reasons, it is important to recognize whether preferential flow pathways are influencing the quality of water from a well.

Fractures and other openings in carbonate rocks (limestone and dolostone) enable water to flow through unsaturated zones and within aquifers while encountering little resistance to flow. Contaminated water traveling along such features will strongly influence the vulnerability of the water from a well completed in this type of aquifer.

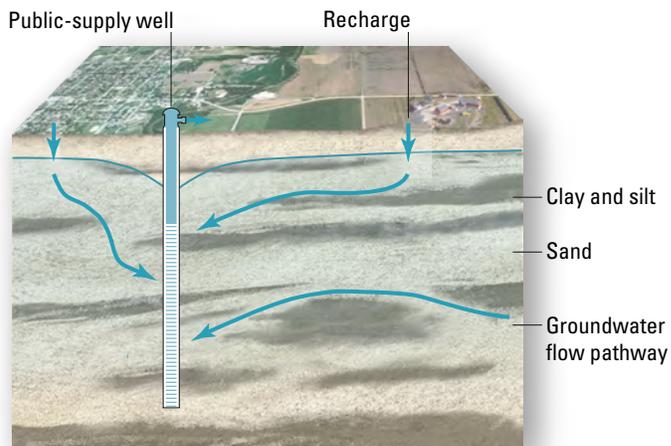


This still-frame photo is from a video that was taken using a camera lowered into a borehole, and it shows a conduit (distinctive void space) intersecting the borehole. Water and contaminants can travel rapidly to a well that is intersected by such natural features.

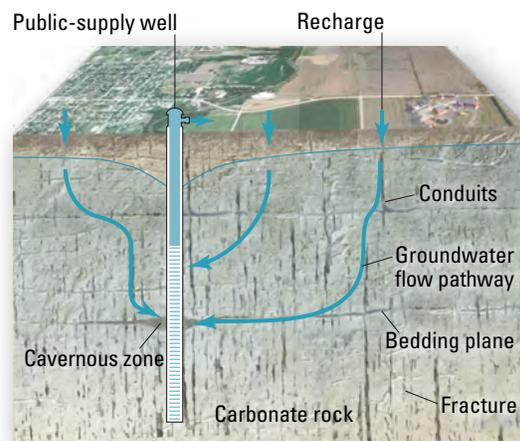


Both natural factors and human activities can lead to preferential flow of groundwater and contaminants in the subsurface, as illustrated below:

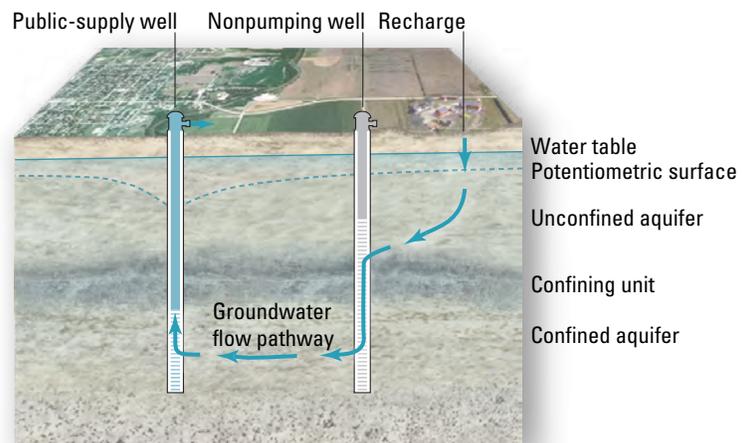
Fast flow pathways are preferential flow pathways that result from natural variations in the water-transmitting properties of aquifer materials. (See figure at right.) For example, water can move more rapidly through interconnected sand lenses than through clay or silt. When a public-supply well begins pumping, water is preferentially drawn towards the well from the most transmissive material in the aquifer, such as a sand or gravel.



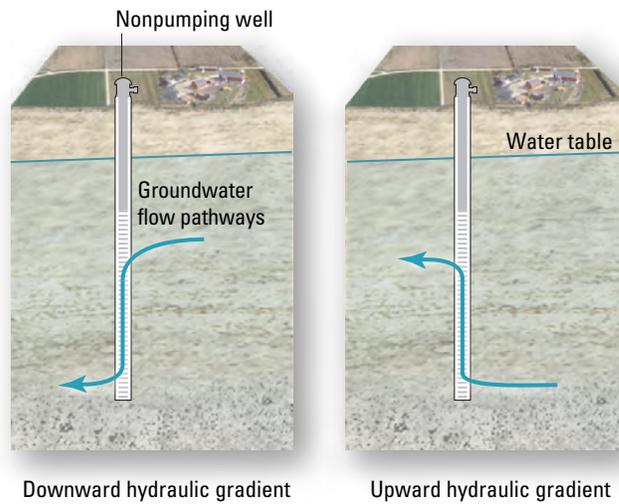
Hydraulic short-circuits are preferential flow pathways that cause water and contaminants to bypass aquifer material through which they would otherwise flow. For example, fractures, bedding planes, conduits, and cavernous zones in bedrock allow fluids to rapidly bypass the aquifer matrix. This type of hydraulic “short-circuiting” occurs because these natural features have relatively wide openings, providing little resistance to flow. The presence and location of naturally occurring hydraulic short-circuits are not usually known. Therefore, it can be difficult to quantify their effect on groundwater flow and contaminant transport to a public-supply well.



Manmade features also can act as hydraulic short-circuits in an aquifer system. For example, wells with screens that connect multiple aquifers (multi-aquifer wells) can allow water and contaminants to move rapidly across confining units that otherwise would restrict flow.

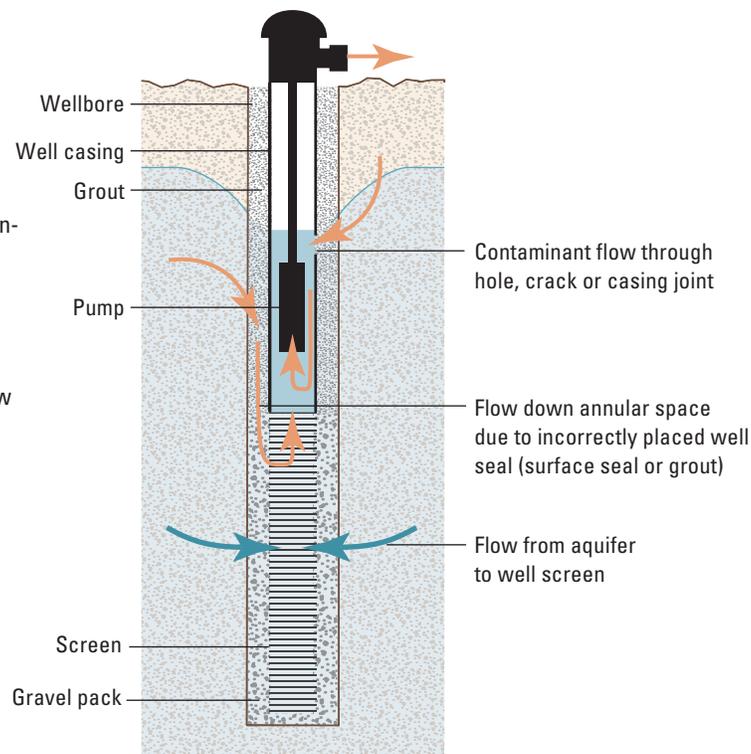


The rapid movement of water within wellbores is not limited to multi-aquifer wells. Any well with a screen that is long enough to intersect different parts of an aquifer having different hydraulic heads will allow water and contaminants to migrate from one location within the aquifer to another by way of the wellbore (see figure at right). The movement can be downward or upward, depending on the direction of the hydraulic gradient. Because pumping affects water levels—a measure of hydraulic head—the movement of contaminants between aquifer units can change under different pumping conditions. Consequently, a change in pumping can affect the quality of the water from a well. (For an example, see pages 70–71.)



Results of modeling scenarios from this study that further explore how wellbores act as preferential flow pathways are presented on pages 75–76.

Shortcomings in the construction or maintenance of public-supply wells also can lead to hydraulic short-circuiting in the vicinity of a well. For example, breaches in the well seal or well casing can allow contaminated water to rapidly enter the well screen. This type of preferential flow pathway was not observed during this study and is not further discussed.



Why Preferential Flow Pathways Matter

Preferential flow pathways can be the most important pathways for the transport of contaminants to a public-supply well.



USGS Ohio Water Microbiology Laboratory



E. coli—A bacterial indicator of fecal contamination of groundwater

- Preferential flow pathways often deliver the youngest, most vulnerable water to a well, along with most of the anthropogenic contaminants that reach the well.
- Preferential flow pathways make it difficult to know where the water from a well has originated. For example, the youngest water from a well might not enter the aquifer in the areas that are closest to the well. As a result, it can be challenging to determine which areas at the land surface to prioritize for reducing water-quality threats. (See page 65.)
- Preferential flow pathways create favorable conditions for the transport of pathogenic (disease-causing) microorganisms: rapid travel times reduce the opportunity for microorganism die-off, and relatively large interconnected openings reduce the opportunity for microorganisms to be removed from the water by filtration or sorption to sediments or rocks (USEPA, 2008).
- Preferential flow pathways cause contaminants to be transported at relatively rapid rates and reduce the effectiveness of natural processes that remove chemical contaminants from groundwater where groundwater velocities become sufficiently high compared with contaminant degradation rates. For example, if groundwater flow is relatively slow, all dissolved nitrate might be degraded before contaminated water reaches a public-supply well. However, if groundwater flow is relatively fast, contaminated water might reach the well before denitrification is complete.
- Preferential flow pathways can cause water and aquifer materials that are not in chemical equilibrium to come into contact. This can lead to chemical reactions that increase concentrations of naturally occurring drinking-water contaminants in the water.
- Preferential flow pathways can transport surprisingly large volumes of water to a well. For example, as much as 35 percent of the water from the Nebraska study well might have traveled along preferential flow pathways on the way to the well. (See pages 72–73.) Where preferential flow pathways are present, the mix of water and contaminants entering a well can change rapidly in response to changing hydrologic conditions and pumping rates, affecting the overall quality of water from the well.
- Preferential flow pathways appear to be pervasive—each study well was affected by at least one type of preferential flow pathway. (See pages 66–73.)

Preferential flow pathways with large interconnected openings are especially important for the transport of pathogenic (disease-causing) microorganisms to public-supply wells. Pathogenic microorganisms in groundwater that is drawn into a well, however, can be difficult to detect. This is because such organisms might appear only intermittently in the water. Therefore, groundwater samples often are analyzed for the presence of indicator microorganisms—organisms that are consistently present in fecal waste and that occur in greater numbers than associated pathogens.

CASE STUDY

Preferential flow pathways lead to complicated contributing areas for study wells

Source water protection is a means of preventing contaminants originating near the land surface from moving toward and reaching a well that is used as a source of public drinking water (USEPA, 1997). Numerous methods have been used to delineate the areas around wellheads for assessment and protection. The most sophisticated and potentially most accurate methods make use of three-dimensional groundwater-flow models. Yet, simpler methods (for example, delineation using a fixed-radial distance from a well) are more common. Regardless of method, source water protection typically focuses on the areas closest to a public-supply well—the assumption being that recharge at the water table near the wellhead will be drawn into the well in the shortest amount of time. However, preferential flow pathways can invalidate this assumption.

Widespread groundwater protection makes sense because preferential flow pathways make it difficult to know which areas at the land surface are most likely to contribute water and contaminants to a well.

For example, the local-scale groundwater-flow models for the California, Florida, and Nebraska study areas, which include enough detail to account for preferential flow, depict situations that might seem surprising. Some of the shortest traveltimes to the wells are associated with recharge areas that are located at great distances from the wells. For the California study area, preferential flow results from natural variations in the water-transmitting properties of the aquifer materials. For the Florida study area, preferential flow occurs within natural conduits and cavernous zones in the bedrock. For the Nebraska study area, preferential flow occurs within the wellbores of multi-aquifer wells located upgradient of the modeled public-supply well.

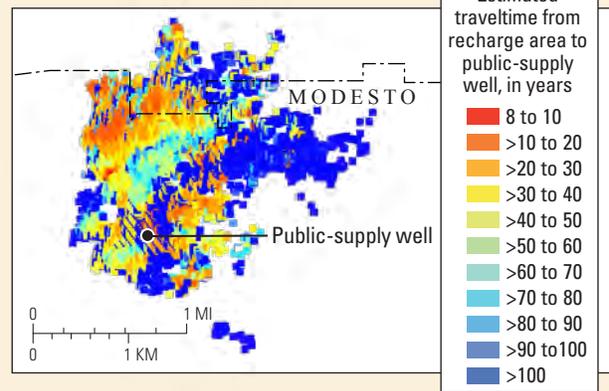
The models used to compute the contributing areas presented here are themselves limited because they simulate only one possible configuration of the preferential flow pathways in each study area. In reality, the exact locations of features that result in preferential flow are rarely known. However, the complex patterns of these simulated recharge areas are realistic.

MORE INFORMATION

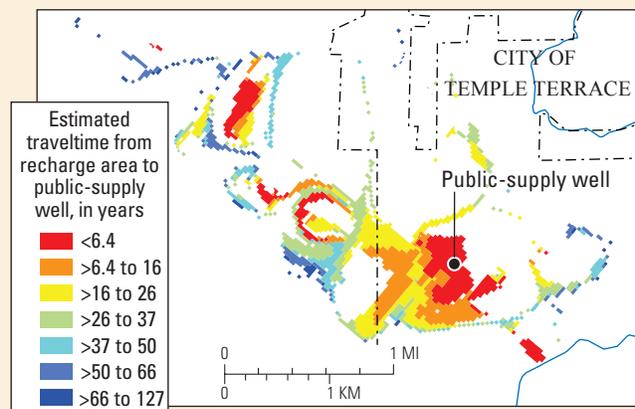
Models used to simulate contributing areas

Burow and others, 2008
Clark and others, 2008
Crandall and others, 2009

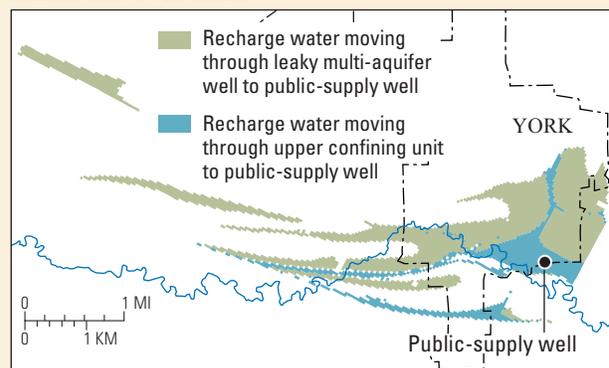
CALIFORNIA STUDY AREA



FLORIDA STUDY AREA



NEBRASKA STUDY AREA



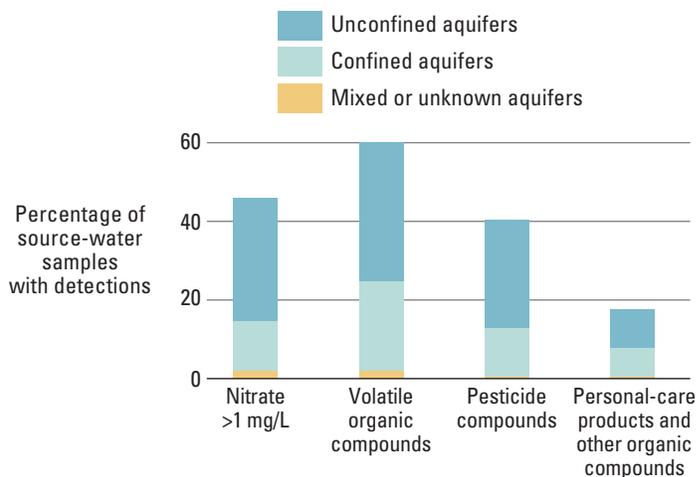
The recharge area for wells that are affected by preferential flow pathways might not be intuitive. This study finding is illustrated in the figures above, which depict simulated areas contributing recharge to study wells in California, Florida, and Nebraska, each of which produces some water that reached the well by way of preferential flow pathways.

Implications for Monitoring and Protecting Public-Supply Wells

Preferential flow pathways contributed to the occurrence of contaminants in each of the public-supply wells selected for detailed investigation, as previously noted. The preferential flow pathways were markedly different in each case, increasing the vulnerability of the wells in different ways. However, an understanding of preferential flow provided an opportunity to improve monitoring or protection strategies for each well, as illustrated in the examples that follow.

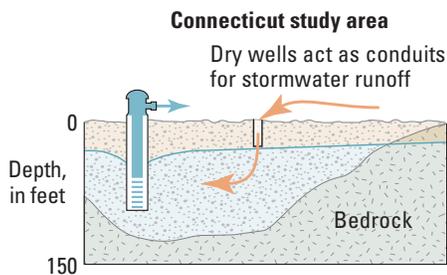
Recognizing the nature and contribution of preferential flow pathways can help resource managers prioritize the most effective measure for protecting groundwater used as a source of drinking water.

Preferential flow pathways can leave water from confined-aquifer wells vulnerable to contamination from anthropogenic chemicals



In a nationwide study of water quality in public-supply wells, about one-third of the detections of anthropogenic contaminants were in water from confined-aquifer wells (Toccalino and Hopple, 2010). This was unexpected because confined aquifers generally are assumed to be protected from anthropogenic contamination by an overlying confining unit. These data indicate that preferential flow pathways that allow contaminants to be transported relatively rapidly across confining units might be common, and (or) the geologic information needed to accurately characterize the extent of confinement in many instances is inadequate.

Linking Stormwater Management and Source Water Protection is Necessary to Limit Vulnerability



MORE INFORMATION

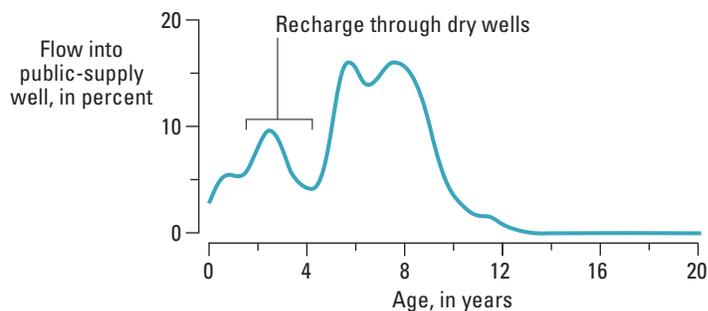
Brown and others, 2009
Jagucki and others, 2010
Starn and Brown, 2007

Findings from the Connecticut study area illustrate the importance of joint planning for stormwater management and source water protection. Such planning can limit situations that inadvertently increase the vulnerability of the water from a public-supply well to contamination.

Stormwater runoff occurs when precipitation flows across the land surface. As it flows, the water can pick up a variety of harmful chemicals and (or) pathogenic microorganisms. Some communities redirect this stormwater into an underlying aquifer by using dry wells (also called stormwater drainage wells). Use of dry wells can reduce flooding and erosion, increase groundwater recharge, and limit the amount of contaminants entering a surface-water body, the latter of which is desirable because discharging contaminated stormwater to surface water is regulated under the National Pollutant Discharge Elimination System (NPDES) program, under the authority of the Clean Water Act (USEPA, 1997). Dry wells, however, can increase contaminant loading to the groundwater because unsaturated-zone processes (such as filtration and degradation) that help remove contaminants from infiltrating water are bypassed. Although dry wells are regulated by the Underground Injection Control (UIC) Program, under the authority of the Safe Drinking Water Act, they are often close to roadways, parking lots, and commercial and industrial loading facilities where spills or illicit discharges of hazardous substances might occur (USEPA, 1999).

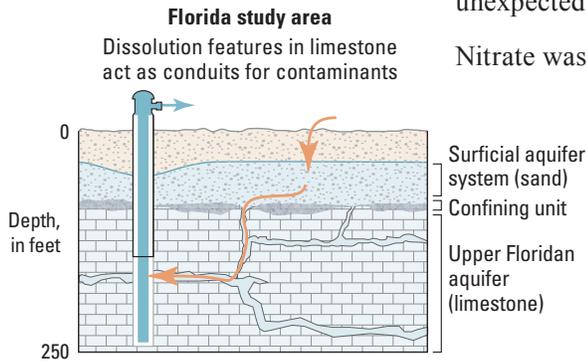
Dry wells in the Connecticut study area redirect stormwater from a commercial area into the underlying shallow aquifer (less than 15 ft to the water table). Results from the local-scale groundwater-flow model of the area indicate that 16 percent of the water from the study well recharged the aquifer by way of dry wells. This means that 16 percent of the water from this public-supply well does not benefit from unsaturated-zone processes that can reduce contaminant concentrations in recharge water. Thus, the dry wells have the potential to increase the vulnerability of the water from the well to contamination—an unanticipated consequence of using dry wells in the area.

Dry wells (storm drains with no outlets) in a commercial area within the Connecticut study area (photo) are located in the recharge area for the study well. The water that is shunted to the water table by means of the dry wells can travel through the aquifer and reach the public-supply well within 2 to 4 years—some of the shortest travel times from the water table to the well. The presence of the dry wells, which circumvent unsaturated-zone processes that can remove contaminants from infiltrating water, leave the public-supply well more vulnerable to contamination than if the dry wells were not present.



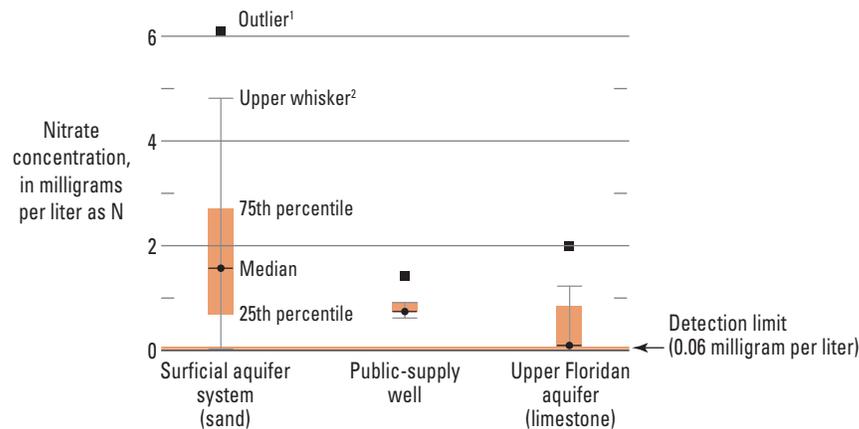
Comprehensive Monitoring Can Be Essential for Detecting the Influence of Preferential Flow

Findings from the Florida study area illustrate why characterizing groundwater chemistry in multiple aquifers (or aquifer units) can be essential for identifying preferential flow pathways bringing low-quality water from unexpected parts of an aquifer system to a well.



Nitrate was detected at concentrations as high as 6.1 mg/L in water from monitoring wells in the surficial (sand) aquifer system in the Florida study area. (See figure below.) Conditions in this aquifer were oxic and favored the persistence of dissolved nitrate. Nitrate was not detected in water from most monitoring wells in the Upper Floridan aquifer. Conditions in this limestone aquifer were anoxic and favored denitrification. However, nitrate was detected at low concentrations in water from the public-supply well, although the well is open solely to the limestone aquifer (median concentration, 0.89 mg/L).

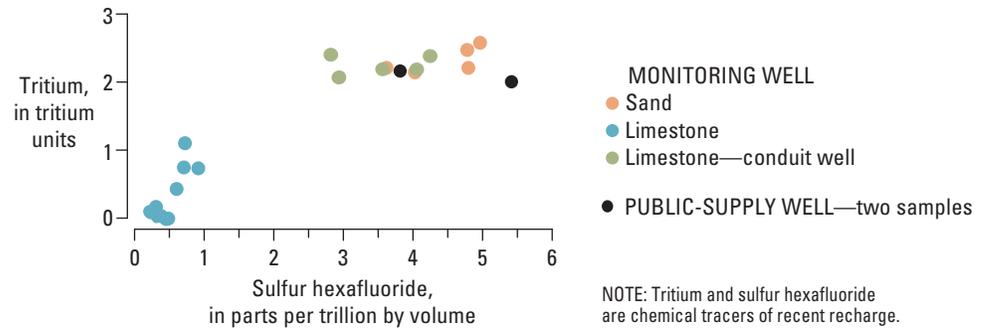
Additional groundwater-chemistry data helped reveal why nitrate was detected in the public-supply well. Concentrations of several chemical constituents in the water from the public-supply well were more similar to concentrations in water from sand-aquifer monitoring wells than from limestone-aquifer monitoring wells. Exceptions included several limestone-aquifer monitoring wells that were completed in a cavernous zone within



¹ Outliers are defined as values outside of the whisker span.

² The whiskers span the largest and smallest values within 1.5 times the interquartile range.

Nitrate detected in the study well in Florida had concentrations above those detected in most monitoring wells in the same (limestone) aquifer. This is because the high rate of pumping at the public-supply well caused contaminated water from the overlying sand to travel rapidly along dissolution features in the limestone to the public-supply well. Thus, the denitrification reaction taking place in the anoxic limestone aquifer could not remove as much nitrate from the groundwater reaching the public-supply well compared with the groundwater reaching most of the limestone monitoring wells.



Environmental tracer concentrations in water from the public-supply well and monitoring wells completed in a cavernous zone within the limestone bedrock were more similar to concentrations in water from the overlying sand aquifer system than water from the remaining limestone-monitoring wells, as illustrated in this figure. These data confirm the finding that dissolution features in the limestone bedrock act as preferential flow pathways causing some limestone-aquifer wells to draw in water from the more vulnerable sand aquifer system.

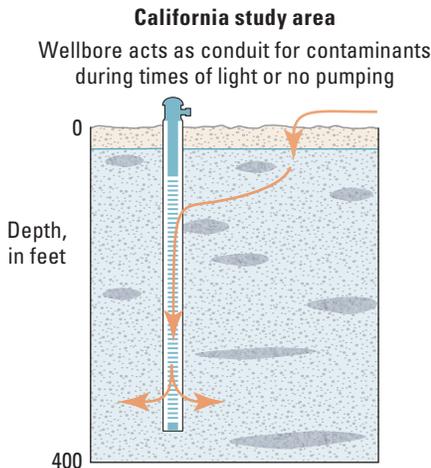
the limestone bedrock. (See figure above.) The monitoring data demonstrated that the cavernous zone provides a hydraulic connection between the overlying sand and some of the limestone wells, including the public-supply well. Nitrate-contaminated groundwater might have reached the public-supply well because pumping at the well increased the groundwater velocity within the cavernous zone to the extent that very little denitrification could take place before the water reached the well. Alternatively, geochemical conditions within the cavernous zone might have been unfavorable for denitrification to occur in the first place (too much dissolved oxygen).

No single monitoring well in the Florida study area provided enough information to conclude that the sand aquifer, by way of a cavernous zone and other karst features, was the source of contaminants in the public-supply well. Rather, the conclusion regarding the contaminant pathway in this study was drawn from a body of evidence that included groundwater-chemistry data for the public-supply well and monitoring wells in multiple aquifers. In general, a monitoring well is unlikely to intersect a preferential flow pathway bringing contaminated water to a public-supply well, but the degree to which the overall water quality at a public-supply well reflects that of an adjacent, more vulnerable aquifer is one way of identifying the most vulnerable wells in an area.

MORE INFORMATION

Crandall and others, 2009
 Jagucki and others, 2009
 Katz and others, 2007

Temporal Fluctuations in Water Quality Can Help Water Managers Identify Preferential Flow

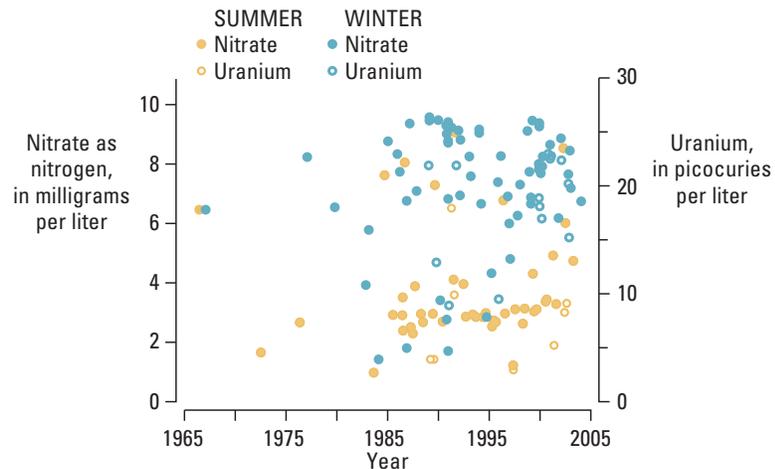


Findings from the California study area call attention to the importance of collecting monitoring data under different hydrologic conditions. Short-term water-quality fluctuations in a deep public-supply well can indicate preferential flow.

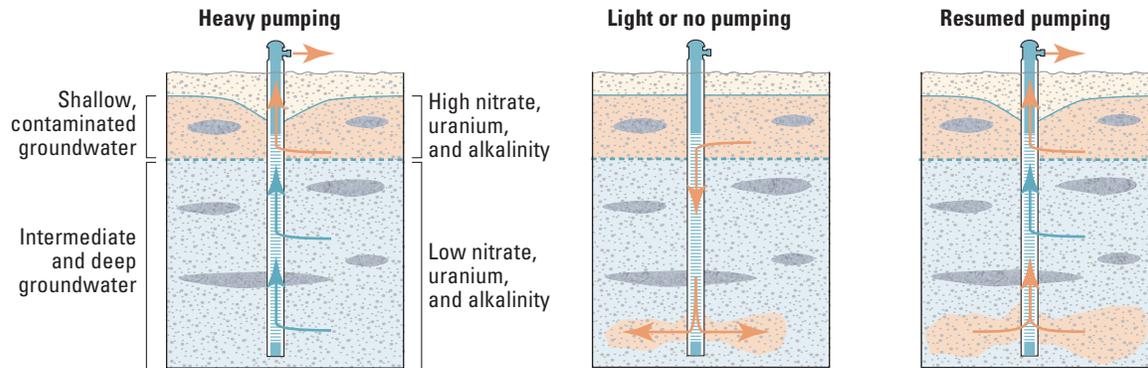
Nitrate and uranium concentrations in the public-supply well had fluctuated seasonally for several decades. (See figure below.) The fluctuations were recorded in the long-term records for the well. Because the well is screened from 60 to 365 ft below land surface, it was unlikely that recharge of a different quality traveled from the water table to the well screen each season. Thus, the very short-term variation in water quality indicated preferential flow, which was confirmed by further investigation.

The local-scale investigation showed that, during times of heavy pumping (summer months), about 20 percent of the flow to the well was from shallow, contaminated parts of the aquifer (figure on opposite page, left). When the well was not pumping, shallow contaminated groundwater moved down the wellbore and out into deeper parts of the aquifer because the vertical-hydraulic gradient in the aquifer was downward. During times of light or no pumping (winter months), a substantial amount of contaminated water accumulated in the aquifer near the base of the well and was detected in samples from a nearby, deep monitoring well (figure on opposite page, center). When pumping resumed after a relatively inactive period, the contaminated water temporarily stored at depth was drawn back into the well. At these times,

Long-term records for a public-supply well can contain evidence of preferential flow, such as the seasonal differences in water quality recorded for the study well in California, as illustrated in this figure.



Seasonal or intermittent operation of a public-supply well can lead to undesirable water-quality variations because public-supply wells create hydraulic short-circuits in an aquifer that can allow contaminated groundwater to alternately enter a well along greater or lesser lengths of its well screen.

**MORE INFORMATION**

Burow and others, 2008
Jurgens and others, 2008

nearly 45 percent of the flow to the well was made up of contaminated water, and contaminant concentrations in water from the well approached drinking-water limits (figure above, right).

The differences in water-quality data for summer and winter helped draw attention to the way in which the California public-supply well functioned as a hydraulic short-circuit. This knowledge enabled the pumping schedule for the well to be updated (longer pumping periods during winter months), and the quality of the water improved.

Water-quality changes linked to disease outbreaks

Changes in hydrologic conditions have preceded most of the worst disease outbreaks attributed to drinking water in affluent nations in recent years (Hrudey and Hrudey, 2004). Consequently, it is important to understand whether changes in hydrologic conditions lead to rapid changes in the quality of water pumped from a public-supply well. Even if contaminant concentrations do not vary significantly, variations in the physical properties (temperature, flow, turbidity) and chemistry (redox, pH, alkalinity) of water from a public-supply well are important to identify. Such changes might disrupt water-treatment processes that function best when conditions are constant or might signal a change in the source(s) of water for a well.

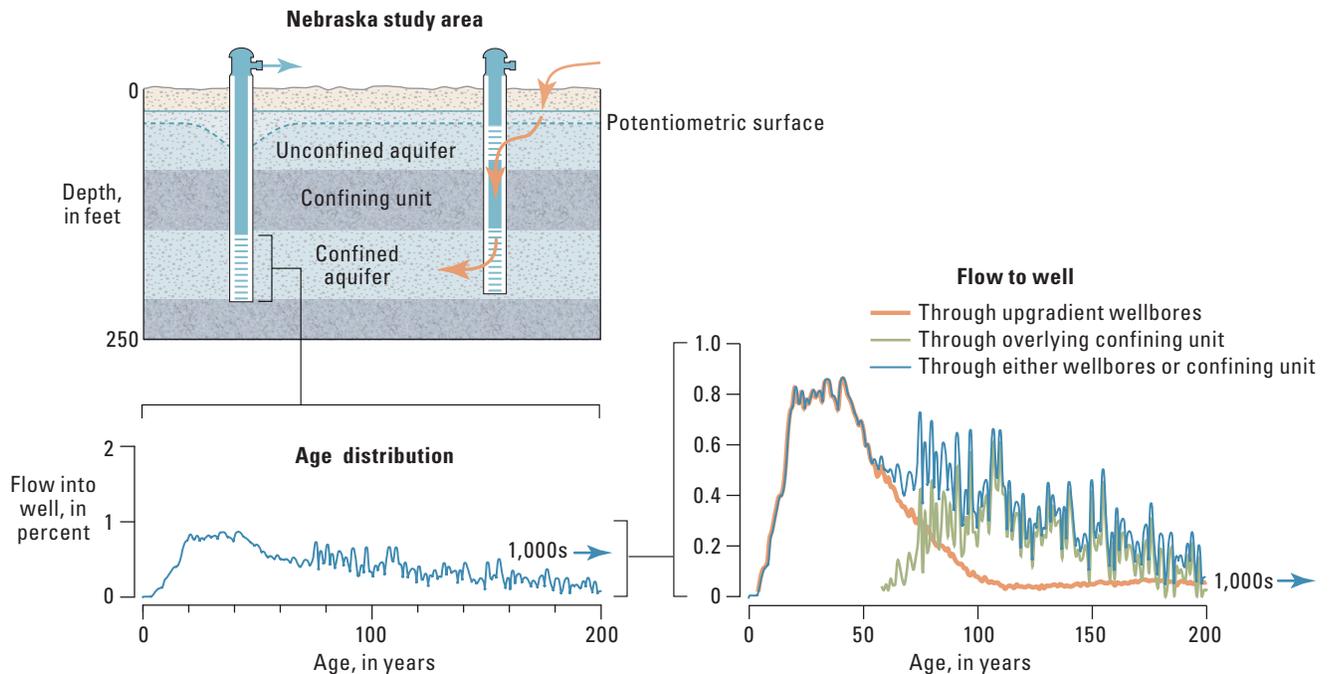
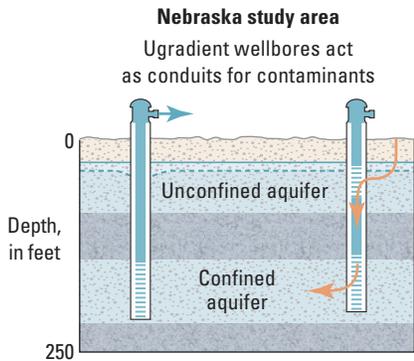


An outbreak attributed to contaminated groundwater sources of drinking water on South Bass Island, Ohio (photo above), affected approximately 1,450 people during summer 2004. The outbreak was caused by the transport of microbial contaminants from wastewater treatment facilities and septic systems to the underlying carbonate-rock aquifer and to Lake Erie after extreme precipitation events in May–July of the same year. Dissolution features in the aquifer facilitated the rapid transport of contaminated water to the drinking-water supply wells (Fong and others, 2007).

Determining How Contaminants Reach a Well Can Help Narrow Protection Options

Findings from the Nebraska study area illustrate how effective protection strategies require an understanding of the dominant pathways of contaminant transport to a public-supply well.

Many irrigation and other production wells in this study area are completed in an unconfined aquifer and the confined aquifer used for public supply. When the multi-aquifer wells are not being pumped or are being pumped at low rates, water in the unconfined aquifer flows within their wellbores down to the confined aquifer. This downward movement occurs because the water levels in the unconfined aquifer are higher than those in the confined aquifer, owing to the widespread withdrawal of water from the confined aquifer for irrigation. The volume of relatively young, contaminated water that reached the confined aquifer in this way was substantial because of the high density of multi-aquifer wells in the area—approximately 2 to 3 wells per square mile. Nearly 25 percent of all water that entered the confined aquifer arrived by means of multi-aquifer wells.



Without upgradient multi-aquifer wells acting as hydraulic short-circuits across the regionally extensive confining unit, most water from the Nebraska study well would have been decades old and would not have carried with it anthropogenic contaminants from recent human activities. The groundwater-flow and particle-tracking models for the Nebraska study area were used to compute how much of the water that entered the investigated public-supply well originally entered the confined aquifer by way of multi-aquifer wells—as much as 35 percent.

A total of 11 confined-aquifer public-supply wells were sampled for this study. Of the 11 wells, 8 were affected by anthropogenic contaminants that had leaked from the unconfined aquifer to the confined aquifer through multi-aquifer wells. Contaminant concentrations differed among the wells according to the proportion of confined and unconfined aquifer waters that mixed in the wells.

As much as 35 percent of the water drawn into the selected study well might have entered the aquifer by means of upgradient multi-aquifer wells. (See figure on opposite page.) However, it was estimated that 100 percent of the anthropogenic contaminants (PCE, TCE, and their degradation byproducts) that were detected in the produced water traveled down a multi-aquifer well before reaching the supply well.

Knowing that multi-aquifer wells are the source of the anthropogenic contaminants in the confined-aquifer public-supply well enables resource managers to focus on devising effective measures to prevent or minimize flow through multi-aquifer wells. In addition, resource managers might treat the confining unit as having been compromised for the purpose of source water protection because it is unlikely that all wells breaching a confining unit will be accurately identified. This can be accomplished by protecting the area at land surface above a zone of transport for a well that is based solely on confined-aquifer groundwater travel times—as opposed to one that is based on combined unconfined aquifer, confining-unit and confined-aquifer travel times. This approach to source water protection can prevent the water from a well from becoming contaminated if an unidentified multi-aquifer well were to shunt groundwater across a confining unit. (See Appendix, pages 119–120, for a sample calculation.)

Historically, individual irrigation and other high-volume production wells in the High Plains aquifer were screened both above and below confining units. This type of construction enables water to move rapidly between aquifers, carrying with it contaminants that might otherwise remain within a single aquifer. A high density of multi-aquifer wells (2 to 3 per square mile within the Nebraska study area) can exacerbate this situation. The density of wells is illustrated by the proximity of circular crop patterns in the photo to the right.



John A. Kelley, USDA Natural Resources Conservation Service

MORE INFORMATION

Johnson and others, 2011
Landon and others, 2008

Recognizing the Influence of Preferential Flow Pathways



There are a number of methods for recognizing the existence of preferential flow pathways and their influence on the quality of water from a public-supply well. Methods that were used in this study are listed below:

- Compare groundwater samples from a public-supply well with samples from monitoring wells in different parts of the aquifer system to determine whether the chemistry of the water from the supply well is more similar to water in an overlying or underlying aquifer than to water in the aquifer tapped by the well itself. (See pages 68–69.) This method includes the use of mixing equations to quantify the amount of the well's water that originates in the different parts of the aquifer system.
- Review water-quality data collected under a range of hydrologic conditions over an extended period of time to uncover patterns in the data that would otherwise be unexpected for a public-supply well in the absence of preferential flow. (See pages 70–71.)
- Use chemical tracers of groundwater age to determine whether young (post-1940s) water occurs where it is not expected, such as beneath a confining unit or beneath older, tracer-free water.
- Characterize redox processes associated with water from a public-supply well to determine whether the wellbore functions as a hydraulic short-circuit, allowing waters with different chemistries to mix. A mixed redox diagnosis in itself cannot be used to conclude that preferential flow pathways exist in the surrounding aquifer, but it can confirm other indications.
- Collect depth-dependent water-quality samples and wellbore-flow data from a pumping public-supply well to determine where contaminated water actually enters the well (Izbicki and others, 1999; Landon and others, 2009).
- Apply groundwater flow and transport models. The influence of preferential flow pathways will be learned only if they are explicitly included in a model. However, failure to include such pathways can call attention to their existence in settings where models are unable to adequately reproduce field-based observations of flow and chemistry without simulation of preferential flow.

Depth-dependent water-quality and borehole flow data were collected from study wells under pumping conditions to determine where and how contaminants entered the wells. Such information can be useful for determining whether preferential flow pathways are affecting a public-supply well. Here, a USGS scientist lowers sampling equipment into a public-supply well through a small access pipe extending from the wellhead on the far side of the well. The access pipe was installed for this study.



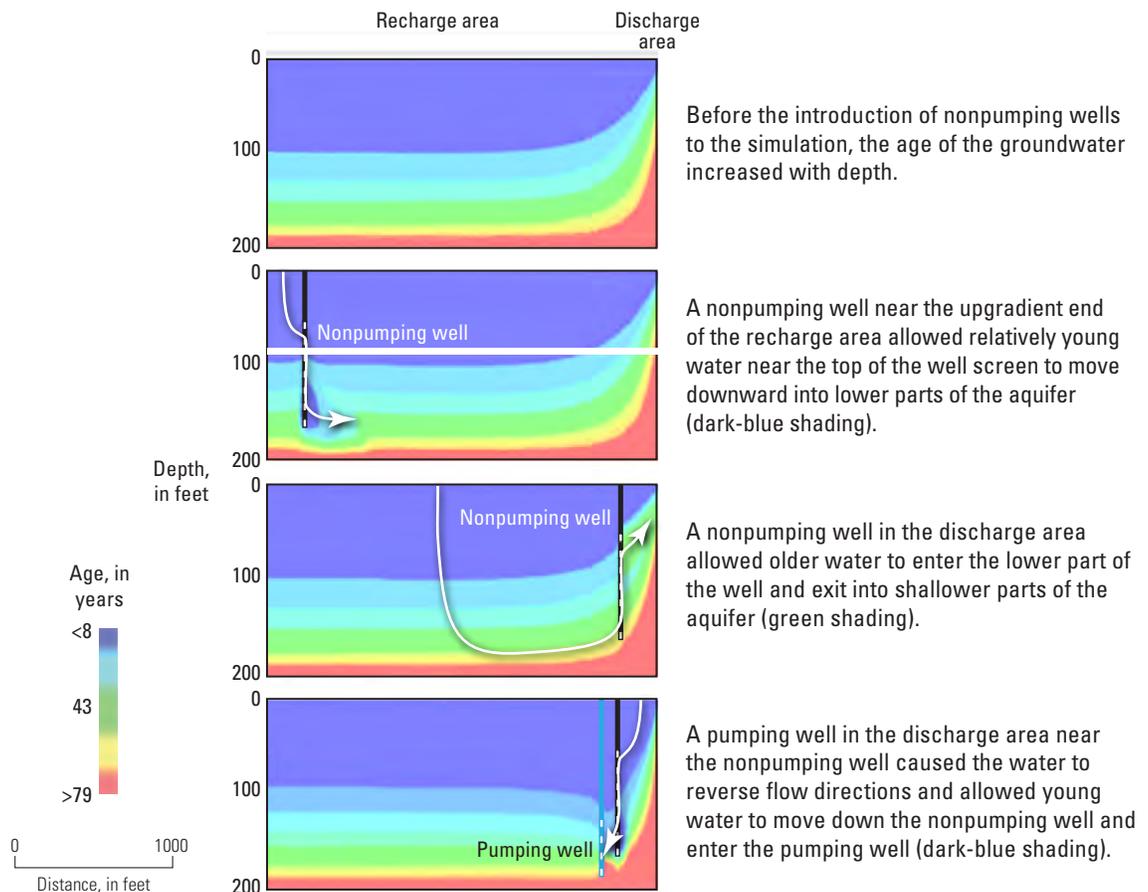
Wellbores as Preferential Flow Pathways— Scenario Modeling

Potential Effect of Wellbores on the Movement of Water in Unconfined Aquifers

Nonpumping wells can have a surprisingly large influence on the movement of water and associated contaminants within an aquifer.

A groundwater-flow and transport model was constructed to assess the possibility that wellbore flow can alter the mix of groundwater ages in an unconfined aquifer, thus affecting groundwater and well vulnerability. The model simulates a hypothetical aquifer in which nonpumping wells with long well screens were placed at different locations.

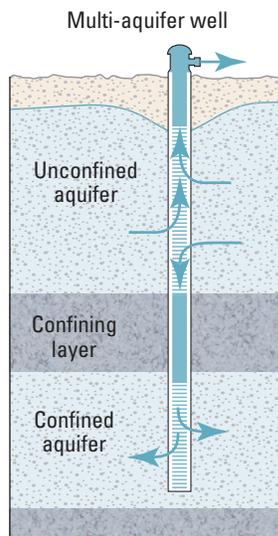
Results demonstrate that inactive wells can allow young, potentially contaminated groundwater to flow where it otherwise would not be expected. (See figure below.) Because inactive wells facilitate the rapid movement of groundwater, they can allow groundwater to move to parts of aquifers where the water is not in chemical equilibrium with the solid aquifer material, potentially releasing natural contaminants to the groundwater. Thus, nearby inactive wells can cause both anthropogenic and natural contaminants to occur in water from a public-supply well.



MORE INFORMATION

Zinn and Konikow, 2007

Potential Effect of Multi-Aquifer Wellbores on the Downward Leakage of Water to Confined Aquifers



Some water in a pumping public-supply well can move downward and out the bottom of the well screen if the pumping rate is insufficient to fully reverse the downward flow of water within the wellbore caused by a downward hydraulic gradient in the aquifer.

A groundwater-flow model was constructed to assess the effect of down-wellbore flow on a confined-aquifer public-supply well under several pumping scenarios. The model simulates a hypothetical aquifer system in which pumping from a confined aquifer creates a large downward hydraulic gradient between an overlying unconfined aquifer and the confined aquifer. At the same time, multi-aquifer wells are present, allowing water to flow down into the confined aquifer.

Results of this modeling scenario indicate that even a single multi-aquifer well located over one-half mile from a confined-aquifer public-supply well can contribute nearly 10 percent of the water produced by the supply well. Stated another way, water produced from such a public-supply well could have a contaminant concentration that is equal to 10 percent of the concentration in an overlying unconfined aquifer.

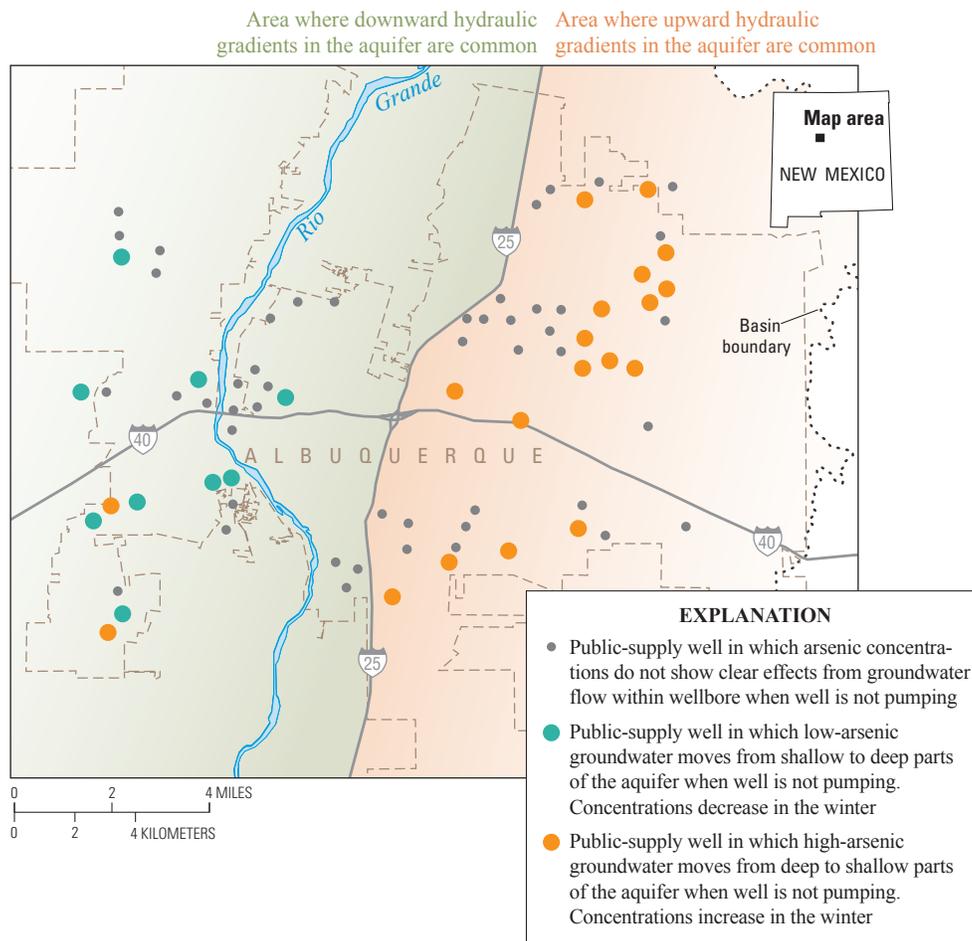
Moreover, model results demonstrate that multi-aquifer wells do not have to be inactive (nonpumping) to serve as hydraulic short-circuits. This is because downward hydraulic gradients in settings where large volumes of water are pumped from a confined aquifer (such as irrigated agricultural settings) can be so great that pumping of an individual multi-aquifer well might not be able to fully reverse the downward flow of water within the wellbore. As a result, water might be moving downward and out the bottom half of a multi-aquifer well even as water is being pumped from the wellhead. (See figure at left.) In fact, simulations in which all wells were pumping (both multi-aquifer and confined-aquifer wells) produced the highest percentage of leaked, unconfined-aquifer water in the confined-aquifer public-supply well.

MORE INFORMATION

Johnson and others, 2011

Wellbore flow leads to patterns in arsenic detections

Arsenic concentrations vary spatially and temporally in water from public-supply wells in Albuquerque, New Mexico, partly because groundwater with different arsenic concentrations migrates between different parts of the basin-fill aquifer within the wellbores of idle supply wells. During times when the wells are not pumping, high-arsenic groundwater from deep within the aquifer moves up and out into the shallow parts of the aquifer in areas where hydraulic gradients are upward. When pumping resumes, arsenic-laden water enters these wells from both shallow and deep parts of the aquifer. Concentrations in the produced water are then elevated until the high-arsenic water is purged from the shallow parts of the aquifer.



Because public-supply wells are pumped less frequently in the winter than in the summer, arsenic concentrations are highest in winter water samples from the deepest wells in the parts of the aquifer having upward hydraulic gradients (orange circles in figure above). Knowing that well construction (depth), well operation (duration of pumping), and position within the groundwater-flow system (location with respect to vertical hydraulic gradients) affect high arsenic concentrations in water from public-supply wells will enable resource managers to better manage concentrations in the produced water by pumping existing wells for longer periods during the winter and by installing new supply wells at shallower depths in certain areas (Laura Bexfield, U.S. Geological Survey, written commun., 2012).



Public-supply-well vulnerability assessments that incorporate monitoring-well data characterizing conditions in different parts of the aquifer system and vulnerability measures characterizing water from the public-supply well can provide insight into how the different waters and contaminants in the aquifer system combine in the well. Such knowledge can draw attention to vulnerabilities that might degrade the quality of water from the public-supply well.

“...a good vulnerability assessment can help a water system focus its limited resources on those factors that present the greatest threat.”

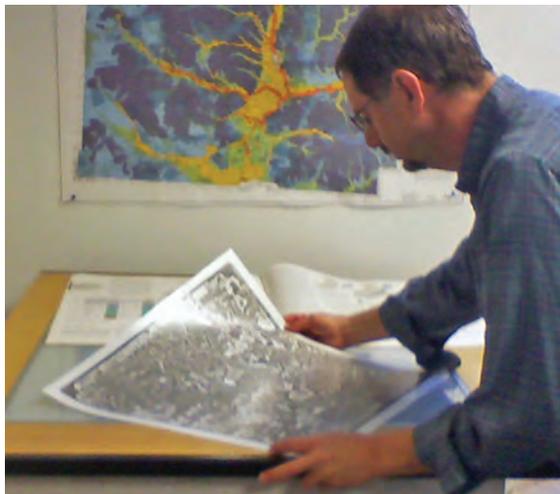
Mike Ekberg,
Miami (Ohio) Conservancy District, 2011

Ideally, data and information on each factor affecting public-supply-well vulnerability to contamination will be pulled together as part of a vulnerability assessment for a public-supply well. The factors are (1) contaminant input, (2) contaminant mobility and persistence, (3) intrinsic susceptibility of the water drawn into a well, and (4) the presence of preferential flow pathways, which can influence the relative importance of each of the other factors.

Four assessments illustrating the vulnerability of water from individual public-supply wells to contamination are summarized in this section. Each assessment represents a common aquifer-well combination (for example, stratified glacial sediments and a shallow well with a short well screen) and depicts vulnerabilities that are likely to be found in similar settings. Measures of vulnerability include the sources of recharge, the geochemical conditions, and the age mixture of the water pumped from the wells. Monitoring-well data characterizing different parts of the aquifer systems also are evaluated. Although water from each of the four wells contained similar contaminants, the findings from this study suggest that the strategies for protecting the different supplies should be different.

Two assessments comparing the vulnerability of public-supply wells in different aquifers to contamination from nitrate or VOCs also are described. Results of these assessments demonstrate the existence of systematic spatial patterns in public-supply-well vulnerability to common groundwater contaminants. Measures of vulnerability for the assessments consist of biodegradation rate (as a measure of contaminant mobility and persistence) and groundwater velocity (as a measure of intrinsic susceptibility). Neither regional assessment uses data on actual contaminant inputs, which can be hard to obtain for spatially large areas. Rather, comparisons are based on common input concentrations, and results call attention to differences in the “relative” vulnerability among the water supplies

Information on land use is important for understanding potential sources of recharge and associated contaminants for a public-supply well. Here, an aerial photo is being reviewed so that USGS scientists can better understand land use in an area of interest.



Vulnerability of Water from Individual Wells

Public-Supply Well in a Glacial Aquifer System

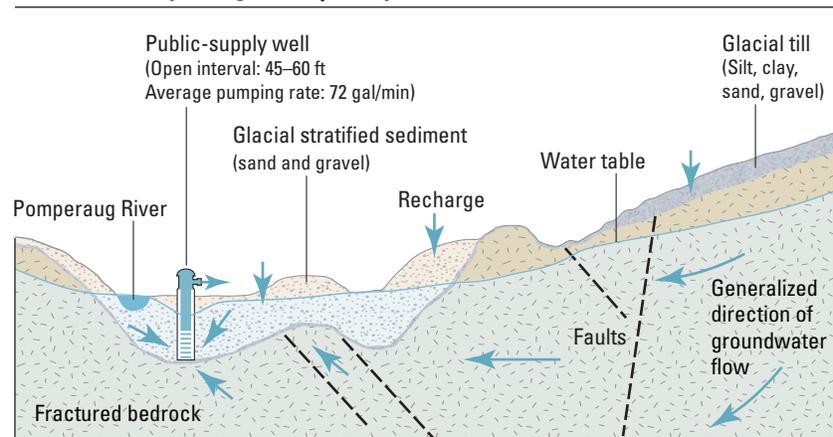


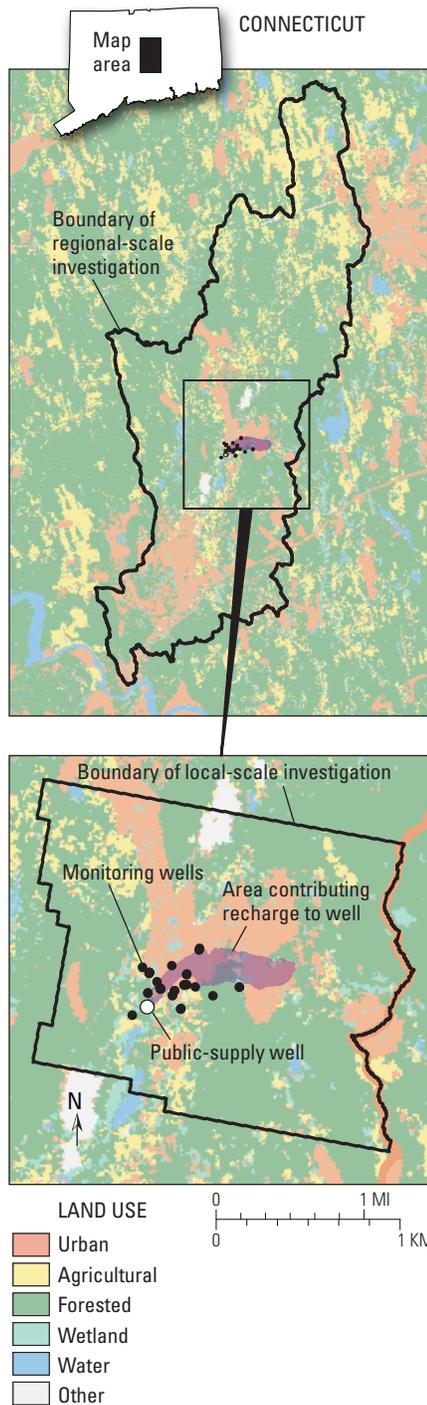
The public-supply well that was investigated in Woodbury, Connecticut, is within the glaciated New England Upland in the west-central part of the State. The area has a humid climate. Average annual precipitation is about 46 inches (in.), and depth to groundwater is about 13 ft below land surface (bls). The most productive part of the glacial aquifer system in this area is a relatively thick section of stratified glacial sediment in the Pomperaug River valley. (See figure below.) Water from the well contained 11 VOCs, nitrate, pesticides, uranium, and radon during the study. Only TCE, an industrial solvent, had a concentration in the raw (untreated) water from the public-supply well that was above a drinking-water standard.

Contaminant Input

The area contributing recharge to the well was computed to be 0.2 mi², of which 75 percent was urban, 13 percent was forested, and 5 percent was agricultural. (See figure on opposite page.) The primary sources of groundwater recharge were precipitation, infiltration of streamflow, and infiltration from septic systems and dry wells. Shallow groundwater beneath urban land had higher concentrations and more detections of VOCs than did groundwater beneath other types of land. Methyl *tert*-butyl ether (MTBE) was the most frequently detected VOC and was from a plume caused by a fuel spill at a gasoline station. Chloroform in the shallow groundwater was from infiltration of chlorinated water by way of septic-system drainfields or leaky distribution pipes that deliver chlorinated water. Nitrate and chloride concentrations above background levels were linked to the widespread use of septic systems and (or) the application of road salt. Mixing equations were used to determine the percentage of nitrate in water from the public-supply well that came from septic systems—about 15 percent. Uranium and radon in the groundwater were from the solid aquifer material.

Connecticut study well; glacial aquifer system





Contaminant Mobility and Persistence

Redox conditions were generally oxic, and nitrate was able to persist in the groundwater. Arsenic generally was not a contaminant of concern. However, locally abundant organic matter or dissolved organic carbon from septic-system leachate caused iron, manganese, arsenic, and other trace elements to be released from the aquifer material to the groundwater. Uranium concentrations in the groundwater were highest where concentrations of bicarbonate were relatively high—conditions that exist in deep glacial deposits and surrounding bedrock.

Intrinsic Susceptibility

Most of the water produced by the public-supply well was less than 10 years old, as estimated from age tracers and groundwater-flow modeling, and was derived from the stratified glacial deposits in areas of urban land use. Only a small percentage of old, bedrock water entered the well.

Preferential Flow Pathways

Dry wells served as hydraulic short-circuits in the upper part of the unsaturated zone, reducing the amount of time it took stormwater runoff carrying contaminants from paved areas to enter the aquifer. Sixteen percent of the water from the public-supply well entered the aquifer by way of dry wells. (See page 67.) In addition to dry wells, thin zones of coarse-grained sediment served as fast flow pathways for water and contaminants to reach the well.

Relevance to Source Protection

Groundwater throughout the aquifer is young, making it particularly vulnerable to contamination. As a result, actions of individual residents and local businesses can influence groundwater quality in this area as demonstrated, for example, by the widespread detection of septic-system-influenced shallow groundwater. Therefore, public education about how actions of individuals can negatively affect the community's water source is of great importance. Dry wells in the commercial area exacerbate the vulnerability of the water from the public-supply well to contamination by reducing the amount of time it would take spilled chemicals to reach the well. Arsenic is not a problem for the well, but it could be a problem for any new well inadvertently screened through a localized organic-rich zone within the aquifer.

MORE INFORMATION

Brown and others, 2009
Jagucki and others, 2010
Starn and Brown, 2007

Public-Supply Well in the Central Valley Aquifer System



California Department of Water Resources

The public-supply well that was investigated in Modesto, California, is in the San Joaquin Valley, which has a semiarid climate. Average annual precipitation is about 12 in. Depth to groundwater is about 30 ft bls. The well has a long well screen (275 ft) and draws in water from a thick section of the Central Valley aquifer system. (See figure below.) Water from the well contained nitrate, VOCs, pesticides, uranium, and arsenic during the study, although none of these constituents were present at concentrations exceeding drinking-water standards.

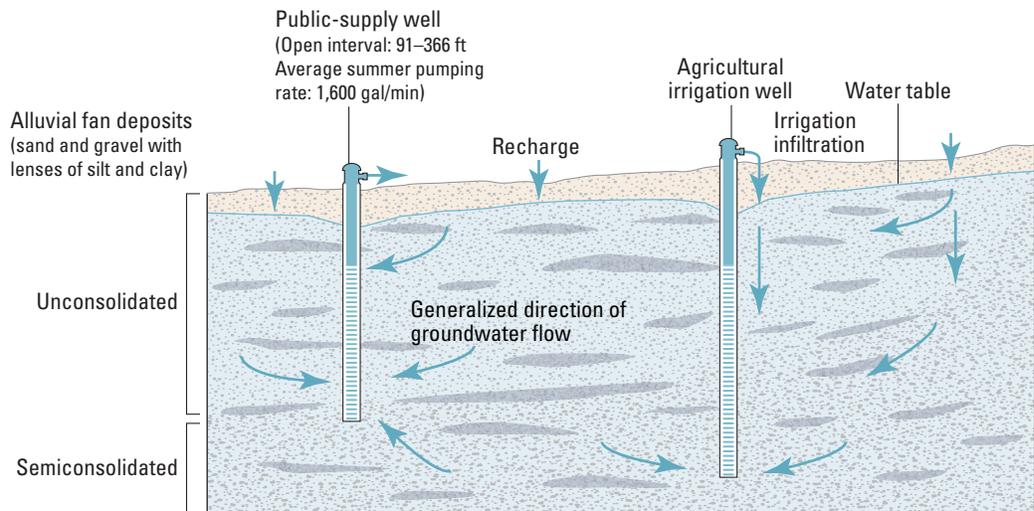
Human activities have significantly altered groundwater flow in the area. A greater percentage of groundwater recharge now comes from infiltration of irrigation water (42 percent) than from precipitation (29 percent). Similarly, irrigation pumping is the largest component of groundwater discharge (50 percent). Water is often pumped and reapplied at the surface multiple times.

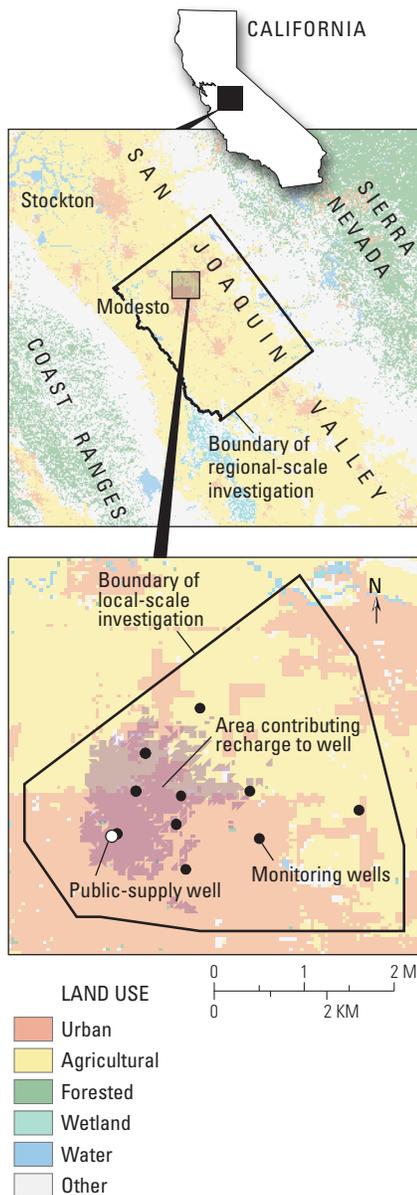
Contaminant Input

The area contributing recharge to the well was computed to be 1.6 mi², of which 67 percent was urban and 30 percent was agricultural. (See figure on opposite page.) Most of the area was sewered, but some older subdivisions relied on septic systems. An extensive network of dry wells facilitated subsurface infiltration of stormwater runoff.

Nitrate concentrations (median value, 12 mg/L) in shallow groundwater (less than 164 ft) were indicative of human activities—likely past or present use of agricultural fertilizer. Widespread detection of very low concentrations of pesticides and VOCs indicated recharge beneath agricultural and urban land, respectively. Uranium and arsenic in the groundwater were from natural sources, although human activities caused uranium concentrations in shallow groundwater to increase over time.

California study well; Central Valley aquifer system





Contaminant Mobility and Persistence

Oxic conditions prevailed throughout the aquifer system, allowing nitrate and uranium to persist once in the groundwater. Uranium concentrations were highest at shallow depths and were linked to an increase in bicarbonate concentrations in the shallow aquifer resulting from an increase in irrigation over time. (See case study on pages 46–47.)

Intrinsic Susceptibility

Shallow groundwater was less than 40 years old. Deep groundwater (greater than 325 ft) was thousands of years old. The public-supply well produced water with a wide range of groundwater ages (approximately 9 years to thousands of years old) because of its long well screen. About 75 percent of the water from the well was old enough to predate human influences on water quality, providing for substantial in-well dilution of anthropogenic contaminants entering the well.

Preferential Flow Pathways

The long screened interval of the well enabled shallow, contaminated groundwater to migrate down the wellbore and out into deeper parts of the aquifer during times of light or no pumping—most notably during winter months. Upon reactivation of the pump, contaminated groundwater simultaneously entered the well from both shallow and deep parts of the aquifer, temporarily increasing contaminant concentrations in the produced water. The quality of water from the well varied seasonally as a result. (See pages 70–71.)

Relevance to Source Protection

A short-term solution to the winter water-quality problems at the well was to pump for longer periods during the winter months. In the long term, nitrate concentrations in the well will likely decrease without intervention because urban land use in the recharge area has increased over time; urban recharge in the study area contains less nitrate than does agricultural recharge. Regardless, nitrate concentrations in water from the well will not become as high as those in the shallow groundwater because a substantial proportion of the water from the well was recharged long before the use of nitrate fertilizer. In contrast, uranium concentrations will likely increase with time as the downward-moving front of irrigation-affected groundwater occupies a larger proportion of aquifer that is tapped by the public-supply wells.

MORE INFORMATION

Burow and others, 2008
 Jagucki and others, 2008
 Jurgens and others, 2008

Public-Supply Well in the Upper Floridan Aquifer



The public-supply well that was investigated near the city of Tampa is within the coastal lowlands of west-central Florida. The climate is subtropical, and the average annual rainfall is 60 in. The well is completed as an open hole in the limestone bedrock of the Upper Floridan aquifer, which is separated from an overlying surficial aquifer system by a discontinuous confining unit. (See figure below.) Depth to groundwater in the surficial aquifer system is generally 10 to 50 ft bls. Water from the well contained VOCs, nitrate, pesticides, uranium, radon-222, and arsenic at concentrations below drinking-water standards, where such standards exist. Historically, total coliform bacteria and fecal streptococci bacteria were detected in water from the well field that includes this well. A current requirement to disinfect all drinking water in the area now protects users of the water from health hazards associated with bacterial contamination.

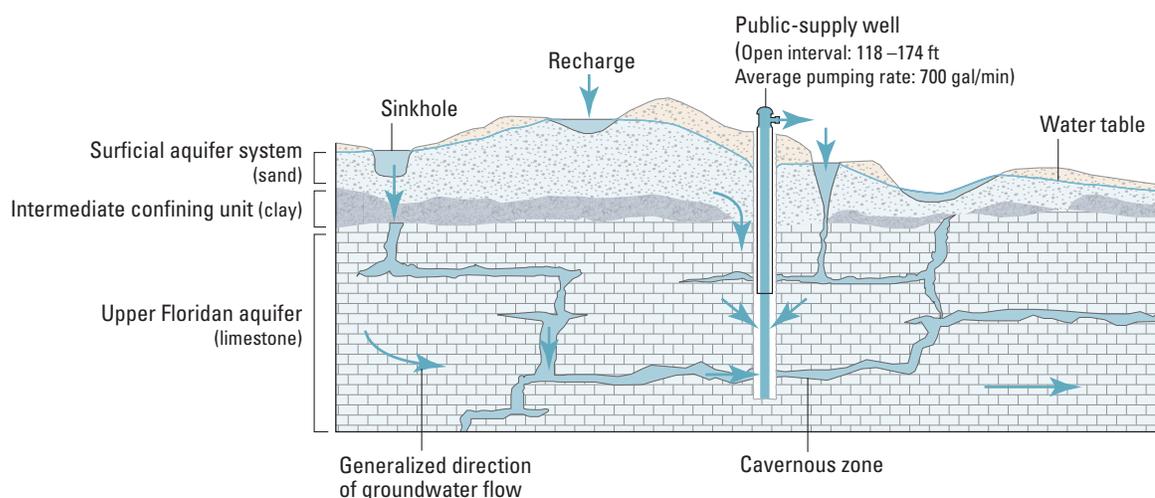
Contaminant Input

The area contributing recharge to the well was computed to be 9.4 mi², of which 84 percent is urban, 5 percent is wetland, and 4 percent is agricultural. (See figure on opposite page.) The urban land is predominantly residential with some commercial and industrial areas. Precipitation and infiltration of streamflow are the primary sources of groundwater recharge. The area is sewered, and stormwater runoff is routed to a series of retention basins.

The surficial aquifer system is an important source of water and contaminants for the Upper Floridan aquifer. Every monitoring-well sample from this aquifer system contained at least one VOC at low concentrations. Most samples also had detectable nitrate at concentrations indicative of human activities, although no concentrations were above the drinking-water standard of 10 mg/L.

Radon-222, uranium, and arsenic in the groundwater were derived from the solid aquifer material. Radon-222 concentrations were higher in the surficial aquifer system than in the Upper Floridan aquifer. In contrast, uranium concentrations were naturally higher in the Upper Floridan aquifer. Elevated arsenic concentrations in water from the public-supply well were associated with a cavernous zone within the Upper Floridan aquifer.

Florida study well; Upper Floridan aquifer



Contaminant Mobility and Persistence

Groundwater in the surficial aquifer system was oxic, whereas it was anoxic in the Upper Floridan aquifer. Nitrate was not detected in samples from most monitoring wells in the Upper Floridan aquifer, and evidence existed for denitrification in the anoxic Upper Floridan aquifer.

Intrinsic Susceptibility

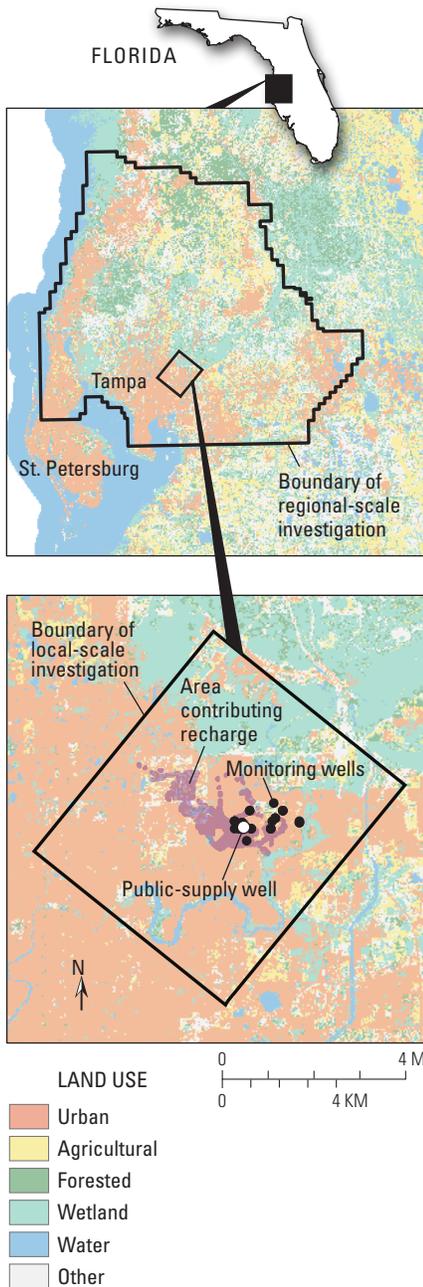
Most water in the surficial aquifer system was recharged within the past 6 years and was vulnerable to anthropogenic contamination. Water in the Upper Floridan aquifer was generally much older (greater than 60 years). Groundwater-age data and modeling results, however, indicated that as much as 70 percent of the water from the public-supply well was very young water that was drawn into the well from the surficial aquifer system. Groundwater-chemistry data revealed multiple similarities between the water from the public-supply well and the water in the overlying surficial aquifer system (for example, similar median concentrations of chloroform).

Preferential Flow Pathways

A cavernous zone that intersects the open interval of the public-supply well was the source of the surficial aquifer system water and most anthropogenic contaminants that entered the well. (See pages 68–69.) The cavernous zone also contributed arsenic to the well. Samples collected over a range of depths in the public-supply well showed that arsenic concentrations in the water from the cavernous zone were highest when the well was pumping. Rapid movement of oxygenated water within the cavernous zone apparently liberated arsenic from the limestone bedrock during periods of heavy pumping. Karst features also led to a complex contributing area for the well, making it difficult to know where at the land surface water from the well originated.

Relevance to Source Protection

The proportion of contaminated and uncontaminated water entering the well can change rapidly in response to changing hydrologic conditions because the cavernous zone enables very young water to be drawn into the well. Consequently, extra vigilance is warranted during changing hydrologic conditions so that water-treatment processes remain effective. Determining the degree to which water from public-supply wells reflects that of the surficial aquifer system is one way to prioritize monitoring and land-use planning in this area so that limited resources can be used to protect the most vulnerable wells.



MORE INFORMATION

Crandall and others, 2009
 Jagucki and others, 2009b
 Katz and others, 2007
 Paschke, 2007

Public-Supply Well in the High Plains Aquifer



The public-supply well that was investigated in Nebraska is in the eastern part of the State in a mostly flat-lying area. The climate is humid continental, and the average annual precipitation is 28 in. Depth to groundwater is about 10 to 80 ft bls. The well is completed in a confined part of the High Plains aquifer (see figure below), as are many of the newer public-supply wells in the area; however, irrigation, commercial, and some older public-supply wells are screened in multiple aquifers. Water from the well contained low concentrations of VOCs, particularly PCE and TCE and their degradation products. Uranium and arsenic, which occur naturally in the aquifer material, also were detected in water from the well. No contaminant was detected at concentrations above a drinking-water standard.

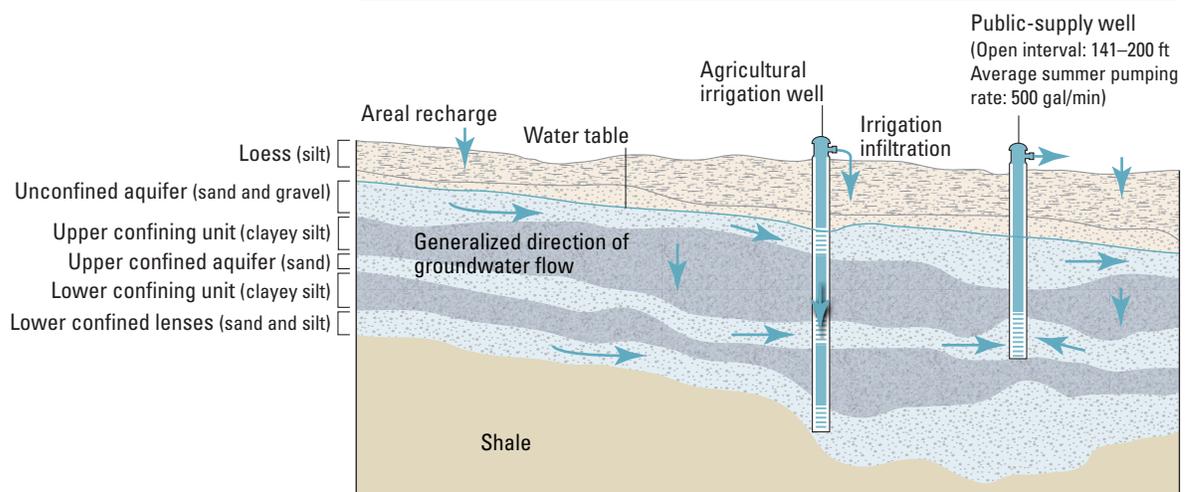
Contaminant Input

The area contributing recharge to the well was computed to be 2.4 mi², of which 45 percent was urban and 39 percent was agricultural. (See figure on opposite page.) Urban land is primarily low-density residential and commercial. Urban areas are mostly sewered, but septic systems are used on the outskirts of some residential areas. Agricultural land is primarily irrigated cropland (corn, soybeans, grains).

Most samples from the unconfined aquifer had elevated concentrations of nitrate. The principal sources of the nitrate were septic systems (or sewer leakage) and agricultural fertilizer. Low concentrations of agricultural pesticides or degradation products also were detected in samples from the unconfined aquifer. Widespread detections of very low concentrations of VOCs were associated with the urban land.

Water from both the unconfined and confined aquifers had widespread detections of uranium and arsenic. The source of these substances was the aquifer material itself. Uranium concentrations generally decreased with depth, but the highest concentrations were detected in samples that were a mix of waters from the unconfined and confined aquifers.

Nebraska study well: High Plains aquifer



Contaminant Mobility and Persistence

Water in the unconfined aquifer was mostly oxic. Water in the upper confined aquifer that was tapped by public-supply well was mostly anoxic and devoid of anthropogenic contaminants.

Intrinsic Susceptibility

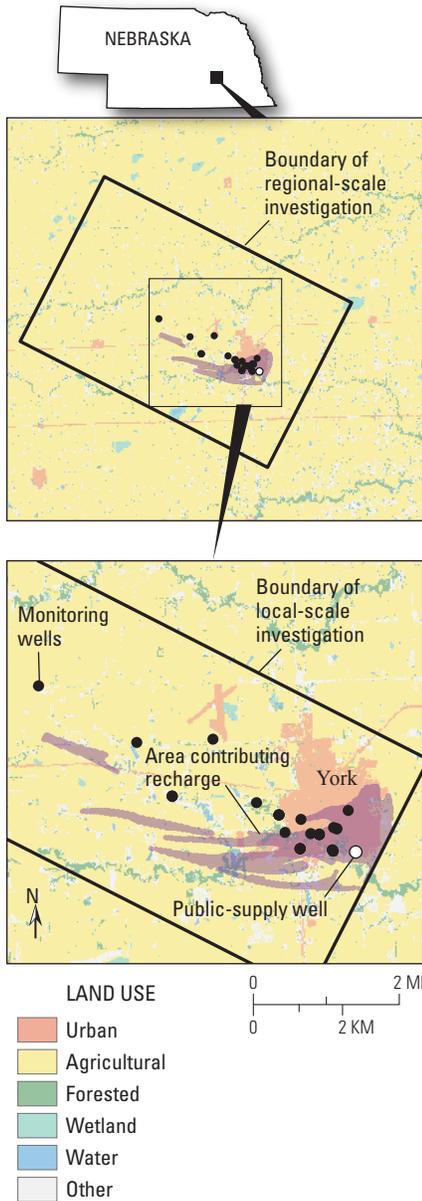
Water in the unconfined aquifer was less than 48 years old based on concentrations of age tracers in water from monitoring wells. Water from the confined aquifer was mostly old enough to predate the widespread use of many chemicals that can contaminate drinking-water sources. Groundwater samples from the public-supply well and from some confined-aquifer monitoring wells were a mix of waters from the unconfined and confined aquifers. At least 12 percent of the water from the public-supply well was young, unconfined-aquifer water that entered the well through the bottom half of the well screen. (See case study on pages 34–35.)

Preferential Flow Pathways

Young, contaminated groundwater from the unconfined aquifer entered the confined aquifer by moving down one or more of the many multi-aquifer wells in the area. Irrigation pumping in the confined aquifer accelerated the downward movement of contaminated water. Although some anthropogenic contaminants in the unconfined-aquifer water reached the public-supply well, nitrate concentrations in the produced water were very low. This was partly because the high-nitrate water from the unconfined aquifer was diluted within the public-supply by the large fraction of low-nitrate water from the confined aquifer that entered the well. In addition, some of the nitrate in the water that short-circuited the confining unit degraded in the anoxic conditions of the confined aquifer before reaching the well.

Relevance to Source Protection

It is unlikely that all leaking multi-aquifer wells within the area will be accurately identified. Therefore, it is useful to plan for a scenario in which the confining unit does not restrict the downward flow of contaminated water from the unconfined aquifer to the “confined” aquifer used as a source for drinking water. However, the large percentage of very old water entering confined-aquifer public-supply wells will dilute any anthropogenic contaminants in water entering the wells. Contaminant concentrations in leaked water would have to be much higher than a drinking-water standard before a water purveyor would need to worry about treating the water.



MORE INFORMATION

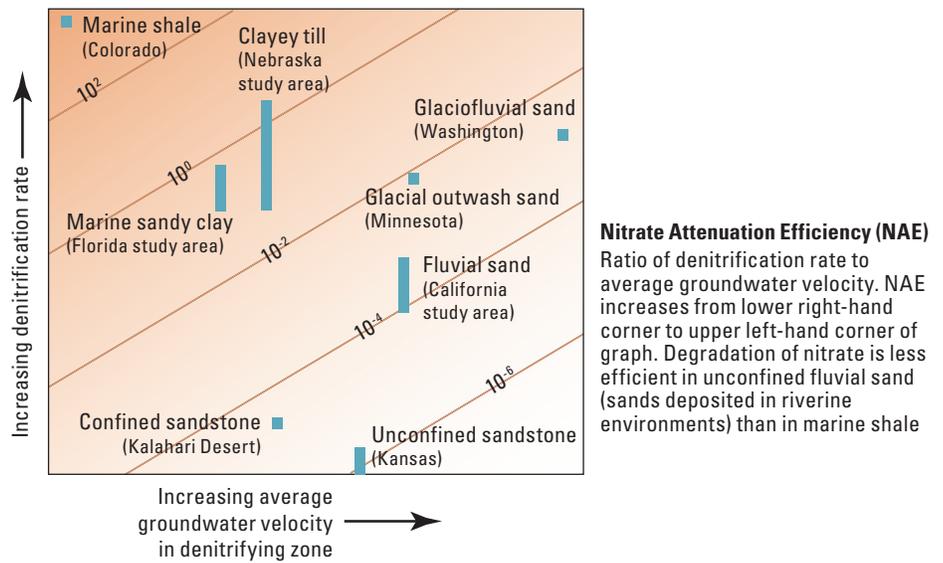
Clark and others, 2008
 Jagucki and others, 2008
 Landon and others, 2008

Relative Vulnerability Among Wells in Different Aquifers

Nitrate

The relative vulnerability of water from public-supply wells to nitrate contamination was evaluated in eight aquifer systems. The relation between the denitrification rate and the groundwater velocity in the denitrifying zone in each aquifer system was computed. The computed ratios were compared and served as a measure of the relative amount of nitrate that could be degraded in each area. The method is founded on the concept that nitrate can persist if groundwater-flow rates are high relative to denitrification rates. Conversely, nitrate in shallow groundwater might not reach a well if groundwater-flow rates are low compared to denitrification rates.

Differences in the efficiency of nitrate attenuation within active denitrification zones of different aquifers are related to differences in the depositional environment of the different aquifer materials. The nitrate attenuation framework depicted in this figure is a useful way to compare groundwater vulnerability to nitrate contamination among aquifer systems.



The efficiency of nitrate attenuation (degradation) in the study areas increased as follows: fluvial sand aquifers < glacial sand aquifers < glacial/marine clay < marine shale. Observed differences are related to differences in the proportions of clay and organic carbon in the different aquifer materials. A high proportion of clay favors the removal of nitrate from groundwater because clay is associated with low groundwater velocities (groundwater-flow rates). A high amount of organic carbon also favors nitrate removal because organic carbon increases denitrification rates by acting as an electron donor during redox reactions that reduce nitrate concentrations (denitrification).

MORE INFORMATION
McMahon and others, 2008

VOCs

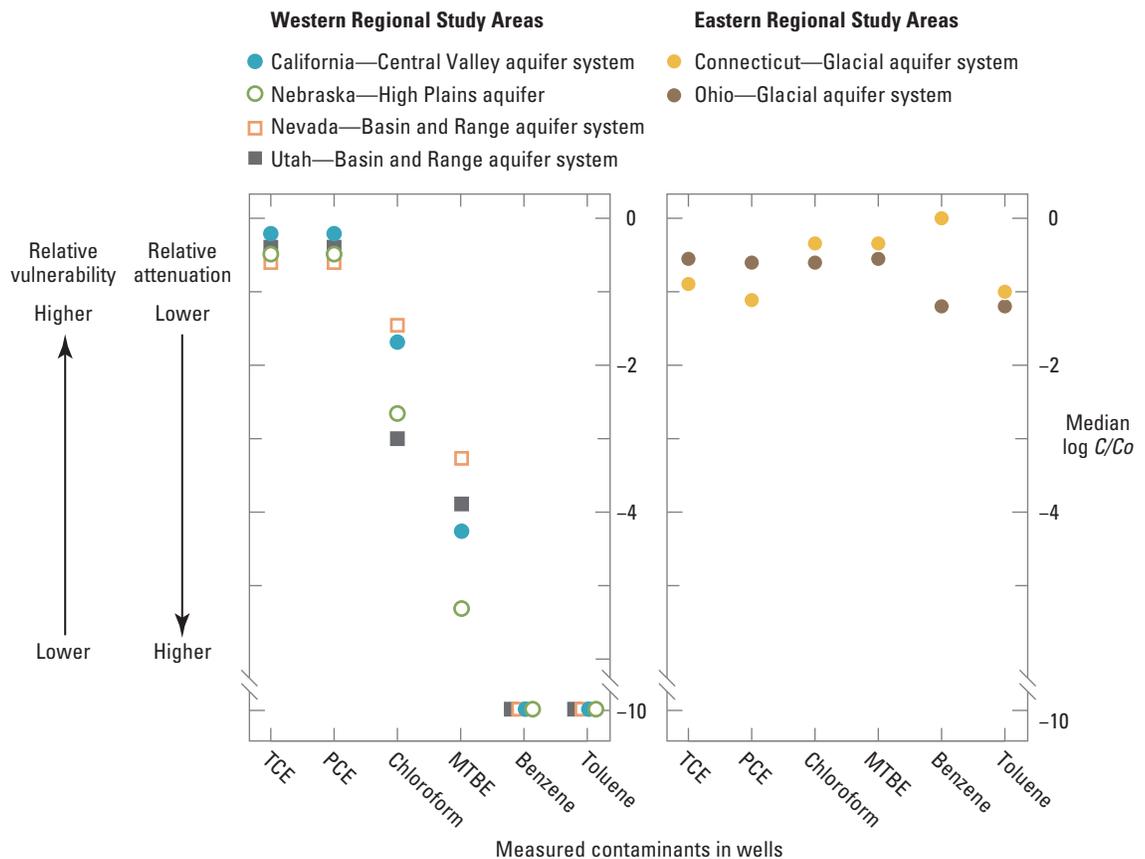
The relative vulnerability of water from public-supply wells to VOC contamination was evaluated in six study areas. The combined effects of redox conditions, contaminant-specific degradation rates, dispersion, groundwater-flow rates and travel times for flow pathways converging on the public-supply wells were considered. The ratio of predicted concentration (at individual wells) to initial

concentration (at the water table) (C/C_0) was used to represent the amount of contaminant attenuation that could occur along a flow pathway between the water table and a well. The overall measure of vulnerability for an individual well was the weighted average C/C_0 value for all flow pathways converging on the well. The vulnerability for an aquifer was represented by the median C/C_0 value for all wells in the aquifer. Public-supply wells in aquifers with low C/C_0 values for a particular VOC are less vulnerable to contamination from that VOC than wells with higher values, given the same contaminant input.

The relative vulnerability of water from the public-supply wells to several commonly detected VOCs varied systematically between wells in the western and eastern study areas. (See figure below.) Computed differences in C/C_0 values for wells in the different aquifers are attributed to regional variations in hydrologic processes and redox conditions among the aquifers. For example, the western study areas have longer groundwater-flow pathways, greater travel times, and more widespread oxic conditions compared with the eastern study areas. Because toluene degrades moderately fast in oxic conditions, a greater amount of toluene could be degraded in the western study areas, where travel times in oxic zones are longer. In contrast, more degradation of PCE could occur in the eastern study areas because degradation of PCE is moderately fast in the anoxic conditions more prevalent in the East.

MORE INFORMATION

Kauffman and Chapelle, 2010



Public-supply wells in four western study areas were inherently less vulnerable to chloroform, MTBE, benzene, and toluene contamination than wells in the eastern study areas. This means that, if sources of these compounds were present, the contaminants would be more likely to show up in the eastern study area wells.



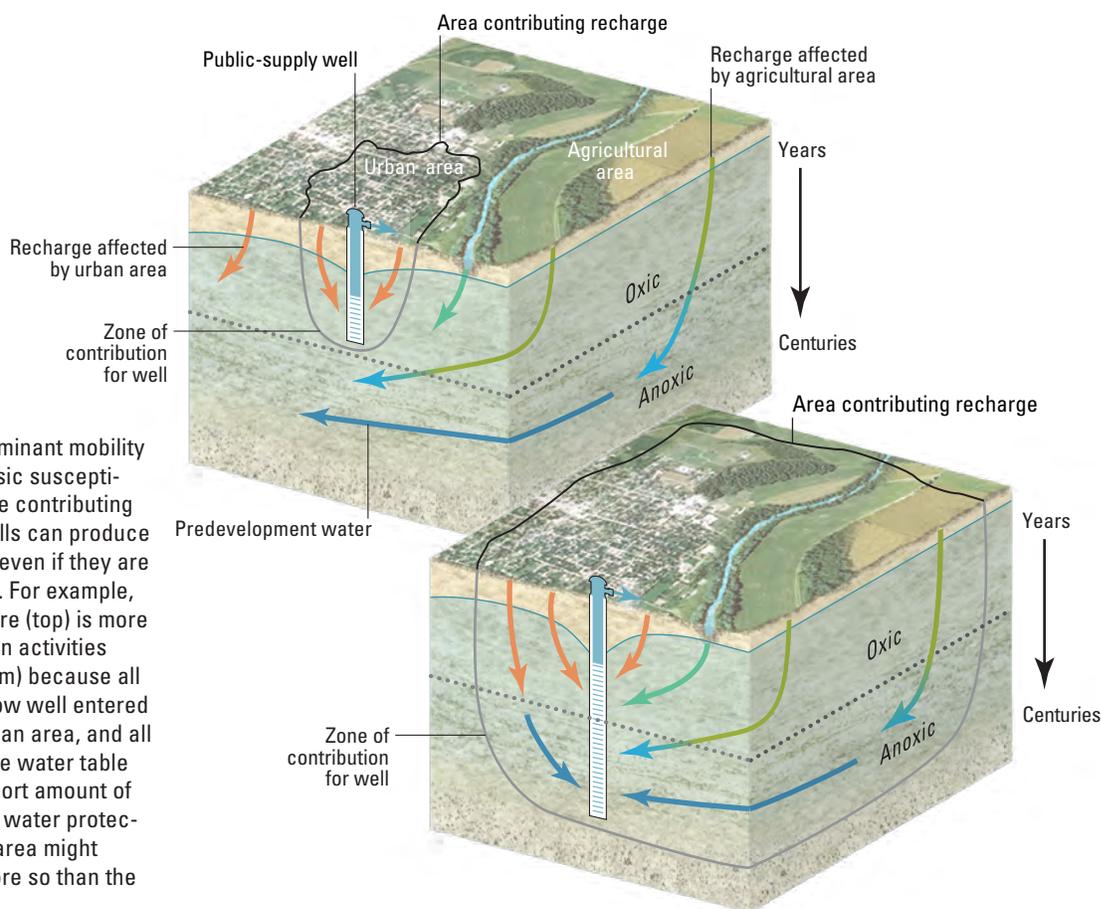
The quality of the groundwater drawn into a public-supply well is important even if it is possible to remove contaminants from the water. In this photo, packed-tower air-stripping systems are used to remove volatile organic compounds from a groundwater source of drinking water, but the treatment comes with a cost. For example, in 2002 it was estimated that the cost to treat groundwater in this way ranged from \$4.00 to \$34.00 per 10,000 gallons, depending on the size of the site and the difficulty of contaminant removal (Van Deuren and others, 2002). For public water systems that serve 100,000 people, this cost could approach \$1,500,000 per year if a typical family of four uses 400 gallons of water per day. Therefore, it can benefit a community to understand which contaminants in an aquifer might reach their well(s) and when, how, and at what concentration they might arrive so that the highest quality of raw (untreated) water can be obtained from the local resource—reducing the risk that contaminated water will be delivered to the public while maintaining an economical supply of water.

Conclusions— Opportunities and Challenges

6

Clean water is necessary for healthy communities and strong economies. Although it might be possible to remove some contaminants from groundwater, the quality of the water drawn into a public-supply well prior to treatment remains important because a high-quality source of water can help eliminate or reduce the risk of delivering contaminated drinking water to the public. The quality of the source water also is an economic issue because removing contaminants from groundwater is expensive and difficult.

Understanding what factors affect public-supply-well vulnerability to contamination can lead to opportunities to enhance source water assessment and protection efforts. Such understanding also can help source water protection partners anticipate and measure protection-related outcomes. In general, the vulnerability of the water from public-supply wells to contamination is a function of contaminant input within the area that contributes water to a well, the mobility and persistence of a contaminant once released to the groundwater, and the ease of groundwater and contaminant movement from the point of recharge to the open interval of a well.



If contaminant input, contaminant mobility and persistence, and intrinsic susceptibility are different within the contributing areas for two wells, the wells can produce water of a different quality even if they are located in the same setting. For example, the shallow well in this figure (top) is more strongly influenced by urban activities than the deeper well (bottom) because all of the water from the shallow well entered the aquifer beneath the urban area, and all of the water travels from the water table to the well in a relatively short amount of time. Consequently, source water protection activities in the urban area might benefit the shallow well more so than the deeper well.

There are many ways to evaluate how these factors affect the vulnerability, and thus water quality, of a well. Measures described in this circular are particularly useful for indicating which contaminants in an aquifer might reach an individual public-supply well and when, how, and at what concentration they might arrive:

- Sources of recharge—Information on the sources of recharge for a well provides insight into contaminants that might enter the aquifer with the recharge water and potentially reach the well.
- Geochemical conditions—Information on the geochemical conditions encountered by groundwater traveling to a well provides insight into contaminants that might persist in the water all the way to the well.
- Groundwater-age mixtures—Information on the ages of the different waters that mix in a well provides insight into the time lag between contaminant input at the water table and contaminant arrival at the well. It also provides insight into the potential for in-well dilution of contaminated water by unaffected groundwater of a different age that simultaneously enters the well.

Preferential flow pathways—pathways that provide little resistance to flow—can influence how all other factors affect public-supply-well vulnerability to contamination. For example, preferential flow pathways can influence whether a contaminant source is physically linked to a well, whether contaminant concentrations are substantially altered before contaminated groundwater reaches a well, and whether contaminated groundwater can arrive at a well within a timeframe of concern to the well owner. Knowing how to recognize the influence of preferential flow pathways on the quality of water from a public-supply well can provide opportunities to prevent or mitigate the deterioration of a water supply. (See page 74.)

A table summarizing the methods and tools used to understand the vulnerability of water from public-supply wells to contamination in this study is included in the Appendix to this circular. Some of the methods and tools are straightforward to apply; others might require the assistance of a technical expert. Many of the tools make use of information that can be collected at a public-supply well itself, simplifying the data-gathering process.

Obtaining the data and information described in this circular might be challenging for some communities. However, even an evaluation of existing data in light of the factors that affect public-supply-well vulnerability to contamination, as described herein, might result in substantial new insight into the quality of water from a well. For example, review of historical well records might reveal water-quality patterns that indicate preferential flow pathways are influencing the water quality. In some instances, the preferential flow pathway might be the wellbore itself, and the pumping schedule might be the underlying cause of the undesirable water-quality fluctuation. Adjustments to pumping schedules might bring about improved water quality in a relatively short amount of time, similar to what was achieved for a public-supply well that was investigated in California. (See pages 70–71.)

Existing groundwater-chemistry data might provide information on the origins of the water from a well or the redox condition of the groundwater entering the well. Information on redox conditions can be used to anticipate

“The variety of tools in this circular will be valuable to source water protection practitioners.”

Chi Ho Sham,
The Cadmus Group, Inc.; and
American Water Works Association,
Water Resources Division Trustee, 2011

which contaminants, once in the groundwater, are more or less likely to reach a public-supply well. This includes naturally occurring drinking-water contaminants such as arsenic, uranium, and radium—chemicals not typically addressed by source water assessment and protection programs but that can prove challenging to communities. A redox framework presented in this circular provides a simple and inexpensive way to identify the redox condition of the groundwater pumped from a well. (See pages 42–43.)

Information on the groundwater-age mixture for a well provides an opportunity for a community to forecast the change in water quality at its well(s) in response to changes occurring near the land surface. Although obtaining estimates for the groundwater-age mixture for a well can be relatively difficult and expensive, it has been shown that available information on aquifer physical properties and well characteristics can be useful for generating a rough estimate of the groundwater-age mixtures for wells in some settings.

In summary, water from a public-supply well is a mixture—frequently an unknown mixture—of water from various parts of the surrounding aquifer. Consequently, water-quality samples from public-supply wells require more elaborate interpretation than do samples from monitoring and domestic wells. However, knowing what water-quality variables to measure, what spatial and temporal scales on which to measure them, and how to interpret the resulting data makes it possible for samples from public-supply wells to provide a broad window into a well’s past and present water quality—and possibly future water quality. Such insight can enable resource managers to prioritize actions for sustaining a high-quality groundwater source of drinking water.





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Glossary

Advection The process by which dissolved substances are transported by the bulk of flowing groundwater.

Alkalinity The acid-neutralizing capacity of water; in most natural waters, this consists of the bicarbonate ion.

Alluvial fan A fan-shaped deposit of generally coarse-grained material eroded from mountain slopes, transported by streamflow, and deposited on a valley floor.

Alluvium Bodies of clay, silt, sand, gravel, or other particulate material that has been deposited by a stream or other form of running water.

Annular space The space between two cylindrical objects, such as a well casing and a wellbore.

Anoxic Having dissolved oxygen concentration less than 0.5 milligram per liter, and having concentration of nitrate, manganese, iron, and sulfate as noted in the redox framework on page 42.

Anthropogenic Related to the presence or activities of humans.

Apparent (tracer-based) groundwater age An estimate for groundwater age based on the assumption that the concentration of a chemical tracer used to estimate the age has been unaffected by mixing either in the aquifer or at the point of discharge (well or spring).

Aquifer A water-bearing layer of soil, sand, gravel, or rock that will supply a usable quantity of water to a well.

Aquifer material Sediments or rocks that constitute the solid material through which groundwater flows.

Aquifer matrix (*see Matrix*)

Aquifer system A body of permeable and relatively impermeable sediment and (or) rock that functions regionally as a water-yielding unit.

Area contributing recharge (ACR) The surface area that defines the location where water entering an aquifer system at the water table flows to a well.

Artificial recharge The addition of surface water to a groundwater reservoir by human activity.

Attenuation The process of decreasing contaminant concentrations in groundwater resulting from physical or geochemical processes such as filtration, biodegradation, dilution, sorption, or volatilization.

Bentonite A clay material that expands when wet, commonly used to fill gaps and seal the annular space inside a wellbore.

Bicarbonate A compound containing the HCO_3^- group, such as sodium bicarbonate (NaHCO_3), which ionizes in water to produce HCO_3^- .

Biodegradation The metabolic breakdown of materials into simpler components by living organisms.

Biofouling The gradual accumulation of waterborne organisms (such as bacteria and protozoa) on the surfaces of well components (such as casing, screens, pumps) that contributes to corrosion and leads to a decrease in efficiency.

Borehole A hole drilled or bored into the earth.

Carbonate rocks Rocks (such as limestone or dolostone) composed primarily of minerals (such as calcite and dolomite) containing the carbonate ion (CO_3^{2-}).

Chlorofluorocarbons (CFCs) Stable, manmade volatile organic compounds first introduced into the atmosphere in the 1930s. In groundwater, the concentrations of CFCs can be used to interpret the age of relatively young water.

Community water system A public water system that supplies water to the same population year round. Includes those systems that rely on public-supply wells for their source of water.

Complex A dissolved species formed by the association of two or more simpler dissolved species.

Cone of depression A depression in the water table (or potentiometric surface) that develops around a pumping well.

Confined aquifer An aquifer that is completely filled with water under pressure and that is overlain by low-permeability sediment or rock (confining unit).

Confining unit A low-permeability layer of sediment or rock that overlies a distinctly more permeable aquifer.

Contamination Impairment of water quality by any chemical, physical, biological, or radiological substance. The degree of permissible contamination depends on the intended use of the water.

Conservative Refers to a constituent that moves with the groundwater and does not undergo chemical reactions or sorption.

Degradation The breakdown of materials into simpler components.

Denitrification A process by which oxidized forms of nitrogen such as nitrate (NO_3^-) are reduced to harmless nitrogen gas. The process is usually brought about by denitrifying bacteria.

Desorption Process of changing from an adsorbed state on a surface to a gaseous or liquid state.

Deuterium A heavy stable isotope of the hydrogen ion (^2H), which is part of the water molecule.

Discharge The volume of water that passes a given point within a given period of time (for example, the outflow of groundwater from an aquifer to a well).

Dispersion The spreading of chemical constituents in groundwater.

Dissolution The process whereby solids dissolve into water. Most dissolved constituents in groundwater are ultimately derived from dissolution of solid aquifer materials.

Domestic well A privately owned well that typically serves one home and supplies water for human consumption and other homeowner uses.

Downgradient The direction that groundwater flows; equivalent to “downstream” for surface-water flows.

Drinking-water contaminant A physical, chemical, biological, or radiological substance or matter that can affect the quality of water for the purpose of drinking.

Dry well A large infiltration trench or pit used to capture relatively clean runoff.

Electron acceptor A species that accepts one or more electrons (thereby becoming more negatively charged) during a redox reaction. In groundwater, common electron acceptors are O_2 , NO_3^- , $\text{MnO}_2(\text{s})$, $\text{Fe}(\text{OH})_3(\text{s})$, SO_4^{2-} , and $\text{CO}_2(\text{g})$.

End-member A term used herein to describe water with a distinct chemical composition representing one component in a mixture of different waters.

Fast flow pathway Preferential flow pathway resulting from natural spatial variations in water-transmitting properties of aquifer materials.

Finished water Water that has passed through all treatment processes but prior to distribution.

Flow pathway Subsurface course followed by groundwater.

Geochemical conditions In reference to groundwater, refers to factors or circumstances that affect the chemical reactivity of substances dissolved in the water.

Global Meteoric Water Line An equation that represents the relative abundance of stable isotopes of hydrogen and oxygen in precipitation from multiple locations around the world.

Groundwater In general, any water that exists beneath the land surface, but more commonly applied to water in fully saturated soils and geologic formations.

Groundwater age The duration of time since water was isolated from the atmosphere by recharge to the saturated zone.

Groundwater-age mixture The mixture of groundwater ages that exist in a water sample, such as from a public-supply well.

Groundwater-flow model A digital computer model that represents a real groundwater flow system by means of mathematical equations.

Groundwater-flow system A system of flow pathways that describe the movement of water in an aquifer or aquifer system.

Groundwater recharge Water that infiltrates the ground and reaches the saturated zone.

Groundwater velocity The rate of movement of groundwater through openings in rock or sediment, measured as the ratio of distance per traveltime.

Groundwater vulnerability The likelihood that a contaminant will reach a specified position (for example, the water table or the depths used for public-water supply) in a groundwater-flow system.

Health-based screening levels (HBSLs) Non-enforceable “human-health benchmark” concentrations of unregulated contaminants in water developed by the USGS in collaboration with the U.S. Environmental Protection Agency and others.

Hydraulic conductivity A variable describing the rate at which water can move through an aquifer or other permeable medium.

Hydraulic gradient The slope of a water table or potentiometric surface. Specifically, the change in static hydraulic head per unit distance in a given direction, usually the direction of greatest head decrease.

Hydraulic head An indicator of the total energy available to move groundwater through an aquifer. Hydraulic head is measured by the height to which a column of water will stand above a reference elevation (or “datum”), such as sea level.

Hydraulic short-circuit Natural or manmade preferential flow pathways that allow water and contaminants to bypass aquifer material.

Infiltration Flow of water from the land surface into the subsurface.

Interquartile range A measure of spread in a collection of data that is equal to the 75th percentile minus the 25th percentile.

Intrinsic susceptibility A measure of the ease with which a contaminant in water can enter and move through an aquifer. It is a characteristic of the aquifer and overlying material, and it is independent of the contaminant characteristics or source.

Ion exchange The substitution of one ion for another on the surface of a solid.

Irrigation return flow The part of irrigation water applied to the land surface that is not consumed by plants or evapotranspiration and that either infiltrates downward to an aquifer or discharges to a surface-water body.

Isotopes Atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus.

Karst/karstic Characterized by features that result from dissolution and collapse of carbonate rocks, such as closed depressions, sinkholes, caves, and underground conduits.

Lumped-parameter mixing model A mixing equation that can be used to describe the mixture of water ages at a point of discharge (well or spring) from an aquifer system.

Major ions Constituents commonly present in water at concentrations exceeding 1.0 mg/L. As used in this circular, major ions include calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, and bicarbonate.

Matrix The solid framework of a porous system.

Maximum Contaminant Level (MCL) The maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are enforceable standards established by the U.S. Environmental Protection Agency.

Mobilize To release a chemical species from the solid aquifer material into the groundwater by a process such as dissolution, desorption, or ion exchange.

Monitoring well A well used to obtain water-quality samples or measure water levels.

Mountain-front recharge Water that enters an alluvial aquifer near the boundary of the aquifer and an adjacent mountainous area as a result of either infiltrating streamflow having headwaters in the mountainous area or flowing groundwater having origins in an adjacent aquifer within the mountainous area.

Multi-aquifer well A well that is screened in more than one aquifer and that penetrates through one or more confining units.

Nonpoint-source contaminant A substance from diffuse sources (for example, lawn and cropland runoff, the atmosphere, and roadways) that pollutes or degrades water.

Nonreactive (*see* **Conservative**)

Nutrient Element or compound essential for animal and plant growth. Nitrogen and phosphorus are common nutrients in fertilizer, but in high concentrations they can degrade water quality.

Open interval (of a well) The length of the screened or unscreened interval through which water enters a well.

Oxic Having dissolved oxygen concentration greater than or equal to 0.5 milligram per liter, and having concentrations of nitrate, manganese, iron, and sulfate as noted in the redox framework on page 42.

Oxygen-18 A heavy stable isotope of the oxygen ion (^{18}O), which is part of the water molecule.

Particle-tracking model A computer program used to track the movement of groundwater particles in a simulated flow field generated by using a groundwater-flow model.

Pathogen A disease-producing agent; usually applied to a living organism. Generally, any virus, bacteria, or fungus that causes disease.

Permeability The capacity of sediment or rock to transmit water.

pH A measure of the relative acidity or alkalinity of water. Water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, whereas pH levels higher than 7 indicate increasingly basic solutions.

Point-source contaminant Any substance that degrades water quality and originates from discrete locations, such as chemical spills or leaky underground storage tanks.

Porosity A measure of the water-bearing capacity of sediment or rock based on the ratio of the volume of pore space to the bulk volume of the sediment or rock.

Potentiometric surface A hypothetical surface representing the level to which groundwater would rise if not trapped in a confined aquifer. The potentiometric surface is equivalent to the water table in an unconfined aquifer.

Precipitation (chemical) Process whereby solids form from dissolved species.

Preferential flow pathway A pathway of least resistance followed by groundwater, such as a bedrock fracture or a nonpumping well. Preferential flow pathways are associated with relatively short groundwater traveltimes.

Probabilistic A situation or model where there are multiple possible outcomes, each having a different degree of certainty or uncertainty of occurrence.

Public-supply well A privately or publicly owned well that provides water for public use to (1) community water systems, (2) transient non-community water systems, such as campgrounds, or (3) non-transient, non-community systems, such as schools.

Public-supply well vulnerability The combined effect of groundwater vulnerability and the interaction between a well and an aquifer on the quality of water from a well.

Recharge Water that infiltrates the ground and reaches the saturated zone.

Recharge area (see **Area contributing recharge**)

Redox condition As used in this circular, redox condition refers to the geochemical status or position of a groundwater system on a scale of very oxidizing to very reducing. The redox condition of groundwater affects the mobility, degradation, and solubility of many contaminants.

Redox reaction An oxidation-reduction reaction, which involves the exchange of electrons between an electron donor and an electron acceptor.

Reduced/Reducing Used in this circular to refer to anoxic groundwater.

Saturated zone A zone extending from the water table downward, in which all pore spaces are filled with water under a pressure greater than atmospheric.

Screened interval (of a well) The depth interval over which water can enter a well through the well screen.

Septic system An onsite system designed to treat and dispose of domestic waste. A typical septic system consists of a settling tank for solids and a system of drainage lines to dispose of fluid.

Solute A substance that is dissolved in another substance, thus forming a solution.

Sorption Removal of a solute from the liquid phase by concentrating it on the solid phase of a medium; encompasses adsorption and absorption.

Source water Water used as a source for public water systems before undergoing treatment at a water facility.

Source water assessment The assessment phase of a program designed to prevent contamination of drinking water. Assessment steps include (1) delineating areas around surface-water intakes or public-supply wells to protect from contamination, (2) inventorying known and potential sources of contamination in these areas, and (3) determining the susceptibility of the water-supply system to these contaminants.

Source water protection area Area around a surface-water intake or public-supply well to protect from contamination.

Stable isotopes Nonradioactive forms of an element that have different molecular weights. The relative abundance of isotopes of elements such as hydrogen, oxygen, nitrogen, carbon, and sulfur provides information related to sources of water and reactions affecting the chemical composition of groundwater.

Stormwater runoff Water and associated material draining into streams, lakes, or sewers as the result of a storm.

Study well A typical public-supply well in each of six study areas, selected to help explore how contaminants arrived at and entered the well. Each study well produced water with low concentrations of anthropogenic and naturally occurring drinking-water contaminants and had recharge areas that included several types of land use. Also referred to as “investigated well.”

Sulfur hexafluoride (SF₆) A volatile organic compound derived from natural and human sources, whose concentration in the atmosphere increased significantly in the 1950s because of increased industrial use.

Susceptibility (*see* **Intrinsic susceptibility**)

Till An unsorted mixture of boulders, gravel, sand, silt, and clay deposited by a glacier.

Time of travel (*see* **Traveltime**)

Tracer A chemical constituent in groundwater that can be used to infer flow pathways and groundwater age. “Environmental” tracers are added by natural processes, although they may have been produced by humans.

Traveltime The time required for groundwater to travel between two locations. Traveltime is equal to groundwater age when the starting location is at the point of recharge.

Tritium A radioactive isotope of hydrogen (³H) that is part of the water molecule. The concentration of tritium in the atmosphere greatly increased in the 1950s and 1960s in response to human activities. In groundwater, tritium concentrations can be used to interpret the presence or absence of relatively young water.

Tritium/helium-3 The ratio of tritium and helium-3, which forms from the radioactive decay of tritium. The tritium/helium-3 ratio can be used to interpret the age of relatively young groundwater. (Helium-3 also can be derived from aquifer materials, and that fraction can be estimated by using concentrations of other gases.)

Turbidity Reduced transparency of water resulting from suspended solids such as clay, silt, organic matter, or microscopic organisms.

Unconfined aquifer An aquifer with the water table as its upper surface.

Unconsolidated Loose and not cemented together. Sand and silt are examples of unconsolidated sediments.

Unsaturated zone A zone that contains both water and air and is generally underlain by a saturated zone in which all interconnected openings or pore spaces are full of water.

Upgradient In the opposite direction that groundwater flows; equivalent to “upstream” for surface water.

Volatile organic compounds (VOCs) Chemicals that are groundwater contaminants of concern because of very large environmental releases, human toxicity, and a tendency for some compounds to persist in and migrate with groundwater to drinking-water supply wells. In general, VOCs have high vapor pressures, low to medium water solubilities, and low molecular weights. Some VOCs may occur naturally in the environment, other compounds occur only as a result of human activities, and some compounds have both origins.

Vulnerability assessment A process by which information relevant to vulnerability is assembled and then evaluated. A groundwater or public-supply well vulnerability assessment serves to direct groundwater or source water protection efforts.

Water quality A term used to describe the chemical, physical, and biological characteristics of water, usually with respect to the water’s suitability for a particular purpose.

Water table The surface that separates the zone that is generally unsaturated from the zone that is generally saturated.

Well A hole in the ground (wellbore or borehole) from which water can be removed.

Wellbore A borehole that has been completed as a well.

Wellhead The top of a well.

Wellhead protection Protection of all or part of the area from which water entering an aquifer system at the water table flows to a well.

Wellhead protection area The area around a wellhead to protect from contamination. Synonymous with source water protection area for public-supply wells.

Well screen A filtering device used to prevent sediment from entering a well.

Zone of contribution (ZOC) A three-dimensional volume of the aquifer through which water flows to a well from its area contributing recharge.

Zone of influence (ZOI) The area surrounding a pumping well within which the water table or potentiometric surface has been changed by groundwater withdrawal.

Zone of transport (ZOT) The area surrounding a pumping well through which water or a contaminant can travel and reach the well within a specified amount of time.



Appendix

TOOLBOX

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Selected Tools Overview

Many methods and tools were used in this study to help assess the vulnerability of groundwater from public-supply wells to contamination. This appendix summarizes information on selected tools, such as (1) why a tool was used in this study; (2) where to find more information on the tool, including where to find downloadable USGS computer programs; and, (3) what can be learned by using the tool as illustrated with data and information from this study. Some of the tools are straightforward to use; others might require the assistance of a technical expert.

Tool	Why it was used	For more information
Contaminant Input (Sources of Recharge)		
Groundwater-flow and particle-tracking models coupled with land-use data	To estimate the percentage of simulated inflow to public-supply wells from areas of different land use. In this study, the USGS MODFLOW and MODPATH models were used for computing the areas at land surface that contribute recharge to public-supply wells, and land use was based on the enhanced National Land Cover Data (NLCDE). (See box on page 32.)	http://water.usgs.gov/nrp/gwsoftware/modflow.html ; http://pubs.usgs.gov/ds/2006/240/#proc ; http://www.mrlc.gov/index.php
Computer scripts for running Monte Carlo simulations	To estimate the uncertainty in simulated recharge areas for public-supply wells. (See page 110.)	Starn and others, 2010; Starn and Bagtzoglou, 2012; http://water.usgs.gov/software/MonteCarloContributingArea/
Mixing equation	To estimate the relative proportions of end-member waters in a mixture. (See page 111 for a sample calculation for a two-component mixture.)	Parkhurst and Appelo, 1999; http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/
Depth-dependent sampling	To collect borehole-flow and water-quality data from discrete intervals within the producing zone of a public-supply well in order to determine where and how water and contaminants actually enter the well. (See case study on page 34.)	Izbicki, 2004; Izbicki and others, 1999; Izbicki and others, 2008
Contaminant Mobility and Persistence (Geochemical Conditions)		
Framework for identifying redox processes	To determine redox conditions associated with water from wells on the basis of threshold concentrations of six water-quality constituents—dissolved oxygen, nitrate, manganese, iron, sulfate, and hydrogen sulfide. (See box on page 39 and also pages 42–43.)	Chapelle and others, 2009; McMahon and Chapelle, 2007; http://oh.water.usgs.gov/tanc/NAWQA-TANCRadox.htm
	Microsoft Excel® workbook that can be used to apply the redox framework to large water-quality datasets.	Jurgens, 2009; http://pubs.usgs.gov/of/2009/1004/
Geochemical models	To simulate chemical reactions and transport processes in natural and contaminated groundwater in order to evaluate the mobility of chemical constituents in an aquifer, especially trace elements. (See page 112.)	Parkhurst and Appelo, 1999; http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/

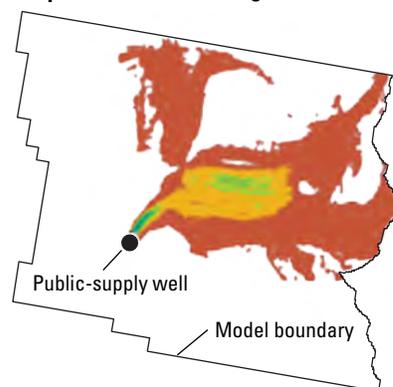
Tool	Why it was used	For more information
Intrinsic Susceptibility (Groundwater-Age Mixtures)		
Groundwater-flow and particle-tracking models calibrated to tracer concentrations	To estimate the groundwater-age mixture in water from public-supply wells on the basis of monitoring- and public-supply-well data that include measured concentrations of chemical indicators (tracers) of groundwater age. (See box on page 50 and also pages 113–114.)	http://water.usgs.gov/nrp/gwsoftware/modflow.html
Lumped-parameter models (TracerLPM computer program)	To estimate the groundwater-age mixture in water from an individual well on the basis of measured concentrations of groundwater-age tracers in the water. (See pages 113, 115.)	Jurgens and others, 2012; http://ca.water.usgs.gov/user_projects/TracerLPM/
Groundwater-stratigraphy models	To generate rough estimates for the groundwater-age mixture in water from a well on the basis of aquifer thickness, porosity, recharge rate, and depth to the top and bottom of the well screen. (See pages 113, 116.)	Cook and Böhlke, 2000; Mendizabal and Stuyfzand, 2009
Water-Quality Forecasting		
TracerLPM computer program	To generate water-quality response curves from information on the groundwater-age mixture for a well and local contaminant degradation rates. (See page 117.)	Jurgens and others, 2012; http://ca.water.usgs.gov/user_projects/TracerLPM/
Direct Observation of Vulnerability		
Low-level VOC analysis	To provide an early warning of public-supply-well vulnerability to contamination from a local source of contaminants on the basis of very low-level detection (parts per quadrillion) of volatile organic compounds (VOCs) in the water. (See page 118.)	Plummer and others, 2008
Preferential Flow Pathways		
Confined-aquifer zone-of-transport calculation	To evaluate the potential for nearby multi-aquifer wells to influence water quality in a public-supply well in a confined aquifer. (See pages 119–120.)	Johnson and others, 2011
Multiple different ways to collect, analyze and interpret water samples to uncover the presence of preferential flow pathways	To recognize the influence of preferential flow pathways on the quality of water from a public-supply well. (See page 74 for a list of methods and related examples.)	
Multi-node well (MNW) package for the USGS MOD-FLOW model	To simulate the effects of hydraulic short-circuiting by production wells that are open to multiple aquifers. (See page 76 for model results obtained by using the MNW package.)	Konikow and others, 2009; http://water.usgs.gov/nrp/gwsoftware/modflow2000/MFDOC/index.html?mnw2.htm

Contaminant Input (Sources of Recharge)

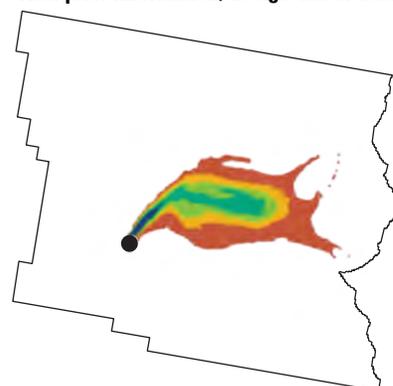
Computer Programs for Estimating Recharge-Area Uncertainty

Areas contributing recharge to wells often are delineated by using steady-state groundwater-flow and particle-tracking models. Simulated recharge areas, however, are only as good as the underlying groundwater-flow models from which they are derived. Monte Carlo simulation can be used to evaluate the uncertainty in simulated recharge areas. The Monte Carlo approach involves running a model many times with different combinations of model parameter values and then combining the results to express the model output in terms of probability. The probability that a location at the land surface contributes recharge to a well—given the simplifications in the model used to represent the natural system—is computed by dividing the number of model runs in which water from that location reached the well by the total number of model runs. The computer scripts GEN_LHS and MCDRIVER_LHS were developed for this study to run Monte Carlo simulations for generating probabilistic recharge areas to evaluate recharge-area uncertainty.

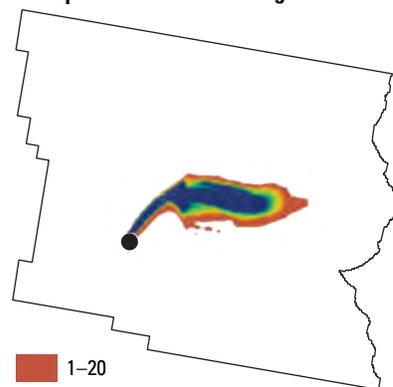
No prior information; no age-tracer data



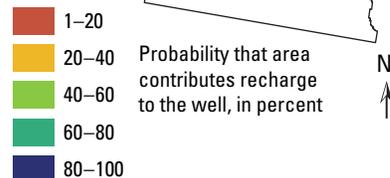
With prior information; no age-tracer data



With prior information and age-tracer data



Results from the Connecticut study area help illustrate recharge-area uncertainty and the importance of calibrating groundwater-flow models to different amounts and types of data. The local-scale groundwater-flow model was originally calibrated to measured groundwater levels and groundwater discharge to streams. The particle-tracking model MODPATH (Pollock, 1994) was used to map the recharge area from the flow-model output. A Monte Carlo simulation was used to evaluate the uncertainty associated with the simulated recharge area. (See top figure at right.) The process was repeated for the Connecticut well after independent (or “prior”) information on several model parameters (for example, porosity) was added to the calibration dataset (see middle figure at right) to help steer the calibration toward realistic values. The process was repeated again after observed concentrations of tritium were added. This last step ensured that the model solution was constrained with observations relevant to groundwater travel-time. (See bottom figure at right.) Simulated recharge areas were more precise (smaller) and less uncertain when the additional types of measurements were used to help calibrate the model.



MORE INFORMATION

Computer programs for generating probabilistic recharge areas

Starn and Bagtzoglou, 2012;
<http://water.usgs.gov/software/MonteCarloContributingArea/>

Reducing recharge area uncertainty

Starn and others, 2010

Two-Component Mixing Equation for Investigating Sources of Recharge for a Well

Relatively simple mixing equations can be used to estimate the proportions of two or more waters that combine in a well, provided that different parts of the aquifer system tapped by the well contain groundwater with distinct concentrations or ratios of conservative constituents. A two-component mixing equation (binary mixing model) and example calculation for the Nebraska study area are given below. (For more complex mixtures, a computer program such as the USGS program PHREEQC (Parkhurst and Appelo, 1999) might be needed to resolve the mixture.)

$$X_1 = (C_{mix} - C_2 / C_1 - C_2) * 100$$

where

X_1 is the proportion of end-member 1 in the mixture (in percent)

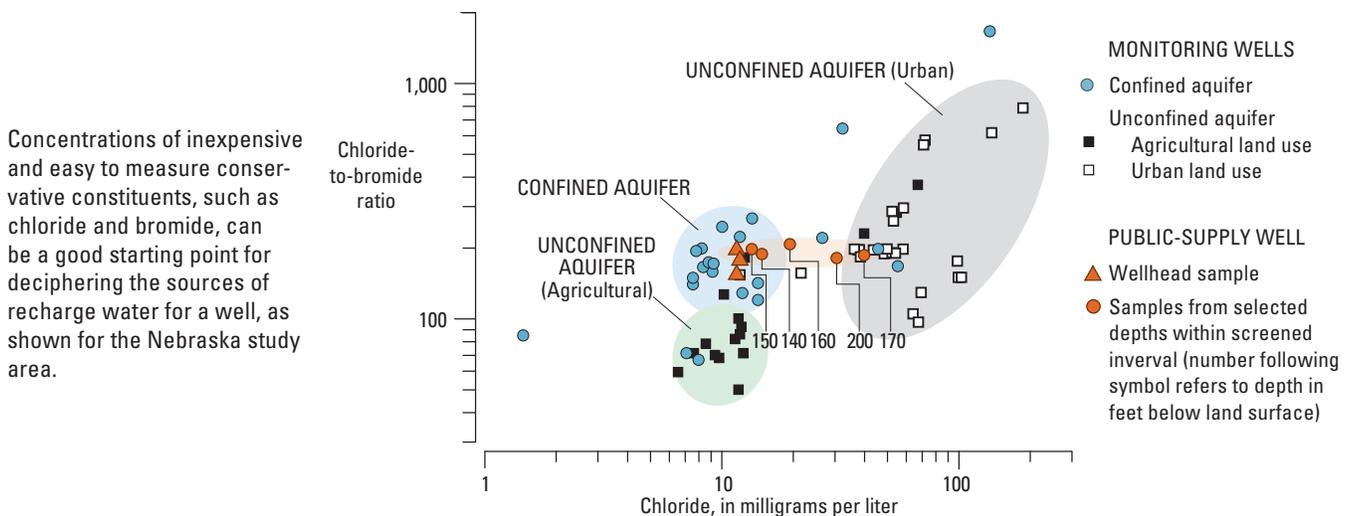
C_1 is the concentration in end-member 1

C_2 is the concentration in end-member 2

C_{mix} is the concentration in the water mixture

Mixing fractions for the Nebraska study well were calculated by using stable isotope data collected throughout the study area. End-member values for deuterium (^2H) were set equal to the average value for monitoring-well samples from each aquifer (-56.89 per mil for water from the shallow, unconfined aquifer and -77.40 per mil for unmixed water from the confined aquifer). The ^2H value for the water mixture—the water from the public-supply well—was set equal to the average ^2H value for water samples from the public-supply well (-74.97 per mil). On the basis of the two-component mixing equation, the percentage of water from the public-supply well that came from the unconfined aquifer was 12 percent.

Although stable isotope data were used to “unmix” the water from the Nebraska study well, this type of data is not always available. However, for some aquifer systems, chloride (Cl) and bromide (Br) data may offer an alternative way to investigate sources and mixing of waters in public-supply wells. For the Nebraska study area, a graph of Cl/Br versus Cl (see figure below) shows patterns similar to those in a graph of ^2H versus ^{18}O (see case study on pages 34–35): (1) samples plot in distinct groups on the basis of aquifer type and land use, (2) samples from the public-supply well plot along a mixing line between the confined aquifer and the unconfined aquifer (in urban areas), and (3) the highest fraction of unconfined-aquifer water is in the bottom half of the producing interval.



Once the mixture of waters captured by a public-supply well has been estimated, the maximum concentration of a chemical constituent in the water from the well can be computed. For example, the maximum chloride concentrations for the unconfined and confined aquifers in the Nebraska study area were 187 mg/L and 32 mg/L, respectively. Using these data, the two-component mixing equation indicates that the maximum future chloride concentration in water from the public-supply well will be about 50 mg/L, assuming that conditions remain unchanged.

Contaminant Mobility and Persistence (Geochemical Conditions)

Geochemical Modeling for Evaluating the Mobility of Chemical Constituents in an Aquifer

It is sometimes necessary to use a complex set of geochemical equations that account for processes such as aqueous speciation, mineral precipitation/dissolution reactions, redox reactions, adsorption behavior, and mixing of different waters to explain the mobility and persistence of a chemical constituent in groundwater. Geochemical modeling programs, such as PHREEQC (Parkhurst and Appelo, 1999), can be an important tool for understanding the fate of chemical constituents in such instances. Trace elements are examples of constituents that frequently require geochemical modeling to evaluate their individual mobility and persistence in an aquifer.

In the Connecticut study area, arsenic concentrations were elevated in water from wells completed in glacial deposits that were derived from the organic-rich Cass Formation. PHREEQC was used to speciate and model the behavior of dissolved arsenic in equilibrium with aquifer sediments. Modeling results indicate that coatings of iron oxyhydroxides on aquifer sediments in the study area can be dissolved, releasing arsenic into solution where the organic carbon content is sufficient to create reducing conditions in the aquifer.

In the California study area, uranium concentrations exceeded the Maximum Contaminant Level (MCL) of 30 $\mu\text{g/L}$ in several public-supply wells and were frequently above one-half the MCL. The uranium content in the soils and aquifer sediments in the study area is naturally high. Uranium concentrations in groundwater were strongly correlated to the concentration of dissolved inorganic carbon (DIC) (mainly bicarbonate); concentrations of DIC have increased over time as a result of agricultural irrigation and crop production. PHREEQC was used to model the effect of different concentrations of DIC on the adsorption of uranium to coatings of iron oxyhydroxides on aquifer sediments. The surface complexation model predicted uranium concentrations similar to those that were measured in the groundwater. Modeling results indicate that the dissolved uranium was controlled by adsorption processes and DIC concentrations within the aquifer, rather than by uranium contained in fertilizers and soil amendments.

In the New Mexico study area, the groundwater is predominately old, having carbon-14 ages ranging from about 4,000 to more than 22,000 years. PHREEQC was used to model the long-term evolution of major ion chemistry in the groundwater and its effect on measured carbon-14 concentrations. This was done so that carbon-14 concentrations could be corrected for estimating groundwater ages. Modeling results indicate that the primary reaction affecting measured carbon-14 concentrations was the dissolution of organic carbon. In addition, PHREEQC was used to help explain the presence of tritium and VOCs—chemical constituents in groundwater recharged after the 1940s—in water from some monitoring wells that also had low carbon-14 concentrations, indicating the presence of very old groundwater. Modeling results indicate that the water from the monitoring wells was a mixture of young and old groundwater, with the young fraction ranging from 1.5 to 46 percent.

MORE INFORMATION

Computer program (PHREEQC) for geochemical modeling

Parkhurst and Appelo, 1999

Geochemical modeling for understanding dissolved constituents in groundwater

Bexfield and others, 2011

Brown and others, 2009

Burow and others, 2008

Clark and others, 2008

Jurgens and others, 2008

Jurgens and others, 2009a

Intrinsic Susceptibility (Groundwater-Age Mixtures)

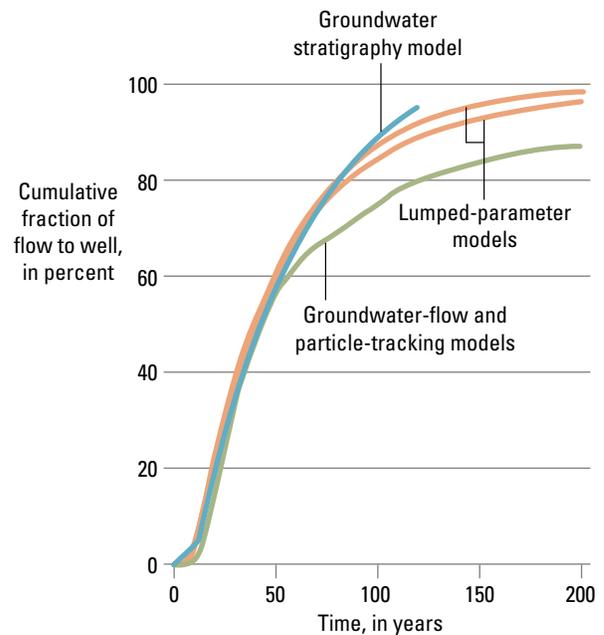
The following pages present three methods that can be used to estimate groundwater-age mixtures in wells. The methods are listed in order of decreasing sophistication and expense. An example comparing age estimates obtained by using the different methods is given for the California study well.

How groundwater-age mixtures from three modeling approaches compared

Three modeling approaches were used to estimate the groundwater-age mixture for the California study well. Although differences exist among the estimated age mixtures (see figure at right), all three approaches describe an age mixture in which 30 to 35 percent of the water from the well recharged the aquifer before the 1950s (more than 60 years ago). Thus, the different models identify a similar potential for in-well dilution of anthropogenic contaminants by old (presumably unaffected) groundwater entering the well.

Groundwater-flow and particle-tracking models were calibrated to data from the study well and from wells completed in the surrounding aquifer. Lumped-parameter models were calibrated to data from the study well alone. A groundwater-stratigraphy model was not calibrated but was based on published values for the aquifer and well geometries (effective porosity ($n=0.3$); aquifer thickness (saturated thickness penetrated by the well, $D=361$ ft); groundwater recharge ($N=1.97$ ft/yr); upper level of the well screen below the water table ($d_U=58$ ft); and lower level of the well screen below the water table ($d_L=333$ ft)) (Burow and others, 2008).

The different modeling approaches might not produce comparable results in other settings. However, in settings where it can be demonstrated that the approaches produce sufficiently similar age estimates, the simpler models could be used to estimate age mixtures for wells where more detailed data and sophisticated models are lacking.



Approach for Calibrating Groundwater-Flow and Particle-Tracking Models for Estimating Age Mixtures in Water from Wells

Probably the most familiar method for estimating the groundwater-age mixture in water from a well involves using three-dimensional groundwater-flow and particle-tracking models. Groundwater-flow models are computer programs that attempt to reproduce a groundwater-flow system with a complex set of mathematical equations. A particle-tracking model calculates the pathways that parcels of water would follow through the simulated flow system. Distance, traveltime, and velocity for the various pathways also can be obtained by using particle tracking. Together, the traveltimes for all pathways to a well describe the age mixture of water from the well (when weighted by how much flow each pathway contributes to the well). Computer programs that were used to estimate groundwater-age mixtures in this study include MODFLOW-2000 (Harbaugh and others, 2000) and MODPATH (Pollock, 1994).

Because groundwater-flow models greatly simplify flow in an aquifer system, they must be calibrated before they can be applied to real-world problems—such as estimating the groundwater-age mixture in a well. Model calibration involves comparing model output with field measurements to demonstrate that the model is capable of reproducing field conditions. During model calibration, model parameter values (such as hydraulic conductivity, recharge rate, or porosity) are adjusted until differences between simulated and measured values (such as water levels, flow rates, or tracer concentrations) are minimized. At least some of the measurements used for model calibration should be related to the types of predictions that will be made in order to reduce uncertainty in the predictions (Reilly and others, 1994; Starn and others, 2009). Therefore, models that will be used to estimate groundwater age and age mixtures should be calibrated to some measure of groundwater age. Because groundwater ages estimated using different chemical tracers in a mixed-age water sample can be different and might not equal the mean age of the water (Plummer and others, 2006), it is better to calibrate groundwater-flow models to measured tracer concentrations (for example, sulfur hexafluoride (SF₆), chlorofluorocarbons (CFCs), and tritium (³H)) than to interpreted ages derived from tracer data.

Calibrating a groundwater-flow model to tracer concentrations necessitates the computation of simulated concentrations. Simulated concentrations for wells can be computed by recording the traveltime and amount of flow associated with each particle that tracks to a well in a groundwater-flow model and then summing the amount of flow to the well in 1-year increments. The volume of flow for each increment is then divided by the total flow from the well to determine the fraction of flow corresponding to each year of recharge. Simulated tracer concentrations are then obtained by multiplying the simulated fraction of flow to the well for a given year by the concentration of the tracer in recharge water from that year and then summing over all years. Tracer input concentrations are determined such that they are relevant to the date a well was sampled so that simulated and measured concentrations can be directly compared. For example, if a well was sampled in 2000 and a 1-year time increment is used to compute the simulated tracer concentrations, all particles with a simulated traveltime of 10 years are assigned a tracer concentration equal to the concentration in 1990 recharge.

MORE INFORMATION

Computer programs for computing groundwater traveltimes

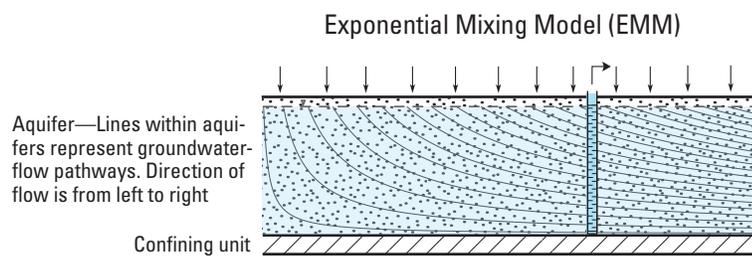
Harbaugh and others, 2000
Pollock and others, 1994

Calibration of groundwater-flow models to tracer concentrations

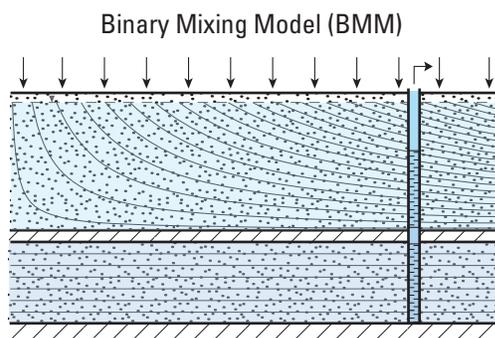
Burow and others, 2008 Crandall and others, 2009
Clark and others, 2008 Eberts and others, 2012

Computer Program for Estimating Age Mixtures in Water from Wells by Using Lumped-Parameter Models

A less resource-intensive method for estimating the groundwater-age mixture in water from a well involves using lumped-parameter models—simple mixing equations. An important assumption for this method is that the aquifer geometry and groundwater-flow patterns are simple enough for the groundwater-age mixture in a well to be described with a single equation. (Spatial variations in aquifer properties are ignored.) Consequently, the modeler must choose a mixing equation that has conceptual relevance to the combination of aquifer(s) and well being modeled. Two examples are given in the figures below.



For an aquifer where groundwater age increases more and more with increasing depth, an equation that describes exponential mixing might be used to estimate the age mixture in water from a well that fully penetrates the aquifer. For example, the exponential mixing model would be appropriate for a well in an unconfined aquifer of constant thickness receiving uniform recharge.



For an aquifer system where groundwater age is distinctly different in different parts of the system, an equation that describes a binary mixture might be used to estimate the age mixture in water from a well that draws in groundwater from different parts of the system. For example, the binary mixing model would be appropriate for a well in a layered-aquifer system.

A variety of lumped-parameter models have been developed and used to estimate age mixtures for water discharging from different types of aquifers (Małoszewski and Zuber, 1982, 1996; Zuber, 1986; Cook and Böhlke, 2000). A computer program, TracerLPM, was developed for this study to make it easier to apply the lumped-parameter models for estimating groundwater-age mixtures for wells (and springs). Within the computer program, the user selects one or more potentially relevant mixing models for the well of interest. Each mixing model has one or two variables that represent parameters such as mean age or dispersion. Values for the model parameters are adjusted until the best match between simulated tracer concentrations and measured concentrations is achieved. This is done (1) manually, while the modeler visually compares curves described by the model equations with measured concentrations on a graph or graphs, or (2) automatically, by inverse methods. The approach for computing the simulated tracer concentration for comparison with measured concentrations is fundamentally the same as the approach described for particle tracking (see page 114) except that the underlying age mixture is derived from the mixing equations rather than from collections of particles and their traveltimes. For public-supply wells with a wide range of ages, it is necessary to calibrate the mixing models to multiple tracer data in order to narrow down the possible combinations of groundwater ages in the well (traveltimes to the well). The calibration data can include observed concentrations for multiple tracers for a single sample and (or) concentrations for a single tracer collected at the well over a sufficient period of time (generally years). Both tracers of young groundwater (for example, SF_6 , CFCs, ^3H , and helium-3) and tracers of old groundwater (for example, carbon-14 and helium-4) can be used in the TracerLPM program.

MORE INFORMATION

Computer program for estimating age mixtures using lumped-parameter models

Jurgens and others, 2012

Comparison of age mixtures from lumped-parameter and particle-tracking models

Eberts and others, 2012

Groundwater-Stratigraphy Models for Estimating Age Mixtures in Water from Wells

Often, the data and models that are best for estimating the groundwater-age mixture in water from wells are not available. However, for simple aquifers with uniformly distributed recharge (meaning no focused recharge from streams or runoff from mountain fronts), it might be possible to estimate the groundwater-age distribution in an aquifer by using information on aquifer thickness, porosity, and recharge rate (Cook and Böhlke, 2000). This type of data is frequently available or readily obtainable.

The relevant models are referred to as groundwater-stratigraphy models. Similar to lumped-parameter (mixing) models, they are single equations that describe different field conditions. The major difference between groundwater-stratigraphy models and lumped-parameter models is that groundwater-stratigraphy models are formulated to describe variations in groundwater ages within an aquifer on the basis of aquifer geometry (Vogel, 1967; Cook and Böhlke, 2000; Solomon and others, 2006; Mendizabal and Stuyfzand, 2009), whereas the lumped-parameter models are formulated to describe age mixtures at points of discharge from the aquifer (wells or springs). The choice between the two types of models depends on the data that are available—data related to aquifer geometry or tracer concentrations for a well or spring. However, by including information on the depth to the top of the well screen and the length of the screened interval, it may be possible to generate a rough estimate of the groundwater-age mixture for a well by using a groundwater-stratigraphy model (Cook and Böhlke, 2000; Mendizabal and Stuyfzand, 2009). A significant limitation of this method is the lack of model calibration to tracer data. Consequently, there is no feedback to indicate whether the selected model and model parameter values are correct for the system. Therefore, the technique is best used for wells where recharge, porosity, and the general pattern of groundwater age in the aquifer are known.

An example of a groundwater-stratigraphy model for an unconfined aquifer with constant thickness follows:

$$T_d = nD/N \cdot \ln(D/D-d) \quad (1)$$

where T_d is the traveltime, in years, to a given depth on the well screen, n is effective porosity, D is aquifer thickness (feet), N is groundwater recharge (feet per year), and d is the depth on the well screen in feet below the water table.

The cumulative-frequency distribution of the age of water from a well is calculated by first replacing d in the model with

$$d = d_U + 0.01P_x(d_L - d_U) \quad (2)$$

where d_L is the lower level of the well screen (feet below water table), d_U is the upper level of the well screen (feet below water table), and P_x is percentile x in the cumulative distribution (0–100 percent),

and then computing T_d for a range of percentiles (for example 0, 20, 40, 60, 80, and 100) using the following form of the equation (Mendizabal and Stuyfzand, 2009):

$$T_d = nD/N \cdot \ln(D/D-(d_U + 0.01P_x(d_L - d_U))). \quad (3)$$

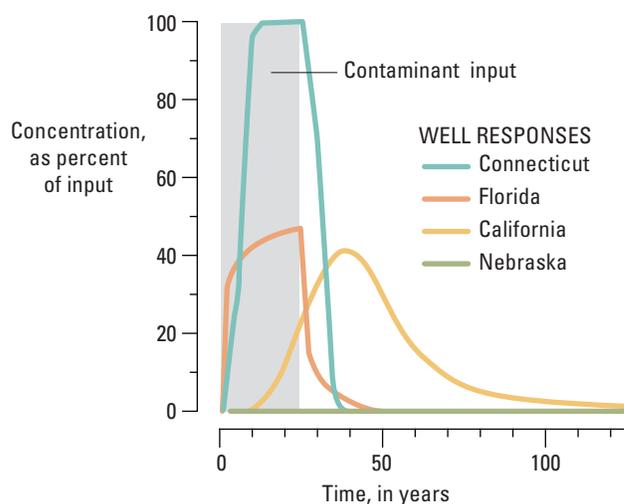
Water-Quality Forecasting

Computer Program for Generating Water-Quality Response Curves for Wells

Once an estimate for the age mixture of water from a well is obtained, it can be combined with information on contaminant input at the water table to forecast the water-quality response at the well to widespread, shallow groundwater contamination (nonpoint-source contamination). Forecasts can account for degradation of reactive contaminants if reaction rates are uniform and are included in the calculations.

The computer program TracerLPM, which was developed for estimating groundwater-age mixtures in wells by using lumped-parameter models (see page 115), has a routine for creating water-quality response curves from estimated age mixtures. The program includes an option for importing estimated groundwater-age mixtures generated outside the program so that water-quality response curves for individual wells also can be created from groundwater-flow and particle-tracking model results.

A limitation of using information on groundwater-age mixtures at individual wells for creating water-quality response curves is the inability to account for spatial variations in contaminant input. This includes contaminant input from most point sources. Three-dimensional models are necessary if such additional insight is desired.



Water-quality response curves were computed for four study wells to explore differences in how the water from the wells might change over time in response to 25 years of nitrate contamination of shallow groundwater. Without this type of analysis, it would be difficult to appreciate the vastly different consequence of nitrate contamination for the four communities relying on these public-supply wells.

MORE INFORMATION

Computer program for forecasting effect of nonpoint-source contamination on water from wells

Jurgens and others, 2012

Response of public-supply wells to changes in nitrate input

McMahon and others, 2008b

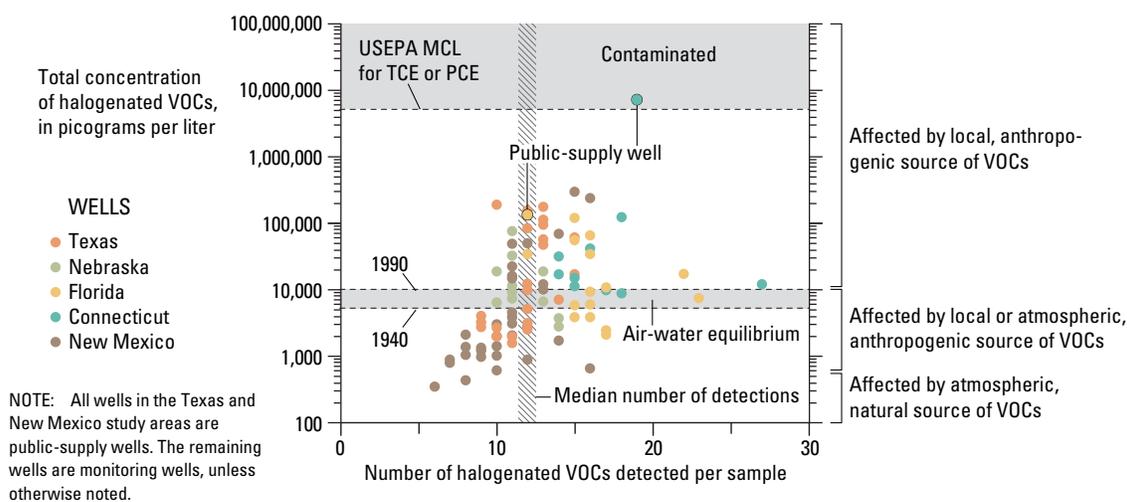
Direct Observation of Vulnerability

Low-Level VOC Analysis for Assessing Vulnerability Independent of Groundwater Age

A classification scheme that can be used to assess the vulnerability of water from an individual well to VOC contamination was developed by using data from this study. The classification scheme is based on the ability to detect halogenated VOCs in groundwater at very low concentrations (parts per quadrillion)—near those expected for water in equilibrium with air. This is accomplished by using gas chromatography with an electron-capture detector (GC-ECD).

Many halogenated VOCs have entered aquifers along with recharge from precipitation since the 1940s. VOCs in groundwater with concentrations at or just below air-water equilibrium can be the result of atmospheric (anthropogenic or natural) sources of VOCs or local, anthropogenic sources of VOCs. Higher concentrations, however, indicate that a local, anthropogenic source of VOCs (such as a solvent plume) must be linked to the well by way of one or more flow pathways.

The classification scheme is useful for providing an early indication of whether a link exists between a well and a local (often unknown) anthropogenic source of contaminants. However, it does not provide information on the long-term threat posed by the contaminant source. Information on the concentrations and proportions of contaminated and uncontaminated waters that mix in a well are necessary to gain such insight. An example of how this classification scheme can be used to assess the vulnerability of water from wells to VOC contamination is given below:



The classification scheme was used to assess the vulnerability of water from wells in this study to VOC contamination. On the basis of very low-level VOC analysis, samples from every well contained PCE, the chlorofluorocarbons CFC-12 and CFC-11, and methyl iodide at low concentrations—indicating that every well has some vulnerability to contamination from VOCs originating near the water table. The data also revealed that approximately 20 percent of the public-supply wells had concentrations of VOCs high enough to indicate that a local, anthropogenic contaminant source had affected the well. Only one of the wells had concentrations above a drinking-water standard. Many VOCs were not detected in any of the wells when more conventional, but less sensitive, gas chromatography with mass spectrometry was used to analyze the samples.

MORE INFORMATION

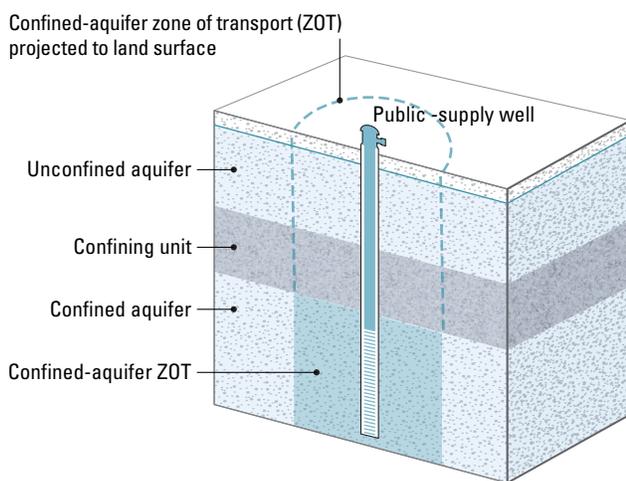
Framework for assessing vulnerability to VOC contamination

Plummer and others, 2008

Preferential Flow Pathways

Approach for evaluating potential for multi-aquifer wells to affect a public-supply well

A simple way to gain insight into the potential for multi-aquifer wells to affect a confined-aquifer public-supply well is to estimate a zone of transport (ZOT) for the public-supply well within the confined aquifer and then evaluate the likelihood that a multi-aquifer well lies within that zone. For this purpose, the ZOT would be defined solely on the basis of confined-aquifer traveltimes—traveltimes through the unconfined aquifer and confining unit would not be considered—because multi-aquifer wells anywhere within a confined-aquifer ZOT are capable of allowing contaminated water to reach a public-supply well within a timeframe of interest.



Zone of transport (ZOT) based on confined-aquifer traveltimes:

$$ZOT = Qt/\theta H$$

where

Q is pumping rate of well,

t is user-defined time of travel,

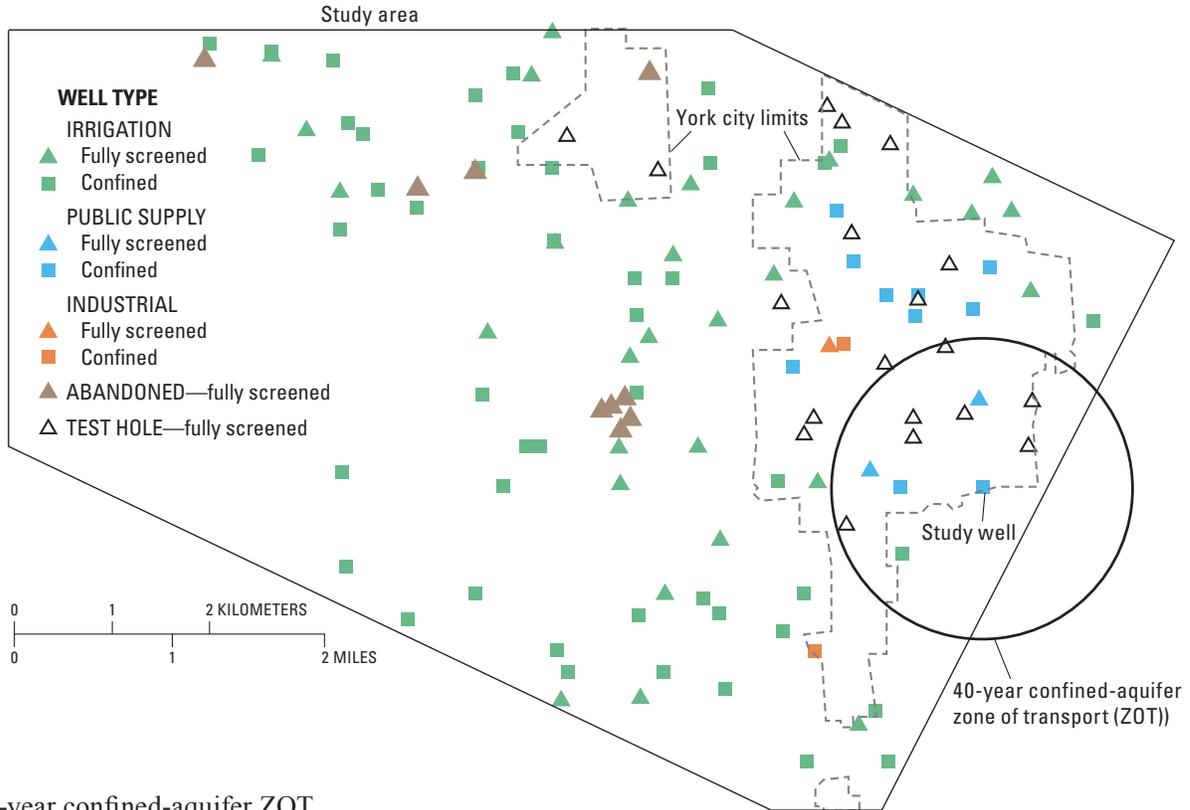
θ is porosity, and

H is height (thickness) of confined aquifer.

(NOTE: This is the cylinder or volumetric-flow equation (USEPA, 1993)).

Protecting the area at land surface above a confined-aquifer zone of transport can help prevent an unidentified multi-aquifer well from shunting contaminated groundwater across the confining unit and affecting the public-supply well within a timeframe of interest.

An example illustrating how this approach might be used to evaluate the potential for multi-aquifer wells to affect water quality at the Nebraska study well is given below. A 40-year ZOT is used in this example because the U.S. Environmental Protection Agency suggests a time of travel of 40 years for differentiating semi-confined conditions from highly confined conditions (USEPA, 1991).



Forty-year confined-aquifer ZOT for the Nebraska study well:

$$Q = 49,087 \text{ ft}^3/\text{d} \text{ (367,196 gal/d)}$$

$$t = 40 \text{ years (14,600 days)}$$

$$\theta = 0.15$$

$$H = 34 \text{ ft}$$

$$ZOT = 140,523,569 \text{ ft}^2 \approx 5 \text{ mi}^2$$

The number of multi-aquifer wells potentially affecting the public-supply well within a ZOT that is 5 mi² is 10 to 15 wells because the density of multi-aquifer wells in the area is approximately 2 to 3 per mi². Although the estimated ZOT does not equate with the area at the water table that ultimately contributes water to the well, simple calculations, such as this, can be used to alert water managers that many multi-aquifer wells might allow unconfined-aquifer water to travel relatively quickly to a confined-aquifer public-supply well.

MORE INFORMATION

Johnson and others, 2011

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