Domestic Wells

Introduction and Overview

John Drage

THE GROUNDWATER PROJECT

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The Groundwater Project
Guelph, Ontario, Canada

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THE GROUNDWATER PROJECT

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The Groundwater Project Foreword

The Year 2022 marks as an important year for groundwater because the United Nations Water Members and Partners chosen the theme of this year's March 22 World Water Day to be: "Groundwater: making the invisible visible". The goal of the Groundwater Project (GW-Project) is in sync with this theme.

The GW-Project, a registered charity in Canada, is committed to contributing to advancement in groundwater education and brings a unique approach to the creation and dissemination of knowledge for understanding and problem solving. The GW-Project operates the website https://gw-project.org/↗ as a global platform for the democratization of groundwater knowledge, founded on the principle that:

"Knowledge should be free and the best knowledge should be free knowledge." Anonymous

The mission of the GW-Project is promoting groundwater learning. This is accomplished by providing accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater. In short, providing essential knowledge tools for developing groundwater sustainably for humanity and ecosystems.

This is a new type of global educational endeavor in that it is based on volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 hundred organizations from 27 countries and six continents, with growing participation.

The GW-Project is an on-going endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. An important tenet of the GW-Project books is a strong emphasis on visualization via clear illustrations that stimulate spatial and critical thinking to facilitate absorption of information.

The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

The GW-Project is a living entity, so subsequent editions of the books will be published from time to time. Users are invited to propose revisions.

We thank you for being part of the GW-Project Community. We hope to hear from you about your experience with using the books and related material. We welcome ideas and volunteers!

The GW-Project Steering Committee

January 2022

Foreword

Domestic wells, also known as private wells, are typically on private property in contrast to publicly owned community municipal wells. Domestic wells need to yield only enough water for a single family and in some cases for small-scale farming. Hundreds of millions are estimated to use such wells for their basic water needs. In the United States and Canada, approximately 46 million people rely on domestic wells.

The quality of water provided by domestic wells is unknown due to an absence of testing requirements. Domestic wells are a common cause of harm to human health although the frequency and degree of harm is poorly documented. Hundreds of billions of dollars have been spent on investigations and remedial actions at contaminated industrial sites across North America and Europe to protect human health from contaminated groundwater, but almost no funds are allocated for assessing or reducing health threats from domestic well water because domestic water quality is deemed to be a matter for the private well owner. There are precedents that suggest private property ownership should not negate government responsibility. For example, some governments regulate the location and design of domestic septic systems, in an effort to protect nearby domestic wells.

Globally, studies that test groundwater pumped from domestic wells have found that many contain harmful constituents from natural sources – such as arsenic, fluoride, manganese and uranium – and/or harmful constituents from human activities such as solvents, flame retardants, road salt and agricultural chemicals. Studies that test domestic wells for pathogenic bacteria typically show one-third of the wells have unsafe levels, but the cause is not known. This well water is also likely to contain harmful viruses, but virus testing is rare. There are stringent modern requirements and building inspections for home construction, but the requirements to ensure the safety of domestic wells have not changed for more than half a century and on-site well inspections are not required.

This book focuses on design, drilling and operation of domestic wells. Although domestic well owners will find this book of interest, it is aimed at professionals working in groundwater related areas to enhance their understanding of problems associated with domestic wells. Safe domestic well water is essential to societal wellbeing and requires solutions from multidisciplinary teams that interface with public health authorities.

Three other Groundwater Project books complement this topic: *Fluoride in Groundwater*, *Septic System Impacts on Groundwater Quality*, and *Water Well Record Databases and Their Uses*. John Drage, author of this book, is a senior hydrogeologist with the Geological Survey of the Province of Nova Scotia, Canada where more than 40% of the population use domestic wells, making it a microcosm of the many problems facing domestic well owners and governments.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, January 2022

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Finally, I would like to thank the domestic well owners and well contractors that I have met during my career and have helped me learn about domestic wells by sharing their water well experiences with me.

John Drage

1 Introduction

Privately owned domestic wells (Figure 1) provide water to hundreds of millions of people around the world. They are the most common type of water supply used in rural areas where public water supplies are not available. Because they are privately owned, and often located in sparsely populated areas, they are difficult to monitor and protect. Domestic wells are largely unregulated, except for their initial construction, and it is the responsibility of the well owner to maintain their well and ensure the water is safe to drink. Although many domestic well owners do an excellent job managing their wells, many others do not have the resources to protect their well or regularly test their water quality. As a result, domestic wells are the most common way for people to be exposed to groundwater contaminants. Despite these risks, the majority of domestic wells provide safe and reliable water supplies. Where public water supplies are not available, domestic wells are usually the best water supply option, as long as they are properly constructed, located away from contaminant sources, and regularly maintained and monitored.

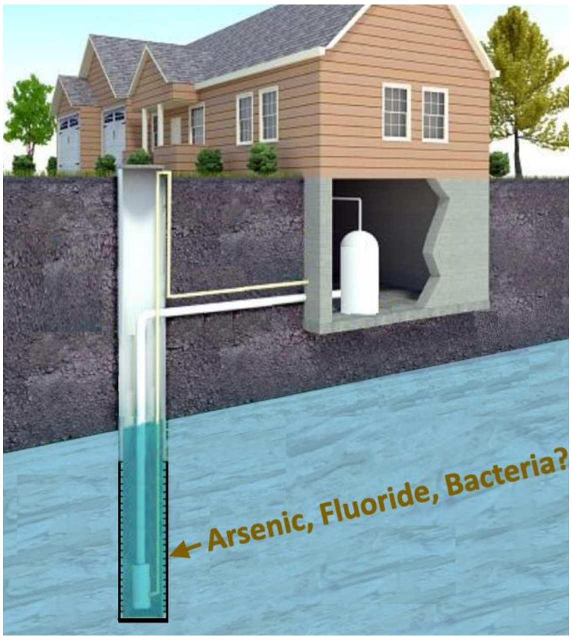

Figure 1 - A domestic well providing water to a private household (modified from USEPA, 2019).

This book provides an introduction to domestic wells, including their construction, regulation, vulnerability, protection, and the valuable data they can provide for groundwater research. It is part of a series of books on domestic wells, each of which provide greater detail on the domestic well topics that are covered at an introductory level here. This book focuses on domestic wells in Canada and the United States, although some information from other countries is presented. For information about domestic wells in other areas of the world, including Africa, Asia, and Latin America, The Rural Water Supply Network↗ is an excellent resource.

This book is primarily written for students, groundwater professionals, and policy makers with a background in water science and a professional interest in domestic wells. Questions that are discussed here include: How many people use domestic wells? How much does domestic well contamination contribute to disease and health care costs? How can the safety of domestic wells be improved? How can we ensure the water quality and quantity of domestic wells remain sustainable?

Throughout this book, the term "domestic well" is used to refer to wells that are privately owned by individuals and used to provide water for domestic purposes (i.e., water for household needs such as drinking, cooking, bathing, and cleaning). A domestic well typically serves a single household or sometimes a few households at a time. Domestic wells are also commonly called private wells or residential wells. For regulatory purposes, domestic wells are often distinguished from public wells based on the ownership of the well (i.e., privately owned by a homeowner versus government owned) or the number of people served by the well. In the United States for example, public water systems are defined as supplies that serve an average of at least 25 people for at least 60 days a year or have at least 15 service connections. Wells that serve less than these thresholds are defined as private water systems.

2 Domestic Well Demographics

2.1 Who Uses Domestic Wells?

About half of the world's population uses groundwater for drinking water (Margat and van der Gun, 2013), but how much of that comes from domestic wells? Unfortunately, the amount is not precisely known because accurate information about domestic well use is not available for all counties, including some counties with large populations such as China. However, the available information indicates that hundreds of millions of people worldwide rely on domestic wells. Sutton (2021) estimated that more than one billion people around the world use self-supplied water (i.e., households providing water by their own means). This estimate is for all types of household self-supplies, including those using surface water sources and rainwater cisterns, but the majority of self-supplies are from groundwater sources.

Domestic wells are used in both urban and rural areas, although they are used more in rural areas where approximately 45 percent of the world's population lives (United Nations, 2018). A study of self-supplied drinking water across the Asia-Pacific region concluded that household self-supplies, of which groundwater is the dominant source, accounted for 20 percent of urban water supplies and 37 percent of rural water supplies (Foster et al., 2021).

Table 1 shows information on domestic well use from a selection of countries. In Canada, 4.2 million people (11 percent of the population) use domestic wells and in the

United States, 42 million people (13 percent of the population) use domestic wells. Although the total number of domestic wells in United States continues to increase, the percentage of the population relying on domestic wells is declining as the population shifts to urban centers where public water supplies are available. In densely populated European countries (e.g., England, Germany), domestic wells are used by less than 1 percent of the population.

Table 1 - Estimated population using domestic wells in selected countries and regions.

Country or Region	Total Population (millions)[1]	Population Using Domestic Wells (millions)	Percent of Population Using Domestic Wells (%)	Source
Australia	25	1.4	6%	Australian Bureau of Statistics, 2013
Bangladesh[2]	165	107	71%	Foster et al., 2021
Canada	38	4.2	11%	Statistics Canada, 2017a
Cameroon	27	2.7	10%	Sutton and Butterworth, 2021
Cambodia	16	4.3	27%	Foster et al., 2021
DR Congo	90	7.4	8%	Sutton and Butterworth, 2021
England	56	0.06	< 1%	DWI, 2020
Germany	84	0.7	< 1%	Umwelt Bundes Amt, 2012
India[2]	1,380	371	27%	Foster et al., 2021
Ireland	5	0.55	11%	Hynds et al., 2013
Japan[3]	126	3.7	3%	Japan MHLW, 2020
New Zealand[3]	4.8	0.8	17%	NZMH, 2020
Nigeria	206	14	7%	Sutton and Butterworth, 2021
Norway[3]	5.4	0.5	9%	NIPH, 2017
Pacific Region[4]	11	0.33	3%	Foster et al., 2021
Pakistan[2]	221	90	42%	Foster et al., 2021
South Asia Region[5]	1,814	599	33%	Foster et al., 2021
Southeast Asia Region[6]	618	142	23%	Foster et al., 2021
United States	332	42	13%	Dieter et al., 2018.

Notes:
1. 2020 population↗.
2. This estimate is for the population served by self-supplied household drinking water supplies. It includes sources from water wells and rainwater, however, the proportion of rainwater supplies included in these estimates is less than 1 percent.
3. This estimate includes both domestic wells and other unregulated small water supplies and, therefore, is an overestimate of domestic well use.
4. Pacific Region includes the following countries: Fiji, Kiribati, Marshall Islands, Micronesia, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu.
5. South Asia Region includes the following countries: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka.
6. Southeast Asia Region includes the following countries: Cambodia, Indonesia, Lao PDR, Myanmar, Philippines, Thailand, Timor-Leste, and Vietnam.

It is difficult to find information about domestic well use in developing countries. New data have been published recently (e.g., Sutton and Butterworth, 2021; Foster et al., 2021) because household self-supply is being promoted as an approach to meet the United Nations Sustainable Development Goal for drinking water (i.e., to achieve universal and equitable access to safe and affordable drinking water for all by 2030).

Although information about domestic well use in developing countries is difficult to obtain, Bangladesh is an exception because domestic wells there have been extensively studied due to concerns about arsenic in groundwater. It is estimated that there are about 17 million domestic wells in Bangladesh (Fischer et al., 2020; Shamsudduha et al., 2019), serving a population of approximately 107 million people. The total number of wells has been steadily growing and a larger percentage of these wells are now privately owned domestic wells. In 1992 the total number of wells in Bangladesh was 2.5 million, 50 percent of which were privately owned and 50 percent were publicly owned. In 2017, the total number of wells was estimated to be 18.4 million, 95 percent of which were privately owned (Fischer et al., 2020). About 15 percent of these domestic wells are in urban areas and the remainder are in rural areas.

It is important to know how many domestic wells are in use and where they are located to determine where people are at risk of exposure to groundwater contaminants. An understanding of the distribution of domestic wells allows targeted interventions (e.g., awareness programs, well water quality testing programs) to be carried out in areas with suspected groundwater contamination. In many cases we can predict which areas are more likely to be at risk from naturally occurring and anthropogenic contaminants. Most naturally occurring groundwater contaminants, such as arsenic and fluoride, come from geologic sources, and the association between these contaminants and specific geologic formations indicates areas are more likely to be impacted. Anthropogenic groundwater contaminants can also be associated with specific areas where human activities pose risks to groundwater, such as agricultural areas where groundwater is often impacted by microbial contaminants, nitrate, and pesticides.

It is also important to know where domestic wells are being used so that water withdrawals from these wells can be included in water budgets. This can be especially important in highly stressed aquifers where the total water withdrawals have reached the aquifer's sustainable limit, or in areas where there is a risk that over-pumping may cause seawater intrusion. In most aquifers, agricultural, municipal, and industrial water withdrawals account for most of the groundwater withdrawal. However, depending on local conditions, a significant proportion of groundwater withdrawals can come from domestic wells.

Groundwater budget calculations for the Province of Nova Scotia, Canada, indicate that 32 percent of the groundwater withdrawals in the province are from domestic wells (Figure 2). The relative proportion of groundwater withdrawals for domestic wells in the province is larger than for most aquifers. Usually, domestic well withdrawals represent a small proportion of the total pumping volume. In addition, where domestic septic systems are in use, most of the water pumped from domestic wells is returned to the shallow aquifer though septic system discharge.

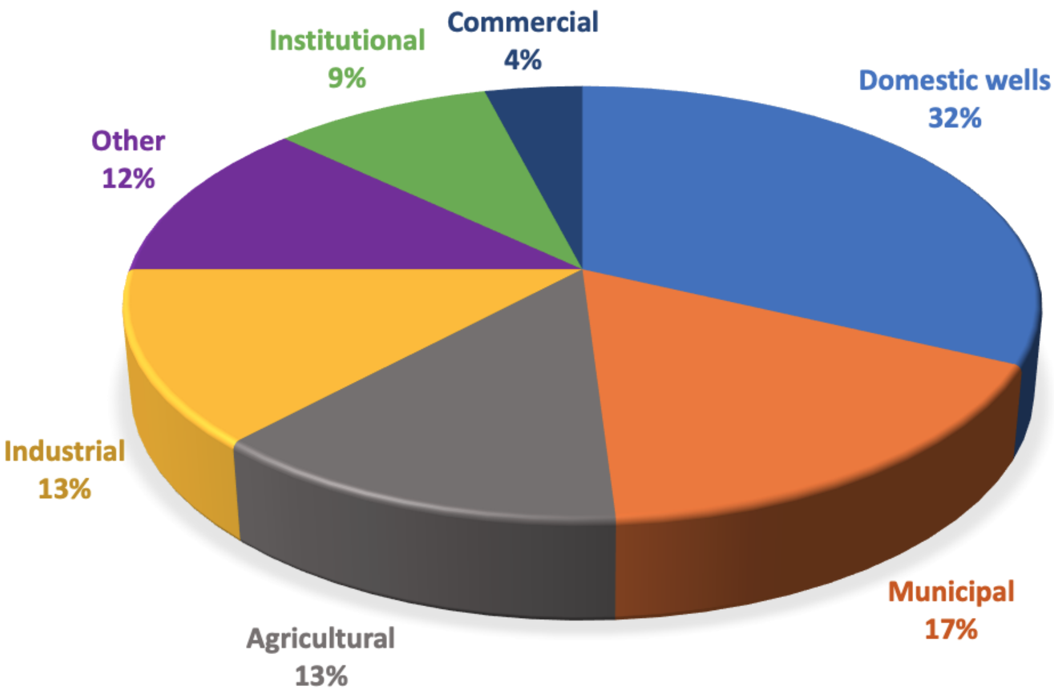

Figure 2 - Groundwater withdrawals by sector as a percentage of the total volume of all groundwater withdrawals in Nova Scotia, Canada (Kennedy, 2020).

2.2 Estimating the Number of People that Use Domestic Wells

Census data can be used to estimate domestic well use if the type of water supply used by each household is included in the census. In the United States, the 1990 census was the last census to collect this information in a nationally consistent manner. However, the United States Geological Survey (USGS) has estimated the number and location of domestic wells across the country using household density per square kilometer. After a threshold is reached, the number of people using domestic wells declines as household density increases. This is consistent with the observation that there are fewer domestic wells in urban areas with high household densities because public water supplies are usually available. Using this approach, the USGS estimated that in 2010 approximately 37 million people in the United States used domestic wells (Johnson et al., 2019). The distribution of people using domestic wells in the United States is shown in Figure 3.

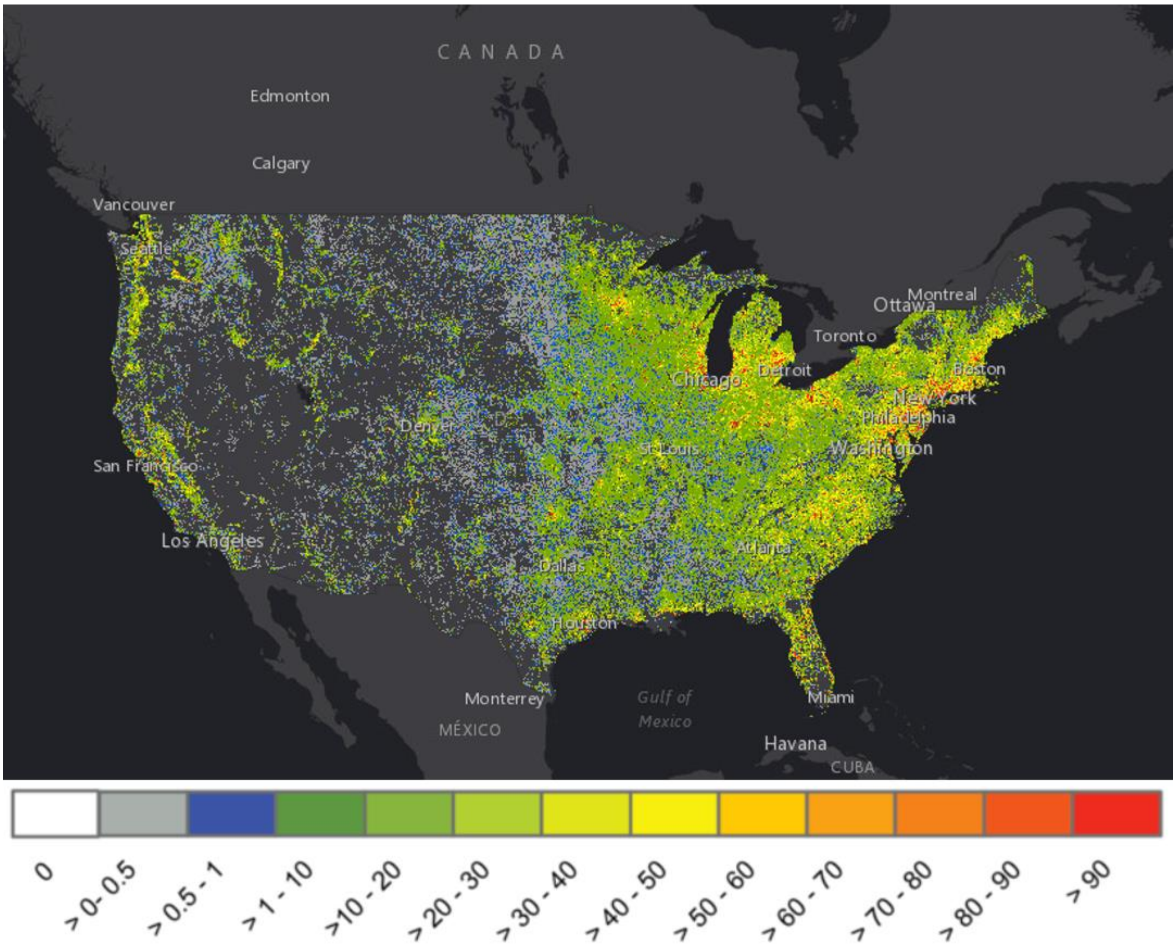

Figure 3 - Number of people per km^2 that used domestic wells in the United States in 2010 (modified from USGS, 2020).

Public water supply information, combined with other data, can also be used to estimate how many people use domestic wells. Because public water supplies are usually regulated, information about the population they serve, and the location of their distribution system is often available. An estimate of the number and location of domestic well users can be made by subtracting the population served by public water supplies from the total population of a given area. This approach assumes that anyone who is not served by a public water supply is using a domestic well. Given that domestic wells are the most common type of water supply in areas without public water supplies, this method provides a reasonable estimate of domestic well use. However, it does not account for people using other types of private water supplies, such as surface water and rainwater cisterns. This method was used in Nova Scotia, Canada, where public-water distribution-zone information was combined with residential address data and household density data in a geographic information system to investigate the sources of domestic water across the province (Kennedy and Polegato, 2017). The study concluded that 42 percent of the population used domestic wells for their water supply.

Many jurisdictions have water well record databases that are a potential source of information about the number and location of domestic wells for a given area. In practice, however, water well record databases are typically not used for this purpose because they do not usually contain a complete list of all water wells or keep track of wells that have been abandoned. For example, the previously referenced Nova Scotia study used civic address points and public water supply zone information to determine that 197,000 households in the province relied on domestic wells. The Nova Scotia provincial water-well database contained 113,000 records of domestic wells at the time of the study, indicating that the database did not account for all domestic wells. Another book in the Groundwater Project series on domestic wells provides more information on water well record databases↗ (Kennedy, 2022).

3 Domestic Well Construction

This section provides an overview of the most common types of domestic wells. Domestic wells are usually classified based on their construction method, for example a drilled well or dug well. Terminology used to describe well type varies from region to region around the world, however, the terms used in this book are widely used in Canada and the United States.

There are numerous domestic well types and construction methods available, each of which are suited to specific well diameters, depths, and geologic conditions. Well construction cost and the local availability of well construction equipment are important factors for determining how a domestic well is constructed. In general, the deeper the well, the more expensive it is to construct because drilling and well casing are usually charged by unit length.

3.1 Drilled Wells

Drilled wells (Figure 4 and Figure 5) are the most common type of domestic well in developed counties. They are usually installed with a truck-mounted drill rig (Figure 6) that uses either a rotary or percussion drill bit to create a relatively small-diameter borehole (< 200 mm diameter). A rotary drill uses a rotating drill stem and drill bit (or a combination of rotation and percussion action) to create a borehole. There are several types of rotary drilling methods, including air-rotary, mud-rotary, and downhole hammer. Rotary drill rigs are powerful enough to drill deep holes (100 m depth) through bedrock in one day, depending on drilling conditions. Percussion drilling, also known as cable tool drilling, is one of the oldest known drilling methods and was developed in China over 4,000 years ago. Cable tool rigs make a borehole by using a cable to repeatedly raise and drop a heavy drill stem and bit into the ground. It is much slower than rotary drilling but is still widely used in some areas because the equipment is simple to operate and less expensive than rotary drilling equipment. This video shows how a drilled well is installed and discusses the main components of a well and water system.

Figure 4 - A drilled domestic well, showing the well casing, electrical line for a submersible pump, and well cap (photograph by John Drage).

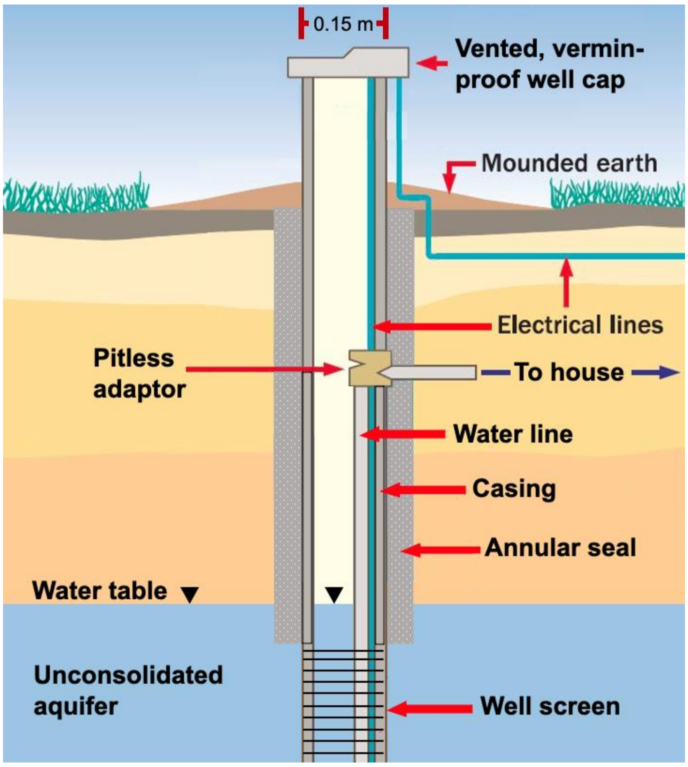

Figure 5 - Schematic diagram of a drilled well (modified from Simpson, 2016).

Figure 6 - Domestic drilled wells being installed using truck-mounted rotary drill rigs. Photograph a) by John Drage and photograph b) by Gavin Kennedy.

Domestic drilled wells are typically constructed by drilling a borehole with a diameter of 200 mm or less and lining the borehole with a 150 mm diameter casing. A casing diameter of 150 mm is large enough to allow a commonly used 100 mm diameter submersible pump to be installed through the casing. Depending on the drilling method, the casing is either installed as drilling proceeds or after drilling is completed. The open space between the casing and the geologic formation (i.e., well annulus) is usually sealed with bentonite or cement grout (or a mixture of the two) to prevent surface contaminants from entering the well and aquifer. A drilled well in unconsolidated sediments is cased for its entire depth and has a well screen or slotted casing throughout its length where groundwater is intended to enter the well.

A domestic well drilled in bedrock will normally only have casing in the top section of the well to keep unconsolidated sediments from collapsing and to provide a space for the grout or bentonite seal. Typically, the casing extends from the ground surface to the bedrock, although it may be extended deeper into the bedrock to provide additional protection from shallow groundwater contamination. If the bedrock is stable, the bedrock section of the well will stay open without casing and is often left as an open hole. If the bedrock has sections with loose, broken rock that may collapse into the well, these sections will be cased and screened.

Drilled wells have several advantages over other well types. Because of their greater depths, they are less vulnerable to shallow groundwater contaminants originating from human activities, and to declining groundwater levels during droughts. They can be installed in both unconsolidated aquifers and bedrock aquifers, and they can be used in settings with deep water tables or deep aquifers that are not accessible by shallow wells.

One of the main disadvantages of drilled wells is that they may access deeper, older groundwater that has had more time in the subsurface to dissolve naturally occurring materials that may produce higher concentrations of dissolved constituents, such as arsenic and fluoride.

3.2 Dug Wells

Dug wells (Figure 7 and Figure 8) have large diameters (typically 600 to 1500 mm) and are usually relatively shallow (3 to 10 m deep), extending only a few meters below the water table. They were historically the most common type of domestic well because they could be constructed by hand without the need for heavy equipment. Nowadays, they are less common than drilled wells in developed countries, but there are still many old dug wells in use and new ones continue to be installed in some areas.

Figure 7 - A domestic dug well (photograph by John Drage).

Dug wells are still widely used in developing countries where hand dug wells are promoted as practical, low-cost, low-technology domestic water supplies (Collins, 2000). In Sub-Saharan Africa it is estimated that 155 million people rely on dug wells and springs for their domestic water (Sutton and Butterworth, 2021).

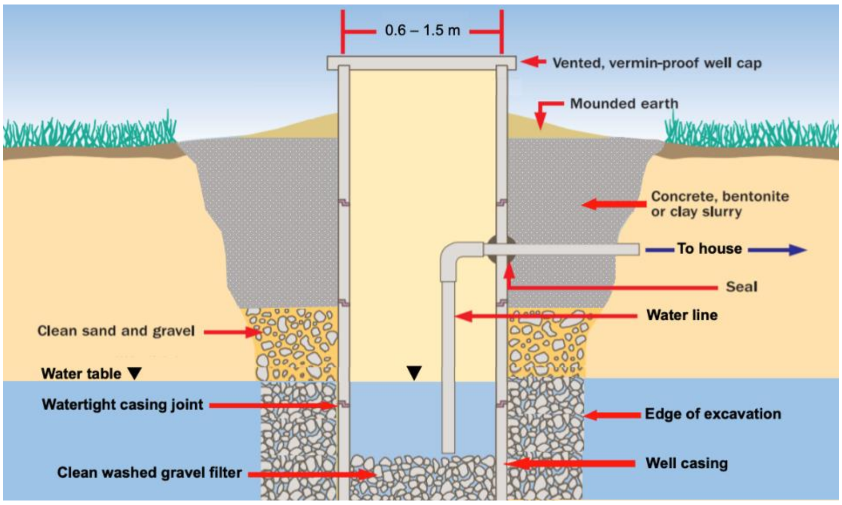

Figure 8 - Schematic diagram of a dug well (modified from Simpson, 2016).

Modern dug wells are usually installed using machines, such as excavators or backhoes (Figure 9), although in developing countries they are also still constructed by hand. Dug wells are constructed by excavating a large diameter hole in the ground and installing casing to keep the hole from collapsing. The casing is commonly made from large diameter concrete rings but may also be made of metal, plastic, or fiberglass. Older dug wells are typically lined with rocks or bricks. The backfill around the outside of the casing in a dug well usually includes clean gravel at the bottom of the hole to provide an additional water storage reservoir, followed by a low permeability seal (made of clay, bentonite, or concrete) in the upper portion of the hole to prevent surface contaminants from entering the well.

Figure 9 - A dug well installed with a machine excavator (photograph by Heather Cross).

Dug wells have the advantage that they can be installed at relatively low-cost without heavy equipment. Another advantage of dug wells is that their large diameter creates a significant amount of water storage. This allows dug wells to be installed in lower permeability unconsolidated aquifers because short-term peak water demands can be satisfied from well storage rather than aquifer yield. In such locales, a shallow drilled well would require a storage tank because the well's flow rate may be insufficient to meet short-term peak water demands.

The main disadvantages of dug wells are their vulnerability to drought and surface contaminants, and that they can only be installed in unconsolidated aquifers with shallow water tables. Dug wells usually extend a few meters or less below the water table, consequently, they have little available drawdown and can go dry when the water table declines during a drought. Drawdown is the difference between the static water level in a well and the water level when the well is pumped. Water level in a well declines in response to pumping. The decline is rapid at first and slows until, in most settings, it reaches a stable level for a given pumping rate. During the drought of 2016 in Nova Scotia, Canada, 93 percent of the wells that went dry were dug wells (Kennedy et al., 2017).

Dug wells draw water from shallow unconfined aquifers so they are vulnerable to shallow groundwater contaminants originating from human activities, such as road salt from de-icing operations, or nitrate from fertilizers and septic systems. Groundwater in dug wells often contains microbial contaminants because the short groundwater flow paths associated with these wells do not allow microbes to be removed by natural filtration within the aquifer. Dug wells are also prone to naturally occurring water quality problems that can occur in shallow groundwater, such as elevated concentrations of humic substances (decomposed plant matter within soil) or organic carbon.

3.3 Other Well Types

Other common domestic well types include bored, driven, and jetted wells. All of these methods are used to install relatively shallow wells (ranging from about 15 to 60 m deep) in unconsolidated (or weakly consolidated) aquifers.

- *Bored wells* are constructed by boring a hole in the ground with an auger and installing a casing. There are several types of augers that can be used, including large-diameter bucket augers (usually < 900 mm diameter), solid-stem augers (usually 350 to 600 mm diameter), and hollow-stem augers (usually 160 to 330 mm diameter). The auger can be hand operated for smaller diameter wells or machine operated for larger diameter wells and deeper boreholes (i.e., power augers or truck-mounted auger drill rigs). Bored wells are typically less than 45 m deep but can be deeper.
- *Driven wells* are constructed by using a downward force to drive a small diameter casing (typically 50 mm or less) into shallow sand and gravel aquifers. A well screen is placed at the bottom of the casing to allow water to enter the well. They are also commonly

referred to as well-points, sand-points, or driven-point wells. Driven wells may use downward force and jetting methods simultaneously to install the well. They can be driven by machine or by hand, using a weighted pipe (similar to how a metal fence post is driven into the ground). Driven wells are usually less than 15 m deep.

- *Jetted wells* use a high-velocity stream of water to create a hole in the ground. This method is most suitable for installing small diameter wells (50 to 100 mm diameter) in unconsolidated sand aquifers. The construction of jetted wells can involve installing a permanent casing and screen while the hole is jetted down. Alternatively, a temporary casing is jetted down that allows a permanent casing and screen to be installed before removing the temporary casing. The casing is either jetted, or simultaneously jetted and driven, into the ground. Jetted wells usually range in depth from about 6 to 60 m.

3.4 Components of a Domestic Well and Water System

Well Components

The main components of a domestic well are shown in Figure 10 and are described below. They include the well casing, well screen, a pitless adaptor (for cold climates), an annular seal, and a well cap. The primary purpose of these components is to allow the well to function properly and to prevent contaminants from entering the well. Not all components are found in all wells, and the materials and design of the components can vary depending on the well type, geologic conditions, local regulations, and local practices.

- *Casing* – a pipe used to keep the ground open and prevent sediment and shallow groundwater from entering the well. The pipe is usually made of steel or plastic. A drive shoe (a hardened section of pipe with a beveled edge) is attached to the base of the casing to act as a cutting edge and protect the casing while it is driven into the ground. In modern dug wells, the casing is often made from several concrete rings joined together, while older dug wells may be lined with rocks or bricks instead of casing.

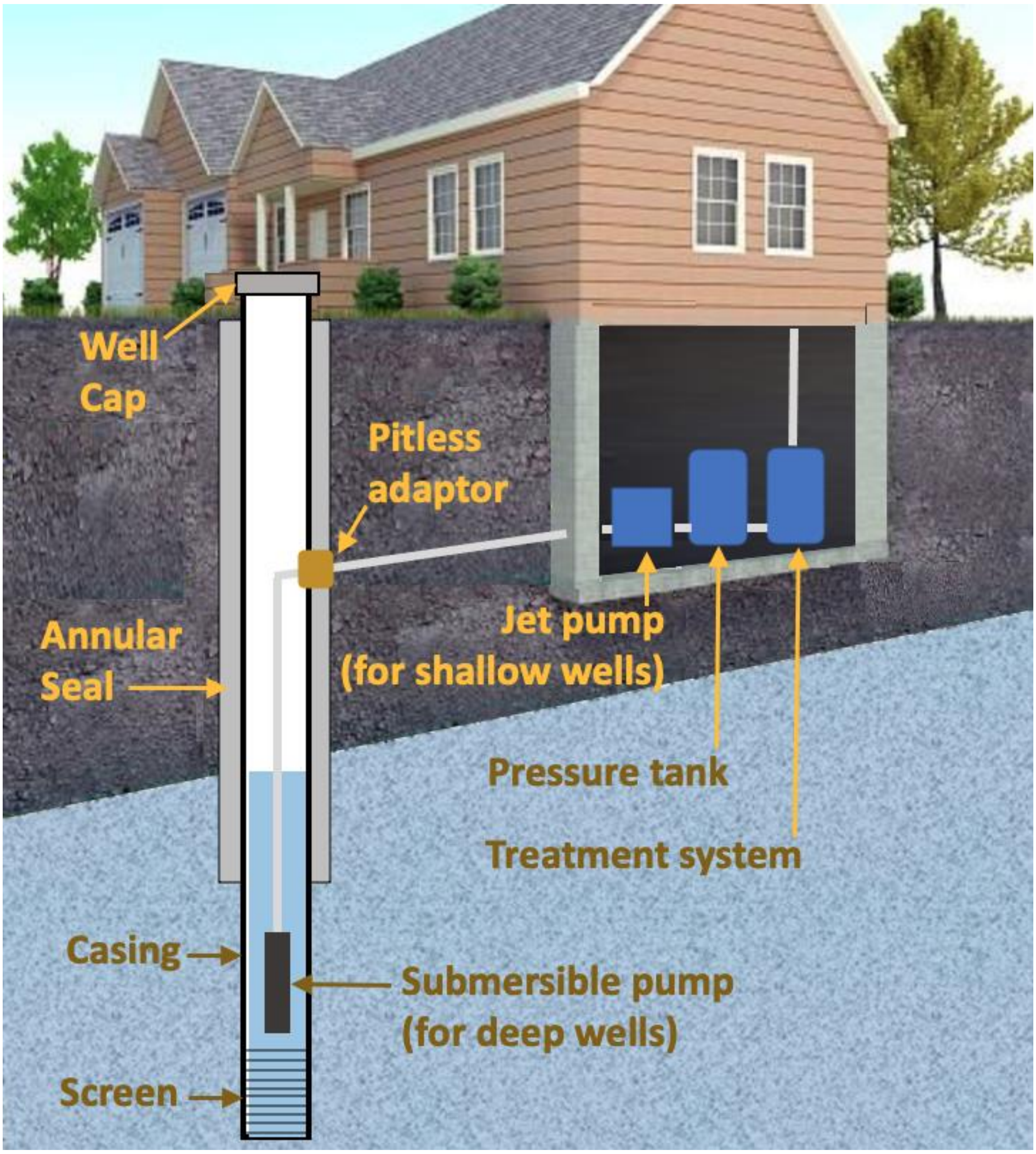

Figure 10 - The main components of a domestic well and water system. Two possible types of pumps are shown here: a submersible pump inside the well for deep wells and a jet pump in the home for shallow wells. Only one of these pumps is needed to operate the water system (modified from USEPA, 2019).

- *Screen* – a section of pipe at the bottom of the casing with openings that allow water to enter the well, while keeping aquifer material (sediment or broken rock) from entering the well. Common screen types include continuous slot (also called wire wrap screens) and slotted or perforated pipe with various opening designs. A screen is not usually used in domestic drilled bedrock wells unless the bedrock is unstable. Dug wells do not have screens because the water enters through the walls of the well (if the casing or lining is not sealed), and the bottom of the well, which is often filled with a layer of clean gravel. This video shows an example of what a well screen looks like and how it is installed in a water well.

- *Pitless adaptor* – an adaptor commonly used in cold regions to provide a frost-free, water line connection while allowing convenient access to the well. It is located below the frost line and allows the water pipe inside the well to pass through the casing and connect to the household water system. Pitless adaptors are designed to provide a watertight seal through the casing to prevent shallow, potentially contaminated groundwater, from entering the well. Historically, well pits were used instead of pitless adaptors to prevent water line connections from freezing. Well pits were constructed over the top of the well, with a typical depth of 2 to 3 m, and may have housed the pump and pressure tank. Well pits are no longer permitted in many jurisdictions because they are vulnerable to flooding which can allow surface water and contaminants to enter the well. However, they may still be in use in older wells.
- *Annular seal* – a seal placed in the annular (ring-shaped when viewed from above) space between the casing and the sides of the borehole to prevent contaminants, surface water, and shallow groundwater from entering the well. The seal is made with grout, which is a low permeability material (such as bentonite, cement, or a bentonite-cement mixture). It is usually installed along the entire length of the casing by pumping a grout slurry through a small diameter pipe (tremie pipe) from the bottom of the casing up to ground surface. Not all jurisdictions require annular seals, and some require only a portion of the casing to be sealed, rather than its entire length. In those cases, the drill cuttings are relied on to seal the annular space.
- *Well cap* – a cap on the top of the well casing that provides access for well maintenance and prevents debris, animals, and insects from entering the well. The cap usually includes a screened vent to allow the passive removal of naturally occurring gases and equalize the pressure inside the well with the outdoor atmospheric pressure. This prevents a vacuum from developing inside the well during pumping.

Water System Components

The main components of a domestic water supply system are shown in Figure 10 and are described below. They include a pump, a pressure tank, and if needed, a water treatment system. An example of a domestic water system is shown in the photograph in Figure 11. In this example, the water system uses a jet pump to draw groundwater from a dug well with a shallow water table and an ultraviolet light for treating microbial contaminants.

Figure 11 - An example of a domestic water system used to provide water from a dug well (photograph by John Drage).

- *Pump* – a pump draws groundwater from the well and delivers it to the house via a water supply line that runs from the well to the house. The two most popular types of pumps for domestic wells are submersible pumps and jet pumps. In deep drilled wells, the most common type of pump is a submersible pump which is placed inside the well and connected to a power source in the house via a power cable. In shallow wells, the most common type of pump is a jet pump which is located above ground, usually inside the house in colder climates. Jet pumps use suction to draw water from the well and, therefore, can only draw water from depths of less than about eight meters. However, deep well jet pumps are available that use two water lines to draw water from greater depths (up to about 30 m depth). Regardless of the pump type, a check valve (foot valve) is usually placed in the water supply line in the well to prevent the water from running back into the well when the pump shuts off. Note that submersible and jet pumps can both be used in deep and shallow wells, although as discussed above, jet pumps are limited to shallow water levels. The choice of pump type will depend on the site conditions and the well owner's preferences (e.g., cost, installation and maintenance requirements, noise tolerance for pumps located inside the house).

- *Pressure tank* – a tank used to store water and provide water pressure to the household. The tank provides water storage that allows some water to be used without the need to turn on the pump. This keeps the pump from running every time water is used and extends the life of the pump. The larger the tank, the larger the volume of water that can be drawn without turning the pump on. Most modern pressure tanks contain a bladder which is filled with air to help regulate the water pressure. For low-yield wells that cannot meet a household's peak water demands from well yield and well storage, the water system may include an additional storage tank that can provide more water than the pressure tank.
- *Water treatment system* – a device used to improve water quality. Treatment units can be "point-of-entry", which are placed immediately after the pressure tank and provide treated water to the entire house. Alternatively, they can be "point-of-use" devices, which are placed at the tap where the treated water is needed. Point-of-use treatment units are normally used to provide potable water for drinking and cooking and are commonly installed at the kitchen tap. This approach provides a cost-effective way to provide potable water and avoids treating water that is to be used for non-potable needs, such as washing and toilet flushing. There is a wide range of possible contaminants that may need to be treated in domestic well water, including contaminants that can cause aesthetic problems (e.g., hardness, iron) and contaminants that cause health problems (e.g., microbial contaminants, arsenic, fluoride, lead, uranium). The most common types of treatment systems include water softeners to treat hardness (and low levels of iron and manganese), adsorptive media and reverse osmosis units to remove trace constituents (e.g., arsenic, fluoride, lead, uranium), and filtration combined with ultraviolet lights to treat microbial contaminants (e.g., bacteria, protozoa, viruses).

4 Water Quantity for Domestic Needs

How much water must a domestic well provide to meet the needs of a household? Estimates vary greatly, ranging from about 70 to 300 L/day per person, depending on the type of fixtures in a house, personal habits and expectations, socio-economic conditions, and cultural factors. The lower estimate of 70 L/day per person is associated with domestic water needs during emergency situations, such as a camp for displaced persons during a natural disaster, of which 30 L/day is for drinking water and cooking (Figure 12). The upper limit represents typical water use in North America, where households use more water per capita than most other countries. In the United States, the average domestic water use is approximately 300 L/day per person (Dieter and Maupin, 2017). In Canada, the average domestic water use is approximately 215 L/day per person (Statistics Canada, 2019). The average domestic water use in European counties is 130 L/day per person (EurEau, 2017), which is about half the amount used in North America.

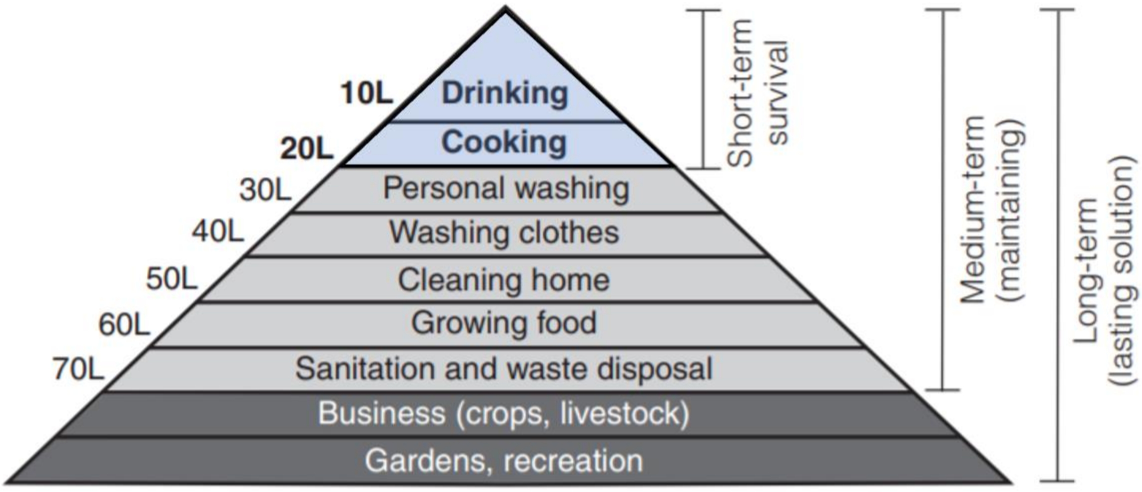

Figure 12 - Domestic water needs during emergencies (modified from WHO, 2011).

Most of the water needed for domestic purposes is for non-potable uses, such as washing and toilet flushing. A typical breakdown of domestic water use is 10 percent for cooking and drinking, 25 percent for laundry and cleaning, 30 percent for toilet flushing, and 35 percent for bathing (Environment Canada, 2011). The amount of water needed for non-potable purposes has been declining as newer water fixtures are made to use less water (e.g., water-efficient toilets, shower heads, clothes washers). This has caused per capita domestic water use to decline in recent decades. For example, in Canada, the average per capita domestic water use declined by 24 percent between 2005 and 2013 (Statistics Canada, 2017b), and in the United States it declined by 7 percent between 2010 and 2015 (Dieter and Maupin, 2017).

Water use in a household may be concentrated into a period of one or two hours. Therefore, a domestic well must be able to meet both the long-term average daily needs of a household and the short-term peak demands. The well yield must be able to meet the long-term daily household needs, but the short-term peak demands can be provided by a combination of the well yield and water storage, either from water stored in the well or from a storage tank incorporated into the home's water system. The amount of water available from well storage can be calculated from the well depth, well diameter, the pump intake setting, and the static water level. Box 1↴ provides examples of how this calculation is done to determine if a domestic well can provide an adequate water supply.

5 Water Quality of Domestic Wells

5.1 Overview

A complete view of domestic well water quality is not available because most well owners do not test their wells regularly and reporting test results is voluntary in most jurisdictions. Furthermore, when domestic well owners test their water, they often analyze only for bacteria or a limited suite of parameters (such as bacteria, nitrate, and arsenic), rather than a comprehensive group of pathogens and chemicals that may be present in well water. Although water quality information for domestic wells is limited compared to public wells, regional and local surveys have been completed that provide some insight. The results from these surveys tell us that a high proportion of domestic wells do not meet drinking water quality guidelines.

Domestic well water quality data from a selection of surveys are provided in Table 2. The data indicate that it is common for more than 40 percent of domestic wells to exceed one or more health-based water quality guideline.

Table 2 - Domestic well water quality results from selected surveys.

Location	Year	Survey Type	Number of Wells Tested	Parameter[1,2]	Percentage of Wells Above Guideline[3]	Reference
Ohio, USA	2009	Agricultural Area	180	Bacteria	45%	Won et al., 2013
Nova Scotia, Canada	1989	Agricultural Area	200	Nitrate Bacteria	13% 9%	Moerman and Briggins, 1994
Ontario, Canada	1991-1992	Agricultural Area	1,300	Nitrate Bacteria Total exceedances	14% 34% 40%	Goss et al., 1998
Wisconsin, USA	2007-2010	Regional	4,000	Nitrate Bacteria Total exceedances	10% 18% 47%	Knobeloch et al., 2013
Pennsylvania, USA	2006-2007	Regional	700	Nitrate Bacteria Total exceedances	2% 33% 41%	Swistock et al., 2013
North Carolina, USA	2011-2015	Regional	16,200	Bacteria (n=9,400) Manganese Arsenic	34% 33% 2%	Lee Pow Jackson and Zarate-Bermudez, 2019
Virginia, USA	2012-2013	Regional	2,100	Lead	20%	Pieper et al., 2015
Virginia, USA	2012	Regional	800	Bacteria	42%	Smith et al., 2014
New Jersey, USA	2002-2007	Regional	51,000	Nitrate Bacteria Arsenic (n=17,700) Lead Manganese	2.7% 13% 3.4% 18% 19%	NJDEP, 2008
Nova Scotia, Canada	1991-1999	Regional	10,500	Arsenic	17%	Dummer et al., 2015
USA	1991-2004	National	2,100	Nitrate Bacteria Fluoride	4% 34% 4%	DeSimone et al., 2009
USA	1970-2013	National	20,500	Arsenic	11%	Ayotte et al., 2017
Bangladesh	2009	National	14,400	Arsenic	32%	Flanagan et al., 2012
India	2005-2014	National	12,600	Fluoride	14%	Podgorski et al., 2018

1. Bacteria = Total Coliform Bacteria.
2. Total exceedances = Total percentage of wells that exceeded at least one health-based water quality guideline. This may include other parameters tested but not shown in this table.
3. Water quality guidelines vary between jurisdictions and are periodically revised. The guidelines presented here are the ones used by each of the referenced surveys. The guidelines used to determine exceedances in these surveys were as follows: Arsenic = 10 µg/L; Bacteria = 10/100 mL (Canadian surveys) and zero detections (USA surveys); Lead = 15 µg/L (Virginia) and 5 µg/L (New Jersey); Manganese = 300 µg/L (North Carolina) and 50 µg/L (New Jersey); Nitrate = 10 mg/L (Nitrate-N); Fluoride = 1.5 mg/L (India surveys) and 2 mg/L (USA surveys).

The high exceedance rates of health-based water quality guidelines in domestic wells and the reliance on domestic wells by hundreds of millions of people worldwide indicate that these wells can have a significant impact on public health. It is important to note, however, that not all domestic wells are used as drinking water supplies because some well owners use bottled water or another source for drinking water and rely on their water well for all other water needs. Therefore, the presence of contaminants in a well does not necessarily mean the well owner is exposed to these contaminants via drinking water (although other exposure routes such as dermal contact and inhalation may be possible depending on the type of contaminant present). For example, census data from Australia indicate that 5.6 percent of the population rely on domestic wells for their water supply but only 0.5 percent of the population use domestic wells for their drinking water (Australian Bureau of Statistics, 2013).

In terms of global health impacts, the most significant contaminants in domestic wells are microbial contaminants, arsenic, and fluoride. These three contaminants have been identified as the highest priority for global monitoring in drinking water (WHO and UNICEF, 2017). Microbial contaminants are a concern in all areas of the world, whereas arsenic and fluoride problems are greater in some areas because of the local geology.

Other contaminants and water quality problems commonly found in domestic wells include those that can cause health problems (e.g., lead, manganese, nitrate, and radionuclides such as uranium, radium, and radon), and those that cause aesthetic concerns (e.g., iron, chloride, hardness, sulphate, odor, color, turbidity). Some common water quality parameters have other adverse effects. For example, turbidity can interfere with treatment systems used for disinfection, which is why filtration is recommended upstream of disinfection systems. Although pH itself is usually not a health concern, groundwater with low pH can cause corrosion of pipes and plumbing fixtures, which can release lead and copper to the water.

Contaminants found in domestic wells can be naturally occurring or anthropogenic. Naturally occurring water quality problems are usually associated with geologic sources, including soils, sediments, and bedrock. Examples of contaminants that are primarily associated with geologic sources include arsenic, fluoride, hardness, iron, manganese, sulphate, and radionuclides (e.g., uranium, radium, radon). The degree and extent of these naturally occurring contaminants in groundwater varies from area to area because their occurrence is controlled by the local geology, groundwater flow path, and groundwater resident time. The most commonly detected anthropogenic contaminants in domestic wells are those associated with septic systems (e.g., microbial contaminants, nitrate, salt), commercial/industrial activities (e.g., chlorinated solvents, petroleum hydrocarbons) and agricultural activity (e.g., microbial contaminants, nitrate, pesticides).

Some contaminants originate from both natural and anthropogenic sources. For example, salt can come from geologic formations that contain salt or from sea spray near the coastline. Salt can also come from road de-icing or dust control operations, from seawater intrusion caused by over-pumping in coastal aquifers, and from the discharge of water softener treatment systems. Another example is microbial contaminants, which can come from natural wildlife activity or from human sources and activities, such as septic systems, domestic pets, and manure spreading.

5.2 Contaminants in Domestic Wells

Descriptions of the most common contaminants found in domestic wells that can affect human health are provided below. Further information about groundwater quality and human health can be found in other Groundwater Project books.

Microbial Contaminants

Microbial contaminants are among the most common type of contaminants found in domestic wells. This group of contaminants includes several types of pathogens, such as bacteria, viruses, and protozoa (including *Giardia* and *Cryptosporidium*). Pathogenic microorganisms can cause gastrointestinal illnesses and usually occur in groundwater supplies that have been contaminated by human or animal waste. Because it is difficult and expensive to test for many of these microorganisms, domestic wells are usually tested for indicator organisms such as total coliform bacteria and *Escherichia coli* (*E. coli*). The detection of an indicator organism, which are themselves not necessarily harmful to human health, suggests that microbial pathogens may be present in the well or that the well is vulnerable to contamination by pathogens.

Microbial contaminants in drinking water have been estimated to cause over a billion cases of gastrointestinal illnesses per year worldwide (Johnston et al., 2001). Although these cases are more often related to surface water sources, several studies have looked at the health impacts of these contaminants in domestic wells. In Canada, it has been estimated that there are 78,000 cases of illness each year due to the consumption of untreated drinking water from domestic wells containing microbial contaminants (Murphy et al., 2016). The microbial contaminants included in this estimate were *Giardia*, *Cryptosporidium*, *Campylobacter*, *E. coli* O157, and *norovirus*. *Norovirus* was estimated to account for about 71 percent of these illnesses (55,000 cases). In the United States, a North Carolina study found that between 2007 and 2013, 99 percent of emergency department visits (29,200 cases) for acute gastrointestinal illness caused by microbial contaminants in drinking water were associated with domestic wells (DeFelice et al., 2016). The estimated cost of the emergency room visits associated with domestic wells in the North Carolina study was 40 million US dollars.

Arsenic

Arsenic is considered to be the second most important contaminant in drinking water after microbial contaminants. It has been estimated that worldwide more than 140 million people drink groundwater with high levels of arsenic (VanDerwerker et al., 2018). In the United States, arsenic is estimated to affect more than two million domestic wells (Ayotte et al., 2017). Long-term exposure to arsenic in drinking water has been linked to many types of cancer (bladder, kidney, lung, skin) and non-cancer health effects (skin lesions, cardiovascular disease, diabetes, neurological effects). The World Health Organization has estimated that arsenic in groundwater at concentrations above 500 μg/L causes death in one in ten adults (van Halem et al., 2009). In Araihazar, Bangladesh, where drinking water is sourced from 6,000 individual wells, it was estimated that 21 percent of all deaths were attributed to arsenic above 10 μg/L in well water (Argos et al., 2010). It has also been estimated that at least 100,000 cases of skin lesions in Bangladesh have been caused by arsenic in well water (Smith et al., 2000).

As shown in Table 2, regional surveys indicate that it is common for domestic wells to exceed water quality guidelines for arsenic. Prior to the 1980s, arsenic was not commonly tested for in drinking water, which caused it to go undetected. As discussed in Box 2↴, in some cases it has been the observed health effects that first led to the discovery of widespread arsenic and other contaminants in well water.

Fluoride

Fluoride is considered beneficial to dental health at low concentrations, but at high concentrations (> 1.5 mg/L) in drinking water it can be harmful to teeth and bones. At very high concentrations (> 10 mg/L) skeletal fluorosis can be crippling (WHO, 2004). It has been estimated that 200 million people from 29 countries around the world are exposed to high levels of fluoride in groundwater (Samal et al., 2015). In India, dental surveys in schools have indicated that 62 million people have dental fluorosis caused by high fluoride levels in drinking water (Podgorski et al., 2018). National surveys of domestic water wells in India (Table 2) indicate that 14 percent of wells exceed the WHO fluoride drinking water guideline of 1.5 mg/L (WHO, 2004). A study in central Malawi sampled 39 domestic groundwater supplies and looked at the results of a survey of 6,804 households for indicators of dental fluorosis. The study found that 44 percent of the wells exceeded the drinking water guideline of 1.5 mg/L and 28 percent of the households had someone in the house with evidence of dental fluorosis (Addison et al., 2020).

Nitrate

Nitrate in drinking water is associated with several health effects, including methemoglobinemia (or "blue baby syndrome") in infants, thyroid effects, and cancer. Nitrate occurs naturally, but concentrations above about 1 mg/L are usually associated with human activities (DeSimone et al., 2009). The most common sources of nitrate include agricultural activities (e.g., fertilizer and manure application) and wastewater disposal (e.g., septic systems). As shown in Table 2, nitrate is commonly found in more than 10 percent of domestic wells in agricultural areas. Nitrate is also commonly found in domestic wells in urban areas, often related to wastewater disposal. A national survey in the USA found that 7.1 percent of domestic wells in areas dominated by agriculture exceeded nitrate drinking water guidelines, compared to 3.1 percent of domestic wells in urban areas (DeSimone et al., 2009). Because nitrate is associated with some of the main sources of groundwater contamination, its presence in water wells is often used as an indicator of aquifer vulnerability and an indicator that other contaminants could be present.

The cost to mitigate nitrate in groundwater can be high. For example, in Wisconsin, USA, nitrate is reported to be the most widespread groundwater contaminant with an estimated 10 percent of domestic wells (i.e., 42,000 wells) exceeding the nitrate drinking water guideline. The cost to replace these wells with deeper wells that access groundwater with low nitrate levels is estimated to be 440 million US dollars (Wisconsin Groundwater Coordinating Council, 2020).

Manganese

Manganese commonly occurs in domestic well water and has been associated with health problems. For example, a study in North Carolina, USA, looked at water quality results from 73,000 domestic wells and the health outcomes of 17,000 children (Langley et al., 2015). The study found an association between the manganese concentration in domestic well water and adverse neurodevelopment and hearing loss in children. Approximately 8 percent of the wells exceeded the North Carolina health advisory level for manganese (200 μg/L).

Lead

Lead is another contaminant commonly found in domestic wells that causes adverse health effects. Lead is a neurotoxin that affects the neurological development and behavior of children and causes high blood pressure and kidney problems in adults. The regional survey results shown in Table 2 reveal that as many as 20 percent of domestic wells have lead levels above water quality guidelines. The presence of lead in domestic wells is usually caused by the corrosion of pipes and plumbing fixtures in the home's water system. Most regulated public water supplies are required to have corrosion control programs to prevent high lead levels, however, domestic well owners rarely treat their water for corrosion control. A study in North Carolina, USA, looked at blood-lead levels in 59,000 children, 7,700 of which used drinking water from domestic wells (Gibson et al., 2020). The study found that children in homes with domestic wells were 25 percent more likely to have increased blood-lead levels compared to children in homes served by a regulated public water supply.

Pesticides and Volatile Organic Compounds

Pesticides are often detected in domestic farm wells, but they are not commonly found at concentrations that exceed drinking water quality guidelines. The two surveys in Table 2 from Nova Scotia and Ontario, Canada, reported that 41 percent and 11 percent of the wells tested had detectable levels of pesticides, respectively. None of the wells in the Nova Scotia survey had pesticide concentrations above drinking water guidelines and 0.5 percent of the wells in the Ontario survey exceeded guidelines. A survey done in agricultural areas of Wisconsin, USA tested 105 domestic wells and found 88 percent had detectable levels of pesticides, although none were found at levels that exceeded enforcement standards (Wisconsin Department of Agriculture, 2019). It is important to note that many pesticides do not have established drinking water guidelines, which makes it difficult to judge the significance of their detection in water wells. For example, no guidelines were available for about half of the 28 pesticides detected in the Wisconsin survey.

Volatile Organic Compounds (VOCs) are common components and additives in many commercial, industrial, and household products. They can be found in petroleum products (such as gasoline, and diesel fuel), carpets, paints, varnishes, glues, spot removers, cleaners, and fumigants. Surveys have detected VOCs in domestic wells, but they are not often found at concentrations above drinking water guidelines. A national survey in the United States tested for 55 VOCs in 2,400 domestic wells and found that 14 percent of the wells had detectable levels of VOCs (i.e., greater than 0.2 ug/L) and less than 2 percent of the wells had levels of VOCs that exceeded drinking water guidelines (Zogorski et al., 2006). The most common VOCs that exceeded guidelines in the survey were the fumigant Dibromochloropropane and the solvents Perchloroethene and Trichloroethene.

Emerging Contaminants

Emerging contaminants are another group of contaminants of concern for domestic wells. These are contaminants whose risk to human health and occurrence and distribution in groundwater are not yet fully understood. They may come from industrial, agricultural, and sewage sources including septic systems. Examples include pharmaceuticals, personal-care products, and per- and polyfluoroalkyl substances (PFAS). PFAS are used for many purposes, such as non-stick coatings for cookware and firefighting foam. They are highly resistant to degradation in the environment, difficult to treat, and have been associated with health problems such as kidney and testicular cancer, bowel disease, high cholesterol, and thyroid disruption (Lee and Murphy, 2020). PFAS monitoring to date has focused on public water supplies and, therefore, less is known about their occurrence in domestic wells. However, PFAS have been detected in domestic wells in Ohio and West Virginia, USA near a manufacturing facility; and in domestic wells in Alabama, USA near agricultural fields where wastewater treatment plant biosolids were applied (Lee and Murphy, 2020). Domestic wells may be more vulnerable to emerging contaminants like

PFAS than public water supplies because domestic well owners are less likely to test their wells for these contaminants.

6 Domestic Well Vulnerabilities

There are several reasons why domestic wells are more vulnerable to water quality and quantity problems than public water wells. It is important to understand these vulnerabilities so that appropriate solutions can be found to improve the safety and reliability of domestic wells.

6.1 Lack of Water Quality Monitoring

One of the most difficult problems associated with domestic wells is ensuring they have safe water quality. This is mainly because domestic well water quality is unregulated and it is the well owner's responsibility to ensure their water is safe to drink. Most jurisdictions recommend that well owners carry out regular well maintenance and testing for chemical and microbial contaminants. The recommended frequency of testing and the parameters to be tested vary, but many jurisdictions recommend that well owners test their well water either yearly or every two years (Colley et al., 2019). Adherence to these recommendations is voluntary, however, and well owners often rely on their own senses (taste, smell, appearance, personal illness) to determine if their water quality is satisfactory. Unfortunately, most groundwater contaminants with adverse health effects have no taste, odor, or visual indicators, so they are invisible to well owners who do not test their water. As indicated by the theme for World Water Day 2022 "Groundwater: making the invisible visible", there are significant challenges to managing an invisible resource like groundwater and this is doubly true for the water quality of domestic wells, which is an invisible problem within an invisible resource.

Domestic water quality testing rates are low. Typically, less than about one third of North American well owners test their well water quality in accordance with government recommendations and less than half have tested their well within the last 10 years (Colley et al., 2019). A well owner's decision to test their well water quality can involve numerous considerations and is influenced by the well owner's income and education level. Colley and others (2019) present a health-belief model that suggests well owners are more likely to test their wells if they believe they are susceptible to a threat, if the threat is sufficiently serious, if testing has clear benefits, if the barriers and costs of testing are not too high, and if an event triggers them to take action (e.g., a noticeable change in well water aesthetics, a real-estate transaction, or learning about contaminated wells in their neighborhood).

There are multiple and complex reasons why a well owner may not test their well water quality (Chappells et al., 2015; Colley et al., 2019; Munene and Hall, 2019). When domestic well owners are asked about their water quality sampling habits, some of the most common reasons for not testing include:

- lack of concern;
- the inconvenience of testing; and
- the cost of testing (Figure 13).

All of these potential barriers must be considered in order to make significant improvements to domestic well testing rates and there is no single approach for motivating all well owners (Morris et al., 2016). The lack of regular water quality monitoring makes domestic wells vulnerable to undetected contaminants, and as a result, domestic well owners may unknowingly be exposed to contaminants for long periods of time.

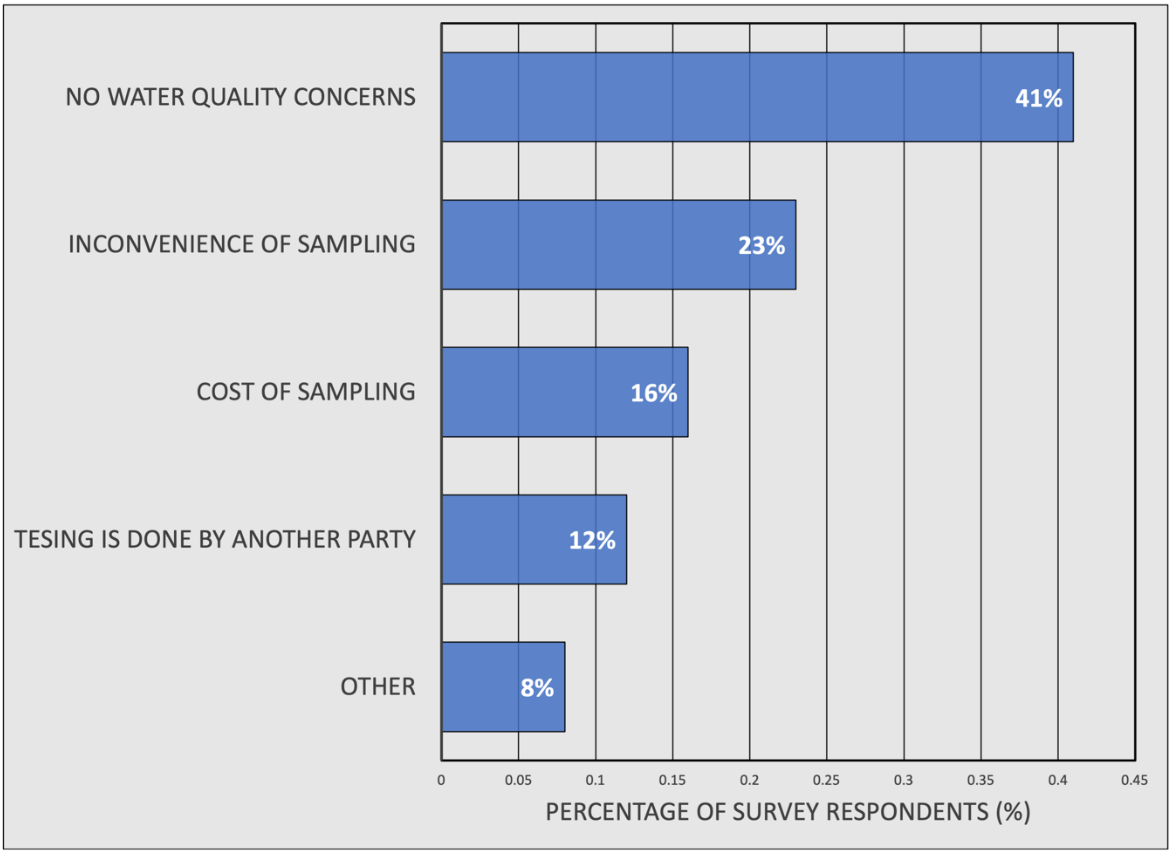

Figure 13 - Reasons given by domestic well owners for not testing their well water. From a survey of 420 well owners in Nova Scotia, Canada (modified from Chappells et al., 2015).

6.2 Water Treatment Challenges

Selecting a water treatment system can be a complex decision requiring knowledge of water chemistry and treatment methods. There is no single treatment technology that treats all contaminants. Treatment systems must be chosen based on the unique water chemistry of each well and must consider which contaminants must be reduced to meet water quality targets, as well as pre-treatment requirements for the selected technology to work properly.

Many domestic well owners do not have the knowledge needed to choose and install their own treatment systems and, therefore, they often rely on well owner educational websites and water treatment companies for help. The water treatment industry is not regulated in most jurisdictions, although there are professional associations that offer voluntary certification to promote high professional standards within the industry. The lack of regulation of the water treatment industry leaves well owners potentially vulnerable to poor advice. A study in Pennsylvania, USA, found that 10 percent of well owners had been sold treatment equipment they did not need, and other surveys have reported that obtaining impartial advice on water treatment equipment is a common problem (Chappells et al., 2014).

Once an appropriate water treatment system is selected and installed, it requires regular monitoring and maintenance to ensure the treatment is effective and the water is safe to drink (Figure 14). As discussed previously, most well owners do not monitor their water quality regularly and, therefore, they are vulnerable to contaminant exposure if their treatment system fails. Surveys of household arsenic treatment systems show that it is common for treatment systems to fail. One study that tested raw and treated water in domestic wells in several states in the United States reported that approximately 23 percent of arsenic treatment systems were not in compliance with arsenic drinking water guidelines (Zheng, 2017).

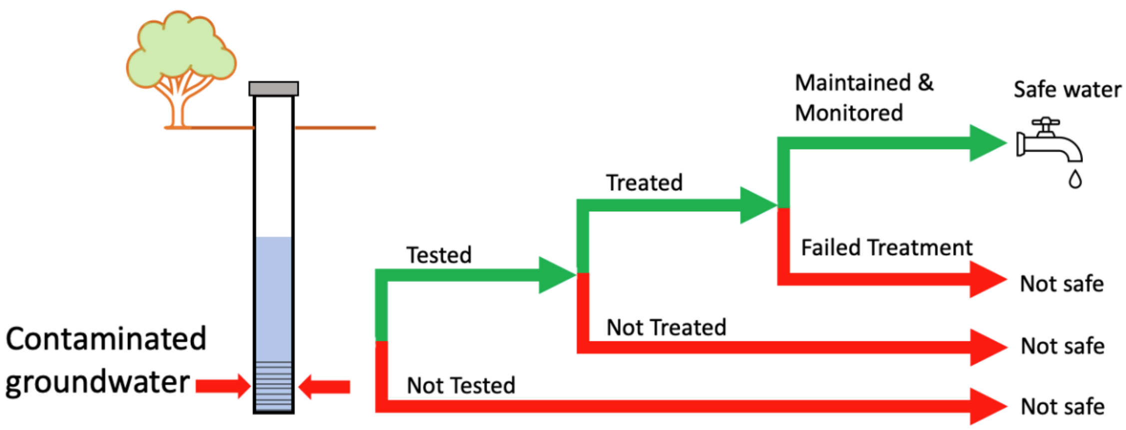

Figure 14 - Steps needed to ensure that well water is safe to drink, including initial testing to identify contamination, installation of an appropriate treatment system, followed by maintenance and monitoring of the treatment system (modified from Zheng and Flanagan, 2017).

As an example of the challenges of selecting and maintaining a water treatment system, consider an ultraviolet light, which is one of the most commonly used methods for treating microbial contaminants in domestic well water. These systems are simple to operate because they use an ultraviolet light to deactivate microbial contaminants as they flow past the light. In the selection of an ultraviolet treatment system, however, the well owner must consider the intensity of the ultraviolet light (different intensities are needed for different concentrations and types of pathogens), the water flow rate (which controls the water's contact time with the light and thus its effectiveness), and the pre-treatment requirements to remove turbidity, color (which reduce light penetration), and dissolved solids (which may precipitate on the light's protective glass sleeve and reduce light intensity). Pre-treatment methods include sediment filters to remove turbidity, and water softeners to remove hardness, iron, and manganese. Once an ultraviolet system is installed, it must be maintained by replacing the light bulb annually and regularly cleaning the protective glass sleeve that houses the ultraviolet light bulb. If well owners are unlikely to carry out regular water quality monitoring, they may also be unlikely to carry out regular treatment system maintenance.

An ultraviolet system for treating microbial contaminants is a relatively simple system compared to others, such as an arsenic treatment system. For arsenic in domestic well water, there are multiple treatment technologies to choose from (e.g., reverse osmosis, adsorption media, anion exchange) and not all technologies are effective for all types of arsenic. Dissolved arsenic can be present as Arsenic (III) and Arsenic (V), depending on redox conditions, which can change over time (e.g., due to seasonal variations) and/or with pumping. Well owners will typically not know which type of arsenic is present in their well water because arsenic speciation is not included in a standard domestic well water quality analysis. One of the most common household treatment methods for arsenic is reverse osmosis and this method is known to be poor at removing Arsenic (III). To compensate for this, a pre-treatment unit can be added that oxidizes Arsenic (III) to Arsenic (V), which is more effectively removed by reverse osmosis. Given the complexities of water treatment, it is understandable that many homeowners rely on a water treatment company to choose and install a treatment system. This may result in the well owner not understanding what type of treatment system they have or even what it is designed to treat. One study that surveyed 99 owners of domestic wells in Maine, USA, found that 26 percent had mistakenly thought their sediment filter or water softener was for arsenic treatment (Zheng, 2017).

6.3 Vulnerability to Contamination

Domestic wells can be vulnerable to contamination because they are often located close contaminant sources, and they often draw water from shallow, unconfined aquifers that are susceptible to contamination from human activities on the land surface. Many domestic well owners do not maintain their well or check the condition of their well regularly. The lack of well maintenance can result in unsanitary conditions and poor water quality, as shown in the examples in Figure 15.

Figure 15 - Examples of unsanitary conditions at domestic wellheads; a) cobwebs inside a well indicating insect activity; b) dead rodents floating in a well; c) dug well with abundant roots protruding though the brick-lined walls; and, d) flooded well pit and missing well cap allowing surface water to enter the well (photographs by Stew Hamilton).

Contaminant Sources Near Domestic Wells

Domestic wells are often located close to contaminant sources, such as a septic system, a heating oil tank (Figure 16), a farmyard, or a road where salt is applied for de-icing during the winter. Household pets are another potential source of contamination, from either pet feces near the well or the burial of deceased pets on the property. The population of cats and dogs in Canada in 2020 was estimated to be about 16 million (CAHI, 2021), equal to about 42 percent of the human population. The proximity of these multiple types of contaminant sources to domestic wells makes the wells vulnerable to contamination. Unlike many municipal wellfields, domestic wells do not have wellhead and wellfield protection plans in place to manage the risks that these contaminants pose.

Figure 16 - Two domestic wells located near a home heating oil tank. This example shows how domestic wells can be subject to multiple vulnerabilities, including droughts and contaminant sources. The dug well (left foreground) has been replaced with a deep drilled well (right, with a blue well cap) because seasonal droughts frequently caused this shallow dug well to go dry. Both wells are located close to a heating oil tank (grey tank beside house), which could contaminate the wells if an oil leak or spill occurred (photograph by John Drage).

In rural areas there is often no central public water supply or central wastewater system available and, therefore, a homeowner will have both a domestic well and a septic system located on their property (Figure 17). Although most well construction regulations specify a minimum separation distance between wells and septic systems (typically ranging from 15 to 30 m), they are usually located relatively close to each other because they must both be located on the homeowner's property and close to the house. In subdivisions, there can be multiple septic systems present and, therefore, even if a well owner installs their well upgradient from their own septic system, it may be down-gradient of their neighbor's septic system.

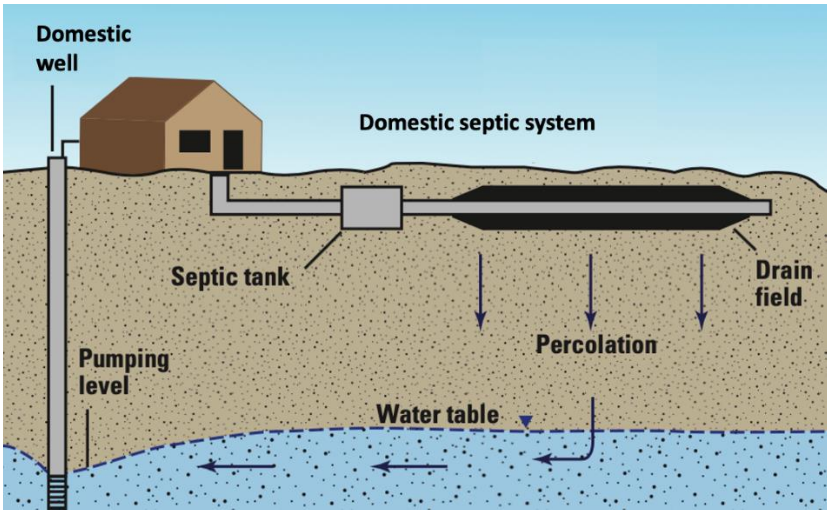

Figure 17 - A household with a domestic well and septic system, showing the potential for septic system effluent to flow towards the well (modified from Waller, 1994).

A properly functioning septic system can reduce contaminant concentrations so they do not adversely impact water wells, provided that both the septic system and well are properly located, designed, constructed, and maintained. Nonetheless, rapid contaminant transport can occur in certain conditions. A study that examined 248 disease outbreaks (23,000 illness cases) associated with untreated groundwater, including public groundwater systems and domestic wells, found that human sewage was the most common source of contamination (Wallender et al., 2014). The study also concluded that for the majority of cases (67 percent) where the contributing factors were known, the contamination was facilitated by improper design, maintenance, or location of septic systems or water wells. Further information about septic system impacts on groundwater quality can be found in another book in the Groundwater Project series (Robertson, 2021)↗.

In addition to the common sources of contaminants located on a homeowner's own property, domestic wells are sometimes located close to commercial, industrial, or agricultural contaminant sources. For example, gas stations, dry cleaners, landfills, and crop fertilizing activities are known to have caused domestic well contamination. Box 3↴ discusses an example of a domestic well that has been contaminated by activities carried out at a waste disposal site.

Domestic Wells in Shallow Aquifers

Domestic wells are inherently more vulnerable to contamination from human activities because they often draw water from shallow aquifers that are susceptible to contamination from human activities on the ground surface. Domestic wells tend to be shallow for economic reasons. Homeowners must pay for their well construction and, to keep costs low, they will usually stop drilling as soon as the well is deep enough to provide enough water to meet their needs. A study in the US that looked at over 1,200 wells of various well types from across the country reported that the median domestic well depth was 49 m, compared to 130 m for public wells (DeSimone et al., 2009).

As indicated in Figure 18, the travel time for contaminants to migrate from the ground surface to the intake of a shallow well may be days to years. This provides limited opportunity for contaminants to be attenuated before they reach the well. In contrast, deeper public water supply wells may have groundwater travel times ranging from years to centuries. The longer the groundwater travel time, the more opportunity there is for the concentrations of anthropogenic contaminants that originate at the ground surface to be reduced by natural attenuation. A deep well is also more likely to be protected from contamination by confining layers located above the well intake zone.

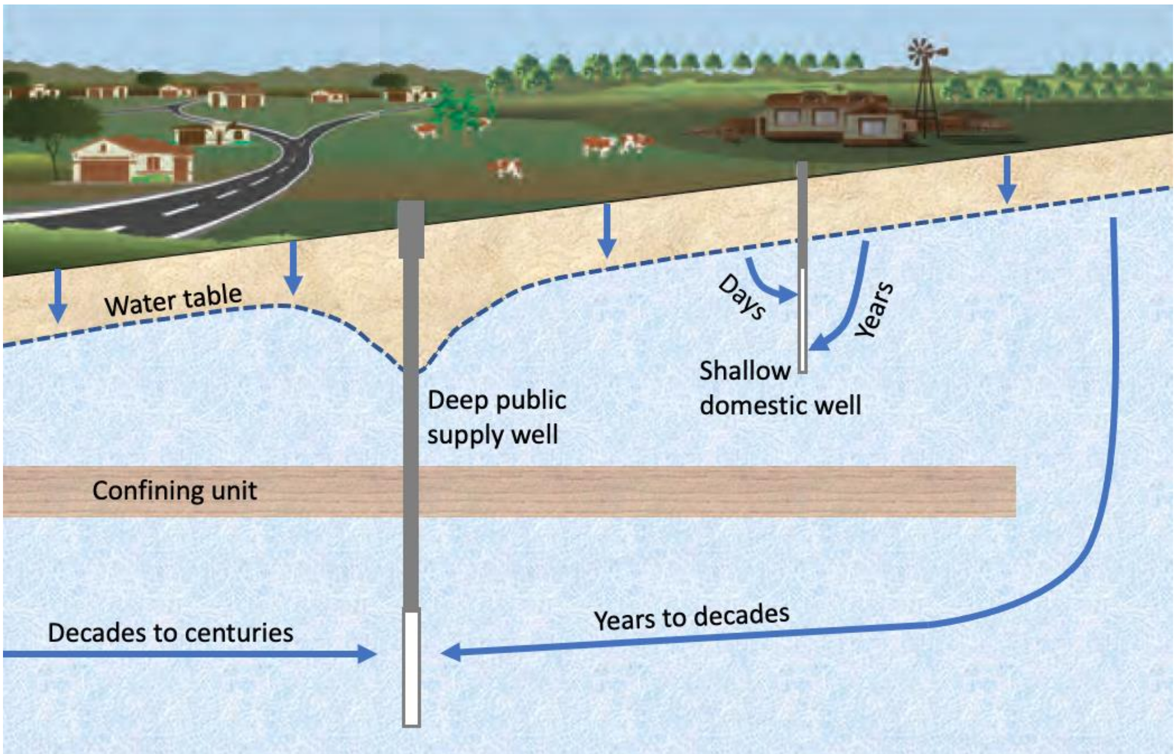

Figure 18 - Groundwater and contaminant travel times for shallow domestic wells are shorter than for deeper public wells, providing less time for anthropogenic contaminants to be attenuated (modified from Dubrovsky et al., 2010).

Microbial Contaminants in Domestic Wells

As discussed in Section 5, Water Quality of Domestic Wells, microbial contaminants are among the most common type of contaminants found in domestic wells. Regional surveys of domestic wells (Table 2) often detect bacteria in about one third of sampled wells. Microbial contaminants are found in all types of wells, not just domestic wells, but they are detected more frequently in domestic wells than public wells. For example, a national survey of microbial water quality in the United States tested 405 domestic wells and 227 public wells and reported that coliform bacteria were detected in untreated water in 33 percent of domestic wells and 16 percent of public wells (Embrey and Runkle, 2006). A review of waterborne infectious disease outbreaks in England and Wales reported that private water supplies, most of which are sourced from domestic wells serving individual households, had incidences of outbreaks up to 35 times more than public water supplies (Smith et al., 2006).

Why are domestic wells more vulnerable to microbial contamination? There are many factors that control the risk of microbial contamination in wells, including the characteristics of the microbial sources near the well (e.g., proximity of the source, quality of construction and maintenance of nearby septic systems) and the migration pathways that allow microbial contaminants to travel from the source to the well. Migration pathways include both hydrogeological pathways and pathways associated with the well's construction. Figure 19 shows examples of common conditions that can cause microbial contamination in domestic wells.

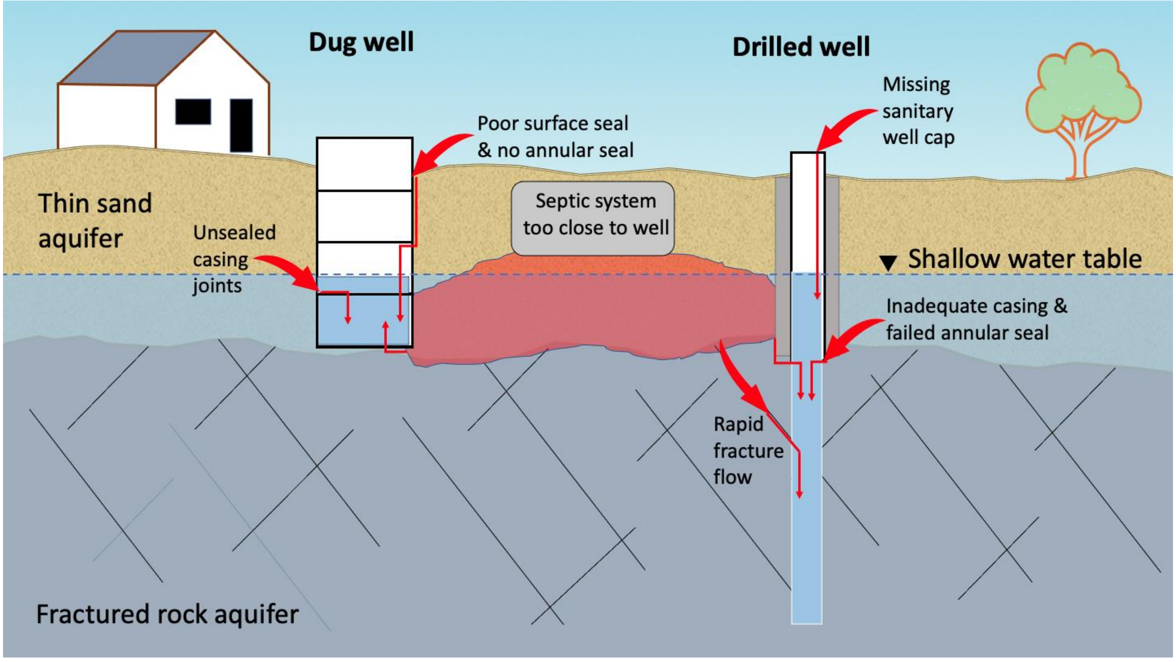

Figure 19 - Examples of common conditions that can cause microbial contamination in domestic wells.

Studies that look at the causes of microbial contamination in domestic wells usually investigate correlations between well contamination and the well characteristics, including its proximity to contaminant sources, its hydrogeologic setting, and its construction. With respect to contaminant sources, septic systems, feedlots, and manure spreading have been associated with microbial contamination. A report that pooled data from 55 studies on pathogen contamination in groundwater systems found that septic systems were the most frequently confirmed or likely source of contamination (Hynds et al., 2013). A study in Florida, USA, found that decreasing distance between domestic wells and septic tanks was correlated with increasing concentrations of fecal coliform bacteria in wells (Arnade, 1999). Studies of domestic wells in agricultural areas have found that wells located closer to animal feedlots and manure spreading activities have a higher risk of bacterial contamination (Goss et al., 1998; Conboy and Goss, 2000).

With respect to hydrogeological settings, several studies have reported that microbial contamination is more common in wells constructed in fractured rock and carbonate rock, compared to wells in unconsolidated aquifers (Lee and Murphy, 2020; DeSimone et al., 2009; Embrey and Runkle, 2006; Kraus and Griebler, 2011). This can be attributed to the lack of natural attenuation of microorganisms and the rapid contaminant transport that can occur in fractures and karst solution channels. A study in New Jersey, USA that analyzed data from 51,000 domestic wells found that bedrock wells were three times more likely to have coliform bacteria present compared to wells in unconsolidated aquifers (Atherholt et al., 2013). The same study reported that bacteria was more frequently detected in wells in areas with thin till layers (< 6 m) overlying the bedrock, than wells with thick till layers (6 to 60 m). Bedrock aquifers with thin overlying soil profiles are more vulnerable to microbial contamination because there is less opportunity for contaminants to be removed by natural attenuation as water percolates through the soil.

Well construction is frequently cited as a cause of microbial contamination in well water. A review of 55 studies of pathogen contamination in groundwater supplies in Canada and the United States reported that there are 50 percent more cases of pathogens in poorly designed and constructed wells than adequately designed wells (Hynds et al., 2014). Well construction factors that are commonly associated with microbial contamination in domestic wells include shallow well depths (or shallow intake zones), dug wells, and older wells (Owusu et al., 2021; Lee and Murphy, 2020; Goss et al., 1998). Shallow wells access shallow groundwater with relatively short travel times that have less opportunity to attenuate microorganisms. It is important to note that it is the minimum depth of the water intake zone that controls whether shallow groundwater enters a well, not the total depth of the well. For example, a well that is 50 m deep with 6 m of casing and annular seal can allow shallow groundwater from a depth of 6 m to enter the well.

Dug wells are more susceptible to microbial contamination because they are shallow and often the casing and/or annular seals are not continuous. Older wells can be susceptible to microbial contamination because they may have deteriorated over time (e.g., cracks or holes have developed in the casing, or annular seals have failed) or may have been installed using outdated well construction methods. Common well integrity problems that can cause microbial contamination include poor surface seals at the wellhead (allowing surface water to enter the well), no sanitary well cap (allowing vermin to enter the well), and inadequate, or failed, casing and annular seals. With respect to annular well seals, researchers have observed that cracks and voids in grout can develop over time and dye tests have shown that these grout failures can allow dye to migrate to significant depths (> 10 m) below the ground surface (Olafsen Lackey et al., 2009).

Risk factors commonly associated with microbial contamination are summarized in Table 3. In general, wells have a higher risk of microbial contamination if:

- they are located near a microbial source (e.g., septic system, animal feedlots, manure spreading);
- they are located in a hydrogeological setting that allows for rapid microbial transport (e.g., fractured rock, carbonate rock, areas with thin soil profiles); and/or,
- they have well construction characteristics or deficiencies that make them susceptible to microbial contamination (e.g., shallow intake depths, inadequate casing and grout, poor sanitary wellhead conditions).

Table 3 - Examples of sources and pathways that can cause microbial contamination in well water.

Sources & Pathways	Risk Factors	Explanation
Sources	Septic systems	Septic systems that have failed, or are too close to water wells, may cause contamination.
	Animal feedlots	Wells close to feedlots are reported to have a higher risk of bacterial contamination.
	Manure spreading	Manure spreading near wells has been reported to increase the risk of bacterial contamination.
Pathways: hydrogeological	Fractured rock	Fractured rock provides less natural attenuation than unconsolidated aquifers and can have fast groundwater velocities that lead to rapid microbial transport.
	Carbonate rock	Carbonate rock can have fractures and karst solution channels with rapid microbial transport and minimal natural attenuation.
	Thin unconsolidated materials	Thin soil and sediment layers provide less attenuation of microorganisms than thick layers of unconsolidated materials.
	Shallow water tables	Shallow water tables or thin unsaturated zones provide less opportunity for attenuation of microorganisms.
Pathways: well construction	Shallow wells	Shallow groundwater has shorter travel times to reach the well and less opportunity for attenuation of microorganisms.
	Dug and bored wells	These wells are shallow and often lack continuous casing and annular seals.
	Older wells	Older wells may have deteriorated casing and annular seals and may not be constructed to modern standards.
	Poor annular seals	Inadequate or failed annular seals can allow shallow water to enter the well.
	Inadequate casing	Inadequate or deteriorated casing can allow shallow water to enter the well.
	Poor surface seal at wellhead	Poor surface seals, that do not slope away from the well and do not provide low permeability seals at the ground surface, can allow surface water to enter the well.
	No sanitary well cap	Sanitary well caps prevent vermin from entering the well.

Some of these factors, especially the hydrogeologic setting, are not specific to domestic wells but can affect all well types. However, as noted earlier, domestic wells are more susceptible to microbial contamination than public water wells because they are more likely to be shallow, located near a microbial source, and have well construction deficiencies.

Because there are multiple risk factors that can cause microbial contamination in wells, public water supplies commonly use a multi-barrier approach to reduce risks. Macler and Merkle (2000) explain that the multi-barrier approach for groundwater supplies typically includes:

- source water protection (i.e., controlling the sources of contamination in the well's capture zone);

- wellhead integrity monitoring and maintenance (i.e., controlling migration pathways at the well);
- water treatment (i.e., water disinfection to remove pathogens); and,
- water quality monitoring.

Most jurisdictions recommend these multi-barrier practices to domestic well owners, including source protection (i.e., maintaining septic systems, setback distances between wells and septic systems), routine well inspection and maintenance, and routine water quality testing. Water disinfection is clearly associated with reduced microbial contamination in public water supplies, and it would be prudent to include disinfection as a standard practice for domestic wells. Water disinfection systems, such as ultraviolet lights, are effective, simple to operate and maintain, and are relatively inexpensive compared to the construction cost of a domestic water well.

6.4 Vulnerability to Groundwater Level Declines

As discussed previously, domestic wells tend to be as shallow as possible to keep well construction costs low. They are often installed just deep enough to meet domestic water needs, based on the groundwater levels at the time of well construction. This can make domestic wells vulnerable to future groundwater level declines caused by seasonal drought, climate change, well interference, or aquifer depletion. If groundwater level declines are sufficiently large compared to the available drawdown in a well, the well owner may be faced with a temporary or permanent water shortage. This may require the well owner to make changes to their well, such as lowering the pump or deepening the well. If these solutions do not work, they may need to install a new deeper well or obtain water from an alternate source.

Aquifer depletion is occurring in most of the major aquifers in the world's arid and semi-arid areas (Famiglietti, 2014). As groundwater levels drop in these aquifers, shallow domestic wells are among the first wells to go dry. Drawing water from new deeper wells may not be possible for domestic well owners because of the increased cost associated with deeper well construction, energy to pump groundwater from greater depth, and treatment of the potentially poorer quality groundwater found at depth.

A drought in California, USA, between 2012 and 2016 was reported to have caused almost 12,000 people to run out of water (Cagle, 2020). The impact of this drought was especially severe in California's Central Valley where it was estimated that about one in five wells ran dry. Aquifer depletion had already lowered the water table here to 250 m below ground surface in some places (Stokstad, 2020). Domestic wells in the Central Valley are going dry more often than other well types because they tend to be shallower. An analysis of dry wells during the 2012-2016 California drought estimated that 6 percent of agricultural wells and 19 percent of domestic wells went dry during this period (Jasechko and Perrone, 2020). Domestic wells are reported to be shallower than agricultural wells in several agricultural areas around the world (Jasechko and Perrone, 2021), indicating that their vulnerability to groundwater level declines compared to other well types is a global issue.

The problem of dry domestic wells is not restricted to California. In the Western United States, a study evaluated more than two million well records and estimated that about 4 percent of domestic wells went dry between 2013 and 2015 (Perrone and Jasechko, 2017). In Nova Scotia, Canada, a drought in 2016 was reported to have caused more than 1,000 water wells to go dry, 93 percent of which were domestic dug wells (Kennedy et al., 2017). Many municipal governments in Nova Scotia are now providing loans to help well owners install deeper wells.

7 Domestic Well Protection

7.1 Regulations

Several types of regulations are currently used to protect domestic wells. The most common are water well construction regulations, which are used by many jurisdictions to ensure that water wells are properly constructed and resilient to contamination from shallow groundwater and contaminants at the ground surface. The goals of most well construction regulations are to: protect the health and safety of the well owner and the environment, protect aquifers and water resources, protect aquitards (i.e., low permeability geologic formations that restrict the flow of groundwater and contaminants between aquifers), and protect groundwater quality and quantity. Well construction regulations typically specify who can construct a well (e.g., a licensed well contractor), the methods and materials that must be used, setback distances from potential sources of contamination, requirements for well development, requirements for sealing abandoned wells (so they do not provide pathways for contaminants to reach aquifers), yield testing, and reporting (water well records). In some jurisdictions, the well construction regulations require that a permit be obtained before a domestic well is constructed (e.g., Colorado and Wyoming, USA). The key elements of water well construction regulations that help protect wells from surface contaminants and shallow groundwater contamination include requirements for a sanitary well cap, adequate well casing, and an annular seal.

Water well construction regulations are usually applicable to the construction of all types of water wells, including domestic wells. In most cases, they apply at the time of well construction and are the only regulations a domestic well owner is required to follow. They do not usually include any chemical testing or ongoing maintenance and monitoring requirements. Specific examples of water well construction regulations include the Province of Ontario's Regulation 903 (Province of Ontario, 1990) and Kansas State's Article 30 (State of Kansas, 2013).

Other types of regulations used to protect domestic wells are those that require water quality testing at the time of well construction or during a property sale. Although these types of regulations have not been widely adopted, a limited number of jurisdictions require initial testing when a domestic well is first installed (e.g., New Brunswick, Canada, and North Carolina, USA) and during real estate transactions (e.g., New Jersey, Oregon, and Rhode Island, USA). Examples of water quality testing regulations for domestic wells include the Canadian Province of New Brunswick’s Potable Water Regulation (Province of New Brunswick, 1993) and the State of New Jersey’s Private Well Testing Act (Atherholt et al., 2009). These one-time sampling requirements can be an effective way to identify existing contamination at a point-in-time, but they do not identify seasonal or future changes to water quality like regular testing can. A study that looked at the frequency of testing for arsenic in domestic wells in both the United States and India concluded that because of temporal variations in arsenic levels in wells, a single test is inadequate to ensure that well water meets water quality guidelines in the long-term (Mailloux et al., 2021). The study found that in order to have less than a 5 percent chance of exceeding the guideline in the future, wells must be tested every year if the concentration in the well water is more than half the guideline, and every five years if the concentration is less than half the guideline. A study in Ontario, Canada reviewed 700,000 *E. coli* sample results from more than 200,000 domestic wells and concluded that, because of temporal variations in *E. coli* detections, one sample is not enough to determine the long-term microbiological safety of domestic wells (Latchmore et al., 2020).

Some jurisdictions have regulations for protecting domestic wells in subdivision developments (Figure 20) which require a hydrogeological assessment prior to the subdivision’s approval. These assessments look at both groundwater quality and quantity issues and evaluate whether future problems are likely and what mitigation measures can be used to lower the risks. For example, if an assessment indicates that the proposed density of lots (the land designated for one home) in a subdivision will result in excessive well interference or aquifer depletion, the number of approved lots can be reduced.

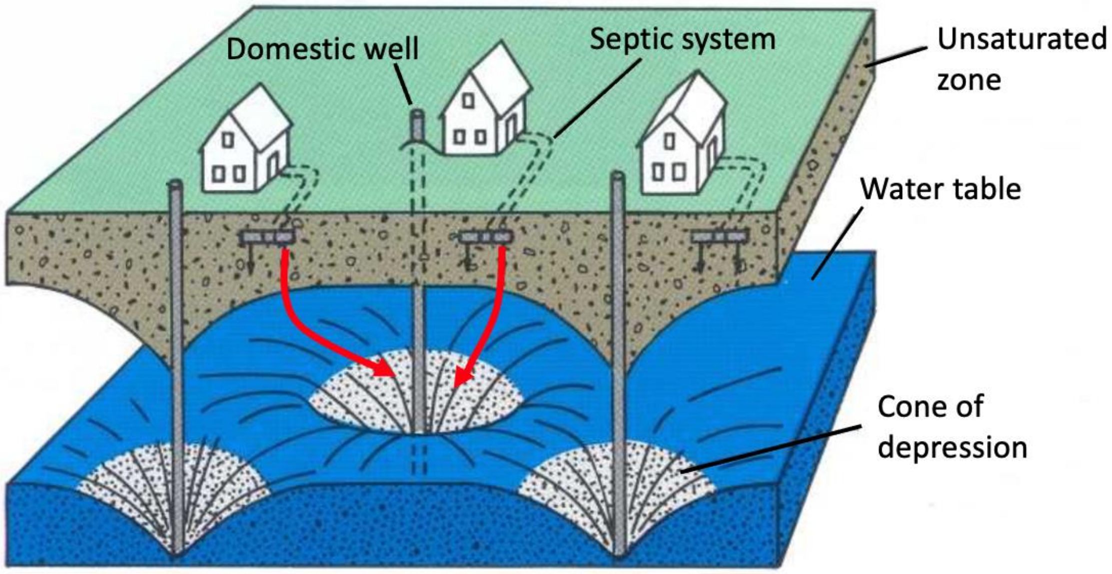

Figure 20 - Domestic wells in a subdivision, showing the potential for septic system impacts on wells and well interference effects from multiple cones of depression (modified from Waller, 1994).

The introduction of regulations to protect domestic wells in subdivisions has often been in response to historical problems. For example, the Province of Ontario, Canada, introduced requirements for hydrogeological studies in subdivisions (Ontario Ministry of Environment and Energy, 1996) after a number of subdivisions with domestic wells were found to have groundwater quality problems, including high nitrate levels from on-site septic systems. In Nova Scotia, Canada, hydrogeological study requirements for subdivision developments were introduced after well interference problems in a subdivision caused numerous domestic wells to go dry and necessitated the extension of central municipal water services. The Nova Scotia guide for hydrological assessments in subdivisions now includes a spreadsheet tool for evaluating the water balance for the planned number of lots and the interference between wells on each lot (Nova Scotia Environment, 2011).

Many jurisdictions regulate groundwater pumping with a permit system and require approvals for certain industrial activities (e.g., quarries, mines, landfills, petrochemical facilities). Examples of using permits to regulate pumping are provided by Nowlan (2005). Requiring permits for pumping and approval of activities are not specifically designed to protect domestic wells, but they sometimes require the proponent to identify nearby domestic wells and evaluate the potential impact that the proposed activity may have on water wells. Permits for these activities may include conditions that protect existing domestic wells, such as baseline surveys (e.g., water quality testing, water level measurements), contingency plans to address well interference problems, and requirements to remedy any impacts on domestic wells caused by the proposed activity. Examples of groundwater permitting systems that address effects on existing water wells include the State of Arizona's well spacing and impact rules (Arizona Department of Water

Resources, 2021) and the Canadian Province of Nova Scotia's groundwater withdrawal approval process (Nova Scotia Environment, 2010).

7.2 Education and Outreach Programs

Education and outreach programs are the most common approach for protecting domestic wells. These programs promote awareness and voluntary stewardship, including regular well maintenance, water quality testing, and the use of water treatment equipment. Many jurisdictions maintain government websites that provide advice and fact sheets for domestic well owners. Examples include the USEPA's Private Drinking Water Wells website↗ and Health Canada's Be Well Aware website↗. Educational websites for domestic well owners are also maintained by some non-government organizations, such as Wellowner.org↗ and The Private Well Class↗.

In addition to fact sheets, educational websites sometimes include other information and tools that can help well owners protect their wells, including hazard maps for common well water contaminants (e.g., maps of arsenic in well water), online access to water well record databases, and story maps, infographics, and webinars. Interpretive tools are also available online that allow well owners to enter their well water chemistry results for comparison to drinking water quality guidelines.

Unfortunately, educational efforts, such as websites and fact sheets, do not necessarily cause behavioral change or prompt well owners to test their well water quality (Chappells et al., 2014; Morris et al., 2016). The lack of effectiveness of educational material at prompting homeowners to test has also been observed in radon gas outreach programs, which have similar objectives to domestic well outreach programs. Radon is a naturally occurring radioactive gas that can accumulate in indoor air and cause lung cancer. Like domestic wells, testing for radon in indoor air by homeowners is voluntary. In 2020, Canada's National Radon Program mailed 1.5 million postcards to homeowners living in high-risk radon areas to encourage them to test their indoor air for radon gas. Follow-up investigations found that this educational initiative increased radon awareness but had little effect on homeowner testing rates, which increased by only 0.5 percent (Penstone and Howe, 2020).

Community-based education programs for domestic well owners appear to be more effective than those that rely solely on websites and fact sheets. Results from the Canadian Province of Ontario's Well Aware educational program indicates that well owners were five times more likely to follow recommendations and fix problems with their domestic wells if they were visited at home by a peer well owner, compared to receiving advice from generic sources, such as a website (Chappells et al., 2014).

A community-based domestic well education program in Pennsylvania, USA, called the Master Well Owner Network, recruited and trained over 200 local volunteers. The volunteers engaged in domestic well education initiatives, including talking to neighbors, presentations at local community meetings, hosting booths at community events, and media interviews. The program was able to reach over 30,000 well owners and surveys indicated that 82 percent of those contacted by a volunteer had taken action to protect their water supply, including water testing and the installation of water treatment equipment (Clemens et al., 2007). Although these types of community-based programs involving face-to-face contact with well owners are effective, they are more costly to operate and more difficult to maintain than educational websites and have not been widely adopted as long-term strategies for protecting domestic wells.

7.3 Other Protection Methods

During a property sale, mortgage lenders may require domestic wells to have a water quality test to confirm that the water meets drinking water quality guidelines and a yield test to confirm that the well can produce enough water to meet domestic needs. In addition, some local governments require wells to be tested as part of their building code and permitting process.

Free or discounted water sampling and analysis is provided to domestic well owners in some jurisdictions. For example, this service is offered in Alberta, Manitoba, and Ontario, Canada. In these jurisdictions, the program includes bacteria analysis only, and the well owner is responsible for collecting the water sample and delivery to the laboratory. Counties in Iowa, USA provide a more comprehensive service, which includes free or discounted sample collection, water analysis (may include bacteria, nitrate, arsenic), as well as assistance to interpret the results and choose a mitigation option. Although the Iowa program processes up to 7,000 water samples each year, the service is under-utilized. This suggests that reducing cost and inconvenience barriers to water quality testing is not enough to encourage widespread testing, and that more outreach and education is also needed to convince well owners of the importance of testing (APHL, 2019).

Financial assistance programs have also been used to help domestic well owners with other problems besides water quality testing. The Well Compensation Program in Wisconsin, USA provides grants to well owners of contaminated wells, including those with high levels of arsenic. The program helps pay for a new well, reconstruction of an existing well, connecting to another water supply, or installing a treatment system (Wisconsin Department of Natural Resources, 2005). In Nova Scotia, Canada, low interest loans are provided by some local governments to assist domestic well owners to install deeper wells that are more resilient to seasonal droughts than shallow wells (Province of Nova Scotia, 2016).

8 Domestic Wells and Research

Much of the research associated with domestic wells focuses on characterizing their vulnerabilities and identifying ways to improve their management and protection (e.g., Chappells at al., 2014; Zheng and Ayotte, 2015; Colley et al. 2019; Jasechko and Perrone, 2020). However, data collected from domestic wells have been used for several other purposes. Domestic wells are extremely useful for carrying out regional groundwater research and monitoring because of the large and geographically distributed datasets they can provide. Domestic well data are commonly used in epidemiological studies and contaminant exposure estimates during the development of drinking water quality guidelines. Chemistry data and geological information from domestic wells have also been used for petroleum and mineral exploration programs.

Installing new test wells and monitoring wells is often the costliest part of regional groundwater research and aquifer characterization. If done appropriately, and with consideration of their limitations, using data collected from domestic wells can avoid or reduce the cost of installing research wells. Some studies have used domestic wells as an exclusive data source, while other studies have used them to supplement data collected from research and monitoring wells. It is important to keep in mind that domestic wells may not represent ambient groundwater conditions because they are actively being pumped, which can affect water levels and water chemistry, and their well construction characteristics (e.g., long open-hole sections and large diameters compared to monitoring wells) can influence groundwater chemistry. Long open-hole sections allow groundwater to enter the well from a relatively long integrated depth interval, and sometimes from multiple aquifers, rather than a discrete point within one aquifer.

One of the most common sources of data provided by domestic wells is water well construction records. Many jurisdictions require a water well record to be submitted when a new well is constructed, and they maintain online water well record databases that are publicly accessibly. Well records include information that is valuable to regional groundwater studies, such as stratigraphy, groundwater level at the time of well construction, and well yield. The short-term yield tests that are usually carried out when a domestic well is installed can be used to estimate the specific capacity of the well and the aquifer's transmissivity. It should be noted that domestic well records may lack detail and accuracy because they are not collected for research purposes and the information may be collected by people without training in hydrogeology. However, if there are enough well records available to correctly assess the general conditions and trends for a given geographical area, then errors in individual records may not have a significant impact on research conclusions. Another book in the Groundwater Project series on domestic wells provides more information on water well record databases↗ (Kennedy, 2021).

Domestic wells have also been used for regional groundwater quality surveys, groundwater level surveys, and long-term groundwater level monitoring. In these cases, groundwater researchers seek permission from domestic well owners to sample their wells or monitor groundwater levels, and the data are either collected by groundwater researchers or in collaboration with the well owners (Figure 21). For example, the USGS sampled approximately 3,670 domestic wells in addition to public supply wells and monitoring wells to assess the water quality of principal aquifers of the United States (DeSimone et al., 2014). Domestic wells have also been used to build community-based groundwater level monitoring networks, which are operated by either non-government groups, or as partnerships between domestic well owners and government researchers (Drage and Kennedy, 2020).

Figure 21 - A hydrogeologist installing a real-time groundwater level sensor in a domestic dug well for a community-based groundwater monitoring network (photograph by John Drage).

9 Summary and Path Forward

Domestic wells are the source of water for hundreds of millions of people around the world. They are one of the safest and most reliable types of water supplies for households that do not have access to public water supplies. However, they can be vulnerable to water quality and quantity problems for several reasons, including:

- their water quality is mostly unregulated and most domestic wells are not monitored regularly;
- they are often located close to contaminant sources;
- they are often relatively shallow and vulnerable to surface contaminants, droughts, and aquifer depletion; and,
- they are privately owned by individuals who often do not have the resources to ensure their wells can provide safe and reliable quantities of water.

The current approach for managing and protecting domestic wells, which relies primarily on voluntary action by the well owner, is failing to effectively address these multiple vulnerabilities.

9.1 Water Quality

With respect to water quality, surveys commonly find that more than 40 percent of domestic wells exceed drinking water guidelines, indicating that they continue to represent a significant public health risk. This is a preventable problem that can be corrected with better support to domestic well owners for both water quality monitoring and water treatment.

Current research suggests a combination of actions are needed to meet this objective, including more appropriate levels of regulations for domestic well testing and water treatment, improved education and outreach programs, which consider vulnerable socio-economic populations and local face-to-face engagement with well owners, and making water quality testing easy and inexpensive. There is also a need for additional large-scale, long-term water quality monitoring initiatives for domestic wells to better understand the risk of contaminant exposure and inform policies for improving the safety of domestic wells. Most domestic well water quality surveys are currently limited in geographic scope, surveillance period, and the suite of contaminants tested.

Microbial contaminants, arsenic, and fluoride are among the highest priority contaminants in domestic wells because of their significant health effects and widespread occurrence. In order to reduce the impact of these contaminants on domestic well owners, we need new reliable, user-friendly and low-cost ways to test, monitor, and treat them. Because of the extent of the public health crisis caused by arsenic, researchers have called for all domestic wells worldwide to be tested for arsenic. They have also recommended that testing be encouraged through policy changes, such as mandatory water quality testing, and by making testing easy, accessible, and free (Zheng, 2020; Zheng and Flanagan, 2017).

9.2 Water Quantity

Domestic well water quantity problems are likely to increase in the future due to increased frequency of droughts associated with climate change and aquifer depletion caused by increased pumping. As water tables decline, shallow domestic wells will be the first to go dry. In the more extreme cases, the water table will become too deep to be accessed by domestic wells at an affordable cost to homeowners.

Researchers have suggested that legislation and sustainable planning initiatives are needed that specifically include the protection of domestic wells from declining groundwater levels. In cases where aquifer depletion is occurring, this could be done by setting minimum groundwater level targets that support domestic well use. This would need to be done in combination with effective groundwater withdrawal permitting systems that include the monitoring of groundwater withdrawal volumes and adequate groundwater level monitoring. Domestic well owners could also be protected by providing grants, low-cost loans, and tax rebates for replacing water wells that have gone dry.

9.3 Domestic Wells and Technological Advances

Technological advances have potential to help domestic well owners to test and monitor their wells as well as provide access to real-time data and groundwater knowledge. Such advances include the widespread availability of internet service, cellular networks, smartphones, low-cost water sensors, and Internet-of-Things (IoT) technologies. Approximately 50 percent of the world currently has access to internet service and two-thirds of the world's population use cell phones, about half of which are smartphones. Researchers are currently working on ways to use smartphones to test for arsenic in well water, either in combination with biosensors that attach to phones (Doyle, 2019) or by using the phone's camera to analyze the color and concentration of arsenic test strips (Haque et al., 2018). New interactive smartphone apps are also being developed that allow domestic well owners to enter their site-specific water well and property data to carry out a personalized risk assessment for their well (O'Dwyer, 2018; Hoffman et al., 2019). Internet-of-Things devices and low-cost sensors are now being used to monitor real-time groundwater levels in domestic wells (Drage and Kennedy, 2020).

Since smartphones and IoT devices are connected to the internet, they can be linked with online dashboards that allow domestic well owners to share and view real-time data in user-friendly formats. It is also becoming more common for governments to provide online interactive risk maps for groundwater contaminants and online water well record databases, both of which are valuable sources of information for domestic well owners.

In addition to technological advances, social media has great potential to be used for education and outreach to domestic well owners. Groundwater researchers have pointed out that, with over 2.3 billion people using social media worldwide, these networks can allow groundwater information to reach a wide audience, including domestic well owners (Re and Misstear, 2017). It is encouraging that new technologies and communication methods have the potential to democratize groundwater data and knowledge for domestic well owners, who are currently left essentially on their own to manage their water supplies in isolation.

10 Exercises

Exercise 1

A homeowner is having a new domestic well installed to supply a household with four people. The well has been drilled to a depth of 50 m below the ground surface and the well yield has been measured to be 2 L/min. The homeowner wants to know if this well can supply enough water for their home or if they should continue to drill deeper. Do you think this well will meet their water supply needs? The home is in Canada where the average domestic water use is 215 L/day per person. It is a drilled well with a diameter of 152 mm and static water level of 5 m below the ground surface. You can assume a 5 m water level allowance above the bottom of the well for the pump setting.

Click for solution to Exercise 1↴

Exercise 2

A domestic well owner has tested their well water and found the arsenic concentration to be 15 μg/L. Is the well water safe to drink? What would you recommend the well owner do? Use the World Health Organization (WHO) drinking water guideline for arsenic to make your decision. Would your recommendation change if you used the drinking water guideline from where you live?

Click for solution to Exercise 2↴

Exercise 3

Why might a domestic well owner not test their well water quality? What policies or programs would you recommend be put in place to encourage well owners to test their wells?

Click for solution to Exercise 3↴

Exercise 4

A homeowner is planning to install a new domestic well. What steps can they take to reduce their well's vulnerability to contamination and ensure their water is safe to drink?

Click for solution to Exercise 4↴

11 References

Addison, M.J., M.O. Rivett, P. Phiri, P. Mleta, E. Mblame, M. Banda, O. Phiri, W. Lakudzala, and R.M. Kalin, 2020, Identifying groundwater fluoride source in a weathered basement aquifer in central Malawi: Human health and policy implications. Applied Sciences, volume 10, issue 14, article number 5006, doi: 10.3390/app10145006↗.

APHL, 2019, Association of Public Health Laboratories, Private well sampling and testing, A guide for public health laboratories. 31 pages, https://www.aphl.org/aboutAPHL/publications/Documents/EH-Nov2019-Private-Well-Water-Testing-Guide.pdf↗.

Argos, M., T. Kalra., P.J. Rathouz, Y. Chen, B. Pierce, F. Parvez, T. Islam, A. Ahmed, M. Rakibuz-Zaman, R. Hasan, G. Sarwar, V. Slavkovich, A. van Geen, J. Graziano, and H. Ahsan, 2010, Arsenic exposure from drinking water, and all-cause and chronic-disease mortalities in Bangladesh (HEALS): a prospective cohort study. The Lancet, volume 376, issue 9737, pages 252-258, doi: 10.1016/S0140-6736(10)60481-3↗.

Arizona Department of Water Resources, 2021, Groundwater Permitting and Wells, https://new.azwater.gov/permitting-wells/well-drilling-arizona↗.

Arnade, L.J., 1999, Seasonal correlation of well contamination and septic tank distance. Groundwater, volume 37, issue 6, pages 920-923, doi: 10.1111/j.1745-6584.1999.tb01191.x↗.

Atherholt, T.B., R.T. Bousenberry, G.P. Carter, L.R. Korn, J.B. Louis, M.E. Serfes, and D.A. Waller, 2013, Coliform bacteria in New Jersey domestic wells: Influence of geology, laboratory, and method. Groundwater, volume 51, issue 4, pages 562-574, doi: 10.1111/j.1745-6584.2012.00997.x↗.

Atherholt, T.B., J.B. Louis, J. Shevlin, K. Fell, and S. Krietzman, 2009, The New Jersey private well testing act: An overview. New Jersey Department of Environmental Protection, Division of Science, Research and Technology, 8 pages, https://www.nj.gov/dep/dsr/research/pwta-overview.pdf↗.

Australian Bureau of Statistics, 2013, 4602.0.55.003 - Environmental Issues: Water Use and Conservation, Mar 2013, https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/4602.0.55.003Mar%202013?OpenDocument↗.

Ayotte, J.D., L. Medalie, S.L. Qi, L.C. Backer, and B.T. Nolan, 2017, Estimating the high-arsenic domestic-well population in the conterminous United States. Environmental Science and Technology, volume 51, number 21, pages 12443-12454, doi: 10.1021/acs.est.7b02881↗.

Cagle, S., 2020, Lost communities: Thousands of wells in rural California may run dry. The Guardian, https://www.theguardian.com/environment/2020/feb/28/california-water-wells-dry-sgma↗.

CAHI, 2021, Canadian Animal Health Institute, 2020 Canadian Pet Population Figures Released, https://www.cahi-icsa.ca/news/2020-canadian-pet-population-figures-released↗.

Chappells, H., N. Campbell, J. Drage, C.V. Fernandez, L. Parker, and T.J.B. Dummer, 2015, Understanding the translation of scientific knowledge about arsenic risk exposure among private well water users in Nova Scotia. Science of The Total Environment, volume 505, pages 1259-1273, doi: 10.1016/j.scitotenv.2013.12.108↗.

Chappells, H., L. Parker, C.V. Fernandez, C. Conrad, J. Drage, G. O'Toole, N. Campbell, and T.J.B. Dummer, 2014, Arsenic in private drinking water wells: an assessment of jurisdictional regulations and guidelines for risk remediation in North America. Journal of Water Health, volume 12, number 3, pages 372-392, doi: 10.2166/wh.2014.054↗.

Clemens, S., B.R. Swistock, and W.E. Sharpe, 2007, The Master Well Owner Network: Volunteers educating Pennsylvania well owners. Journal of Extension, volume 45, pages 1-7, https://archives.joe.org/joe/2007august/rb7.php↗.

Colley, S.K., P. Kane, and J. M. Gibson, 2019, Risk communication and factors influencing private well testing behavior: a systematic scoping review. International Journal of Environmental Research and Public Health, volume 16, number 22, article number 4333, doi: 10.3390/ijerph16224333↗.

Collins, S., 2000, Hand-Dug Shallow Wells. SKAT, Swiss Centre for Development Cooperation in Technology and Management, Saint Gallen, Switzerland, 102 pages, https://www.rural-water-supply.net/_ressources/documents/default/256.pdf↗.

Conboy, M.J. and M.J. Goss, 2000, Natural protection of groundwater against bacteria of fecal origin. Journal of Contaminant Hydrology, volume 43, issue 1, pages 1-24, doi: 10.1016/S0169-7722(99)00100-X↗.

DeFelice, N. B., J.E. Johnston, and J.M. Gibson, 2016, Reducing emergency department visits for acute gastrointestinal illnesses in North Carolina (USA) by extending community water service. Environmental Health Perspectives, volume 124, number 10, pages 1583-1591, doi: 10.1289/EHP160↗.

DeSimone, L.A., P.A. Hamilton, and R.J. Gilliom, 2009, Quality of water from domestic wells in principal aquifers of the United States, 1991–2004—Overview of major findings. United States Geological Survey, Circular 1332, 48 pages, https://pubs.usgs.gov/circ/circ1332/↗.

DeSimone, L.A., P.B. McMahon and M.R. Rosen, 2014, The quality of our Nation's waters—Water quality in principal aquifers of the United States, 1991–2010. United States Geological Survey, Circular 1360, 151 pages, doi: 10.3133/cir1360↗.

Dieter, C.A. and M.A. Maupin, 2017, Public supply and domestic water use in the United States, 2015. United States Geological Survey, Open-File Report 2017-1131, 6 pages, doi: 10.3133/ofr20171131↗.

Dieter, C.A., M.A. Maupin, R.R. Caldwell, M.A. Harris, T.I. Ivahnenko, J.K. Lovelace, N.L. Barber, and K.S. Linsey, 2018, Estimated use of water in the United States in 2015. United States Geological Survey, Circular 1441, 65 pages, doi: 10.3133/cir1441↗.

Doyle, S., 2019, Smartphone biosensor detects arsenic in drinking water. Engineering and Technology Magazine, March 2019, The Institution of Engineering and Technology, https://eandt.theiet.org/content/articles/2019/03/smartphone-biosensor-detects-arsenic-in-drinking-water/↗.

Drage, J. and G.W. Kennedy, 2020, Building a low-cost, Internet-of-Things, real-time groundwater level monitoring network. Groundwater Monitoring and Remediation, volume 40, number 4, pages 67-73, doi: 10.1111/gwmr.12408↗.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M Gronberg, P.A. Hamilton, K.J. Hitt, D.K. Mueller, M.D. Munn, B.T. Nolan, L.J. Puckett, M.G. Rupert, T.M. Short, N.E. Spahr, L.A. Sprague, and W.G. Wilber, 2010, The quality of our Nation's waters—Nutrients in the Nation's streams and groundwater, 1992-2004. United States Geological Survey, Circular 1350, 174 pages, https://pubs.usgs.gov/circ/1350/↗.

Dummer, T.J.B., Z.M. Yu, L. Nauta, J.D. Murimboh, and L. Parker, 2015, Geostatistical modelling of arsenic in drinking water wells and related toenail arsenic concentrations across Nova Scotia, Canada. Science of the Total Environment, volume 505, pages 1248-1258, doi: 10.1016/j.scitotenv.2014.02.055↗.

DWI, 2020, Drinking Water Inspectorate, Drinking water 2019—Private water supplies in England. Drinking Water Inspectorate, 77 pages, https://cdn.dwi.gov.uk/wp-content/uploads/2020/12/07081721/PWS-2019-England-1.pdf↗.

Embrey, S.S. and D.L. Runkle, 2006, Microbial quality of the Nation's ground-water resources, 1993-2004. United States Geological Survey, Scientific-Investigations Report 2006-5290, 34 pages, https://pubs.usgs.gov/sir/2006/5290/index.html↗.

Environment Canada, 2011, Everyone's talking about water—It's time for action. Environment Canada Fact Sheet, 8 pages, http://publications.gc.ca/collections/collection_2011/ec/En4-119-2010-eng.pdf↗.

EurEau, 2017, Europe's water in figures—An overview of the European drinking water and waste water sectors, 2017 edition. The European Federation of National Associations of Water Services, Brussels, Belgium, 22 pages, https://www.eureau.org/resources/publications/1460-eureau-data-report-2017-1/file↗.

Famiglietti, J., 2014, The global groundwater crisis. Nature Climate Change, volume 4, pages 945-948, doi: 10.1038/nclimate2425↗.

Fischer, A., R. Hope, A. Manandhar, S. Hoque, T. Foster, A. Hakim, M.S. Islam, and D. Bradley, 2020, Risky responsibilities for rural drinking water institutions: The case of unregulated self-supply in Bangladesh. Global Environmental Change, volume 65, article number 102152, doi: 10.1016/j.gloenvcha.2020.102152↗.

Flanagan, S.V., R.B. Johnston, and Y. Zheng, 2012, Arsenic in tube well water in Bangladesh: Health and economic impacts and implications for arsenic mitigation. Bulletin of the World Health Organization, volume 90, number 11, pages 839-846, doi: 10.2471/BLT.11.101253↗.

Foster, T., C. Priadi, K.K. Kotra, M. Odagiri, E. Christensen Rand, and J. Willetts, 2021, Self-supplied drinking water in low- and middle-income countries in the Asia-Pacific. npj Clean Water, volume 4, number 37, doi: 10.1038/s41545-021-00121-6↗.

Gibson, J.M., M. Fisher, A. Clonch, J.M. MacDonald, and P.J. Cook, 2020, Children drinking private well water have higher blood lead than those with city water. Proceedings of the National Academy of Sciences of the USA, volume 117, number 29, pages 16898-16907, doi: 10.1073/pnas.2002729117↗.

Goss, M.J., D.A.J. Barry, and D.L. Rudolph, 1998, Contamination in Ontario farmstead domestic wells and its association with agriculture: 1. Results from drinking water wells. Journal of Contaminant Hydrology, volume 32, issues 3-4, pages 267-293, doi: 10.1016/S0169-7722(98)00054-0↗.

Grantham, D.A., 1986, The occurrence and significance of uranium, radium and radon in water supplies in Nova Scotia—A report on the investigation carried out by the provincial uranium task force. Nova Scotia Department of Health, Nova Scotia Department of Mines and Energy, Open File Report 1986-070, 256 pages, https://novascotia.ca/natr/meb/data/ofr/OFR_ME_1986-070_2.pdf↗.

Grantham, D.A. and J.F. Jones, 1977, Arsenic contamination of water wells in Nova Scotia. Journal of the American Water Works Association, volume 69, issue 12, pages 653-657, doi: 10.1002/j.1551-8833.1977.tb06844.x↗.

Haque, E., B.J. Mailloux, D. de Wolff, S. Gilioli, C. Kelly, E. Ahmed, C. Small, K.M. Ahmed, A. van Geen, and B.C. Bostick, 2018, Quantitative drinking water arsenic concentrations in field environments using mobile phone photometry of field kits, Science of The Total Environment, volume 618, pages 579-585, https://doi.org/10.1016/j.scitotenv.2016.12.123↗.

Hoffman, T., P. Hynds, C. Schuster-Wallace, S. Dickson-Anderson, and A. Majury, 2019, Harnessing smart technology for private well risk assessment and communication. Water Security, volume 6, article number 100026, doi: 10.1016/j.wasec.2019.100026↗.

Hynds, P.D., B.D. Misstear, and L.W. Gill, 2013, Unregulated private wells in the Republic of Ireland: Consumer awareness, source susceptibility and protective actions. Journal of Environmental Management, volume 127, pages 278-288, doi: 10.1016/j.jenvman.2013.05.025↗.

Hynds P.D., M.K. Thomas, and K.D.M. Pintar, 2014, Contamination of groundwater systems in the US and Canada by enteric pathogens, 1990-2013: A review and pooled-analysis. PLoS ONE, volume 9, issue 5, article number e93301, doi: 10.1371/journal.pone.0093301↗.

Japan MHLW, 2020, Ministry of Health, Labor and Welfare, Water Supply in Japan. Japan Ministry of Health, Labor and Welfare, https://www.mhlw.go.jp/english/policy/health/water_supply/menu.html↗.

Jasechko, S. and D. Perrone, 2020, California's Central Valley groundwater wells run dry during recent drought. Earth’s Future, volume 8, article number e2019EF001339, pages 1-12, doi: 10.1029/2019EF001339↗.

Jasechko, S. and D. Perrone, 2021, Global groundwater wells at risk of running dry. Science, volume 372, issue 6540, pages 418-421, doi: 10.1126/science.abc2755↗.

Johnson, T.D., K. Belitz, and M.A. Lombard, 2019, Estimating domestic well locations and populations served in the contiguous U.S. for years 2000 and 2010. Science of the Total Environment, volume 687, pages 1261-1273, doi: 10.1016/j.scitotenv.2019.06.036↗.

Johnston, R., H. Heijnen, and P. Wurzel, 2001, Safe water technology, Chapter 6 *in* United Nations synthesis report on arsenic in drinking-water. World Health Organization, 390 pages, https://www.ircwash.org/sites/default/files/UNACC_2001-United.pdf↗.

Kennedy, G.W., 2020, Personal communication.

Kennedy, G.W., 2022, Water Well Record Databases and Their Uses. The Groundwater Project, Guelph, Ontario, Canada, https://gw-project.org/books/↗.

Kennedy, G.W., J. Drage, and G. Check, 2017, Development of indices to assess the potential impact of drought to private wells in Nova Scotia. GeoOttawa 2017 Conference, October 1-4, 2017, Ottawa, Ontario, Canada, https://novascotia.ca/natr/meb/data/pubs/cs/cs_me_2017-005.pdf↗.

Kennedy, G.W. and A. Polegato, 2017, Where does our tap water come from? An analysis of domestic water source and supply demographics in Nova Scotia. Nova Scotia Department of Natural Resources, Geoscience and Mines Branch, Open File Report ME 2017-004, https://novascotia.ca/natr/meb/data/pubs/17ofr04/ofr_me_2017-004.pdf↗.

Knobeloch, L., P. Gorski, M. Christenson and H. Anderson, 2013, Private drinking water quality in rural Wisconsin. J Environ Health, volume 75, number 7, article id PMID 23505770, pages 16-20, https://pubmed.ncbi.nlm.nih.gov/23505770/↗.

Krauss, S. and C. Griebler, 2011, Pathogenic Microorganisms and Viruses in Groundwater. Acatech, 70 pages, https://en.acatech.de/publication/pathogenic-microorganisms-and-viruses-in-groundwater/↗.

Kundu, D.K., B.J.M. van Vliet, and A. Gupta, 2016, The consolidation of deep tube well technology in safe drinking water provision: the case of arsenic mitigation in rural Bangladesh. Asian Journal of Technology Innovation, volume 24, number 2, pages 254-273, doi: 10.1080/19761597.2016.1190286↗.

Langley, R. L., Y. Kao, S.A. Mort, A. Bateman, B.D. Simpson, and B.J. Reich, 2015, Adverse neurodevelopmental effects and hearing loss in children associated with manganese in well water, North Carolina, USA. Journal of Environmental and Occupational Science, volume 4, issue 2, pages 62-69, doi: 10.5455/jeos.20150403060427↗.

Latchmore, T., P. Hynds, R. S. Brown, C. Schuster-Wallace, S. Dickson-Anderson, K. McDermott, and A. Majury, 2020, Analysis of a large spatiotemporal groundwater quality dataset, Ontario 2010-2017: Informing human health risk assessment and testing guidance for private drinking water wells. Science of the Total Environment, volume 738, article number 140382, doi: 10.1016/j.scitotenv.2020.140382↗.

Lee, D. and H.M. Murphy, 2020, Private wells and rural health: Groundwater contaminants of emerging concern. Current Environmental Health Reports, volume 7, pages 129-139, doi: 10.1007/s40572-020-00267-4↗.

Lee Pow Jackson, C. and M. Zarate-Bermudez, 2019, Exposure to contaminants among private well users in North Carolina: Enhancing the role of public health. Journal of Environmental Health, volume 81, number 8, pages 36-38, https://www.neha.org/sites/default/files/jeh/JEH4.19-Column-Direct-From-CDC-EHS.pdf↗.

Letman, M.M., J. Drage, A.M. Ryan, C. Lake, and R. Jamieson, 2018, Development of a leaching procedure to assess the risk of uranium leaching due to construction and demolition waste disposal. Waste Management, volume 78, pages 144-150, doi: 10.1016/j.wasman.2018.05.038↗.

Macler, B. and J. Merkle, 2000, Current knowledge on groundwater microbial pathogens and their control. Hydrogeology Journal, volume 8, pages 29-40, doi: 10.1007/PL00010972↗.

Mailloux, B.J., N.A. Procopio, M. Bakker, T. Chen, I. Choudhury, K.M. Ahmed, M.R.H. Mozumder, T. Ellis, S. Chillrud, and A. van Geen, 2021, Recommended sampling intervals for arsenic in private wells. Groundwater, volume 59, issue 1, pages 80-89, doi: 10.1111/gwat.13020↗.

Margat, J. and J. van der Gun, 2013, Groundwater Around the World; A Geographic Synopsis. CRC Press, Taylor and Francis Group, Boca Raton, 372 pages, https://www.un-igrac.org/sites/default/files/resources/files/Groundwater_around_world.pdf↗.

Moerman, D. and D. Briggins, 1994, Nova Scotia farm well water quality assurance study; Final report. Nova Scotia Department of Agriculture and Marketing and Nova Scotia Department of the Environment, 79 pages, https://novascotia.ca/nse/groundwater/docs/NSFarmWellWaterQualityAssuranceStudy1994.pdf↗.

Morris, L., S. Wilson, and W. Kelly, 2016, Methods of conducting effective outreach to private well owners—A literature review and model approach. Journal of Water Health, volume 14, issue 2, pages 167-182, doi: 10.2166/wh.2015.081↗.

Munene, A. and D.C. Hall, 2019, Factors influencing perceptions of private water quality in North America: A systematic review. Systematic Reviews, volume 8, number 111, doi: 10.1186/s13643-019-1013-9↗.

Murphy, H., M. Thomas, P. Schmidt, D. Medeiros, S. McFadyen, and K. Pintar, 2016, Estimating the burden of acute gastrointestinal illness due to *Giardia*, *Cryptosporidium*, Campylobacter, *E. coli* O157 and norovirus associated with private wells and small water systems in Canada. Epidemiology and Infection, volume 144, issue 7, pages 1355-1370, doi: 10.1017/S0950268815002071↗.

NIPH, 2017, Norwegian Institute of Public Health, Drinking water in Norway. Norwegian Institute of Public Health, Public Health Report, 4 pages, https://www.fhi.no/en/op/hin/infectious-diseases/drinking-water-in-Norway/↗.

NJDEP, 2008, New Jersey Department of Environmental Protection, Private well testing act program—Well test results for September 2002–April 2007. New Jersey Department of Environmental Protection, 75 pages, https://www.state.nj.us/dep/watersupply/pwta/pdf/pwta_report_final.pdf↗.

Nova Scotia Environment, 2010, Guide to groundwater approvals. Nova Scotia Department of the Environment, 19 pages, https://novascotia.ca/nse/water/docs/guideToGroundwaterWithdrawalApprovals.pdf↗.

Nova Scotia Environment, 2011, Guide to groundwater assessments for subdivisions services by private wells. Nova Scotia Department of the Environment, 33 pages, https://novascotia.ca/nse/groundwater/docs/Guide.to.Groundwater.Assessments.for.Subdivision.Developments.pdf↗,

Nova Scotia Environment and Labour, 2004, Before you construct a water well. Nova Scotia Department of Environment and Labour, Halifax, Nova Scotia, Canada, 40 pages, https://novascotia.ca/nse/water/docs/ConstructWell.pdf↗.

Nowlan, L., 2005, Buried Treasure: Groundwater Permitting and Pricing in Canada. The Walter and Duncan Gordon Foundation, 118 pages, https://waterbucket.ca/wcp/files/2006/12/Linda-Nowlan_Buried-Treasure_2005.pdf↗.

NZMH, 2020, New Zealand Ministry of Health, Annual report on drinking-water quality. Wellington: Ministry of Health, 101 pages, https://www.health.govt.nz/system/files/documents/publications/annual-report-drinking-water-quality-2018-2019-25june2020.pdf↗.

O'Dwyer, J., 2018, Groundwater risk application for local evaluations (GRAppLE). Ireland Department of Communications, Climate Change and Environment and the Geological Survey of Ireland, Research Program, Short Calls, Final Report, 10 pages, https://www.gsi.ie/documents/2017-sc-045_FinalReport_O%27Dwyer.pdf↗.

Olafsen Lackey, S., W.F. Myers, T.C. Christopherson, and J.J. Gottula, 2009, Nebraska grout task force in-situ study of grout material 2001-2006 and 2007 dye tests.

University of Nebraska – Lincoln, Conservation and Survey Division, number 413, 39 pages, https://digitalcommons.unl.edu/conservationsurvey/413↗.

Ontario Ministry of Environment and Energy, 1996, Procedure D-5-5 Technical guideline for private wells: Water supply assessment. Ontario, Canada, 11 pages, https://www.ontario.ca/page/d-5-5-private-wells-water-supply-assessment↗.

Owusu, C., G.S. Silverman, D.S. Vinson, R. Paul, K.M. Baker, and E.M. Delmelle, 2021, Predicting coliform presence in private wells as a function of well characteristics, parcel size and leach field soil rating. Science of the Total Environment, volume 758, article number 143701, doi: 10.1016/j.scitotenv.2020.143701↗.

Penstone, K. and J. Howe, 2020, National radon program: Behavioral study 2020, Final report. Health Canada and Deloitte, 28 pages, https://www.canada.ca/en/health-canada/services/publications/science-research-data/compilation-research-abstracts-2019-2020.html#112↗.

Perrone, D. and S. Jasechko, 2017, Dry groundwater wells in the western United States, Environmental Research Letters, volume 12, number 10, article number 104002, doi: 10.1088/1748-9326/aa8ac0↗.

Pieper, K.J., L.A. Krometis, D.L. Gallagher, B.L. Benham, and M. Edwards, 2015, Incidence of waterborne lead in private drinking water systems in Virginia. Journal of Water and Health, volume 13, issue 3, pages 897-908, doi: 10.2166/wh.2015.275↗.

Podgorski, J.E., P. Labhasetwar, D. Saha, and M. Berg, 2018, Prediction modeling and mapping of groundwater fluoride contamination throughout India. Environmental Science and Technology, volume 52, issue 17, pages 9889-9898, doi: 10.1021/acs.est.8b01679↗.

Province of New Brunswick, 1993, New Brunswick Regulation 93-203 under the Clean Water Act (O.C. 93-979). The Queens Printer for New Brunswick, Canada, 8 pages, http://laws.gnb.ca/en/showfulldoc/cr/93-203//20201128↗.

Province of Nova Scotia, 2016, News release: Legislative amendments will help municipalities support residents experiencing water shortages. Nova Scotia Municipal Affairs, 3 pages, https://novascotia.ca/news/release/?id=20161103002↗.

Province of Ontario, 1990, Regulation 903: Wells. Ontario, Canada, 24 pages, https://www.ontario.ca/laws/regulation/900903#BK1↗.

Re, V. and B.D.R. Misstear, 2017, Education and capacity development for groundwater resources management *in* Advances in Groundwater Governance, editors, K. Villholth, Lopez-Gunn, Conti, Garrido. and van der Gun, Chapter 11, CRC Press/Taylor and Francis, pages 212-229, doi: 10.1201/9781315210025↗.

Robertson, W., 2021, Septic System Impacts on Groundwater Quality. The Groundwater Project, Guelph, Ontario, Canada, 38 pages, https://gw-project.org/books/septic-system-impacts-on-groundwater-quality↗.

Samal, A.C., P. Bhattacharya, A. Mallick, M.M. Ali, J. Pyne, and S.C. Santra, 2015, A study to investigate fluoride contamination and fluoride exposure dose assessment in lateritic zones of West Bengal, India. Environmental Science and Pollution Research International, volume 22, number 8, pages 6220-6229, doi: 10.1007/s11356-014-3817-4↗.

Shamsudduha, M., G. Joseph, S.S. Haque, M.R. Khan, A. Zahid, and K.M.U. Ahmed, 2019, Multi-hazard groundwater risks to water supply from shallow depths: Challenges to achieving the sustainable development goals in Bangladesh. Exposure and Health, volume 12, pages 657-670, doi: 10.1007/s12403-019-00325-9↗.

Simpson, H., 2016, Private rural water supplies. Ontario Ministry of Agriculture, Food and Rural Affairs, Factsheet 15-047, 8 pages, http://www.omafra.gov.on.ca/english/engineer/facts/15-047.pdf↗.

Smith, A., M. Reacher, W. Smerdon, G.K. Adak, G. Nichols, and R.M. Chalmers, 2006, Outbreaks of waterborne infectious intestinal disease in England and Wales, 1992-2003. Epidemiology and Infection, volume 134, issue 6, pages 1141-1149, doi: 10.1017/S0950268806006406↗.

Smith, A.H., E.O. Lingas, and M. Rahman, 2000, Contamination of drinking-water by arsenic in Bangladesh: A public health emergency. Bulletin of the World Health Organization, volume 78, number 9, pages 1093-1103, https://www.who.int/bulletin/archives/78%289%291093.pdf?ua=1↗.

Smith, T., L.A. Krometis, C. Hagedorn, A.H. Lawrence, B. Benham, E. Ling, P. Ziegler, and S.W. Marmagas, 2014, Associations between fecal indicator bacteria prevalence and demographic data in private water supplies in Virginia. Journal of Water and Health, volume 12, issue 4, pages 824-834, doi: 10.2166/wh.2014.026↗.

State of Kansas, 2013, Article 30—Water well contractor's license; water well construction. Bureau of Water, Geology Section, Kansas Department of Health and Environment, 33 pages, https://sos.ks.gov/publications/pubs_kar_Regs.aspx?KAR=28-30↗.

Statistics Canada, 2017a, Households and the Environment Survey, Dwelling's Main Source of Water, https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810027401↗.

Statistics Canada, 2017b, Human activity and the Environment 2016—Human activity and the environment: Freshwater in Canada. Minister of Industry, 158 pages, https://www150.statcan.gc.ca/n1/pub/16-201-x/16-201-x2017000-eng.pdf↗.

Statistics Canada, 2019, Potable water use by sector and average daily use, https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810027101↗.

Stokstad, E., 2020, Deep Deficit—Droughts highlighted California's unsustainable use of groundwater–Now, the state is trying to refill its aquifers. Science, doi: 10.1126/science.abc2671↗.

Sutton, S., 2021, Virtual launch of the book "Self-Supply – Filling the Gaps in Public Water Supply Provision". Rural Water Supply Network – blog, https://rwsn.blog/2021/04/21/virtual-launch-of-the-book-self-supply/↗.

Sutton, S. and J. Butterworth, 2021, Self-Supply: Filling the Gaps in Public Water Supply Provision. Practical Action Publishing, 362 pages, doi: 10.3362/9781780448190↗.

Swistock, B.R., S. Clemens, W.E. Sharpe, and S. Rummel, 2013, Water quality and management of private drinking water wells in Pennsylvania. Journal of Environmental Health, volume 75, issue 6, pages 60-66, https://pubmed.ncbi.nlm.nih.gov/23397651/↗.

Umwelt Bundes Amt, 2012, Healthy water from private wells. Umwelt Bundes Amt, Press Release number 13/2012, 2 pages, https://www.umweltbundesamt.de/sites/default/files/medien/479/dokumente/pe12-013_healthy_water_from_house_wells1.pdf↗.

United Nations, 2018, World urbanization prospects: The 2018 revision, File 1: Population of urban and rural areas at mid-year (thousands) and percentage urban, 2018. United Nations, Department of Economic and Social Affairs, Population Division, https://population.un.org/wup/Download/↗.

USEPA, 2019, United States Environmental Protection Agency, Learn About Private Water Wells. United States Environmental Protection Agency, https://www.epa.gov/privatewells/learn-about-private-water-wells↗.

USGS, 2020, United States Geological Survey, Domestic wells in the United States, Where are Domestic Wells Located and How Many People Use Them?, https://ca.water.usgs.gov/projects/USGS-US-domestic-wells.html↗.

VanDerwerker, T., L. Zhang, E. Ling, B. Benham, and M. Schreiber, 2018, Evaluating geologic sources of arsenic in well water in Virginia (USA). International Journal of Environmental Research and Public Health, volume 15, issue 4, 787, doi: 10.3390/ijerph15040787↗.

Wallender, E.K., E.C. Ailes, J.S. Yoder, V.A. Roberts, and J.M. Brunkard, 2014, Contributing factors to disease outbreaks associated with untreated groundwater. Groundwater, volume 52, issue 6, pages 886-897, doi: 10.1111/gwat.12121↗.

Waller, R.M., 1994, Ground water and the rural homeowner. United States Geological Survey, 38 pages, https://pubs.usgs.gov/gip/gw_ruralhomeowner/↗.

WHO, 2004, World Health Organization, Fluoride in drinking-water—Background document for development of WHO guidelines for drinking-water quality. World Health Organization, Geneva, 17 pages, https://www.who.int/water_sanitation_health/dwq/chemicals/fluoride.pdf↗.

WHO, 2011, World Health Organization, How much water is needed in emergencies. WHO, Technical notes on drinking-water, sanitation and hygiene in emergencies, Technical Note 9, Geneva, 4 pages, https://www.who.int/water_sanitation_health/publications/2011/tn9_how_much_water_en.pdf↗.

WHO and UNICEF, 2017, World Health Organization and the United Nations Children's Fund, Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines. WHO and UNICEF, Geneva, 66 pages, https://www.who.int/mediacentre/news/releases/2017/launch-version-report-jmp-water-sanitation-hygiene.pdf↗.

Wisconsin Department of Agriculture, Trade and Consumer Protection, 2019, Targeted Sampling Summary Report, 2019. Wisconsin Department of Agriculture, Trade and Consumer Protection, Agricultural Resource Management Division, Environmental Quality Unit, 23 pages, https://datcp.wi.gov/Documents/TargetedSamplingSummary2019.pdf↗.

Wisconsin Department of Natural Resources, 2005, Special well casing depth area in Outagamie and Winnebago counties; Arsenic in drinking water. Wisconsin Department of Natural Resources and UW-Extension Winnebago County, 8 pages, https://www.co.winnebago.wi.us/sites/default/files/uploaded-files/SpecCaseArsenic.pdf↗.

Wisconsin Groundwater Coordinating Council, 2020, Report to the legislature, Fiscal year 2020. State of Wisconsin, 187 pages, https://dnr.wi.gov/topic/groundwater/documents/GCC/Report/FullReport.pdf↗.

van Halem, D., S.A. Bakker, G.L. Amy, and J.C. van Dijk, 2009, Arsenic in drinking water: A worldwide water quality concern for water supply companies. Drinking Water Engineering and Science, volume 2, pages 29-34, doi: 10.5194/dwes-2-29-2009↗.

Won, G., A. Gill ,and J. LeJune, 2013, Microbial quality and bacteria pathogens in private wells used for drinking water in northeastern Ohio. Journal of Water and Health, volume 11, issue 3, pages 555-562, doi: 10.2166/wh.2013.247↗.

Zheng, Y., 2017, Lessons learned from arsenic mitigation among private well households. Current Environmental Health Reports, volume 4, pages 373-382, doi: 10.1007/s40572-017-0157-9k.

Zheng, Y., 2020, Global solutions to a silent poison. Science, volume 368, issue 6493, pages 818-819, doi: 10.1126/science.abb9746↗.

Zheng, Y. and J.D. Ayotte, 2015, At the crossroads: Hazard assessment and reduction of health risks from arsenic in private well waters of the northeastern United States and Atlantic Canada. The Science of the Total Environment, volume 505, pages 1237-1247, doi: 10.1016/j.scitotenv.2014.10.089↗.

Zheng, Y. and S.V. Flanagan, 2017, The case for universal screening of private well water quality in the U.S. and testing requirements to achieve it: Evidence from arsenic. Environmental Health Perspectives, volume 125, number 8, article number 085002, doi: 10.1289/EHP629↗.

Zogorski, J.S., J.M. Carter, T. Ivahnenko, W.W. Lapham, M.J. Moran, B.L. Rowe, P.J. Squillace, and P.L. Toccalino, 2006, The quality of our Nation's waters, Volatile organic compounds in the Nation's ground water and drinking-water supply wells. United States Geological Survey Circular 1292, 101 pages, https://pubs.usgs.gov/circ/circ1292/pdf/circular1292.pdf↗.

12 Boxes

Box 1 - How Much Water is Needed from a Domestic Well?

In the United States, the average domestic water use is about 300 L/day per person (Dieter and Maupin, 2017). Using this amount as an example, a domestic well serving a single-family, four-person household needs to provide 1,200 L/day and must be able to provide this in a two-hour period to meet peak water demands. This can be achieved with a combination of well yield and water storage. The storage component can be supplied from both the standing water in the well and/or a storage tank. Wells with higher yields need less water storage to meet water quantity requirements compared to wells with lower yields.

The amount of available water stored in the well can be calculated from the well depth, well diameter, static water level, and the pump intake setting allowance from the bottom of the well. For example, consider a 20 m deep, 152 mm diameter drilled well with a static water level of 5 m below the ground surface, a pump intake setting allowance of 5 m (i.e., an available height of the water column of 10 m and a radius of 0.076 m), and a 9 L/min well yield will meet the 1,200 L/day requirement as illustrated in Figure Box 1-1 and using calculations as outlined in Box Table 1-1. However, if that same well had a lower yield of 6 L/min, then it would need to be at least 40 m deep to meet the 1,200 L/day requirement. The additional water stored in the casing of the 40 m deep well will make up for the lower well yield during peak demand. Figure Box 1-1 shows examples of well yields and depths that can meet the 1,200 L/day requirement and Table Box 1-1 shows the calculations used to prepare the figure.

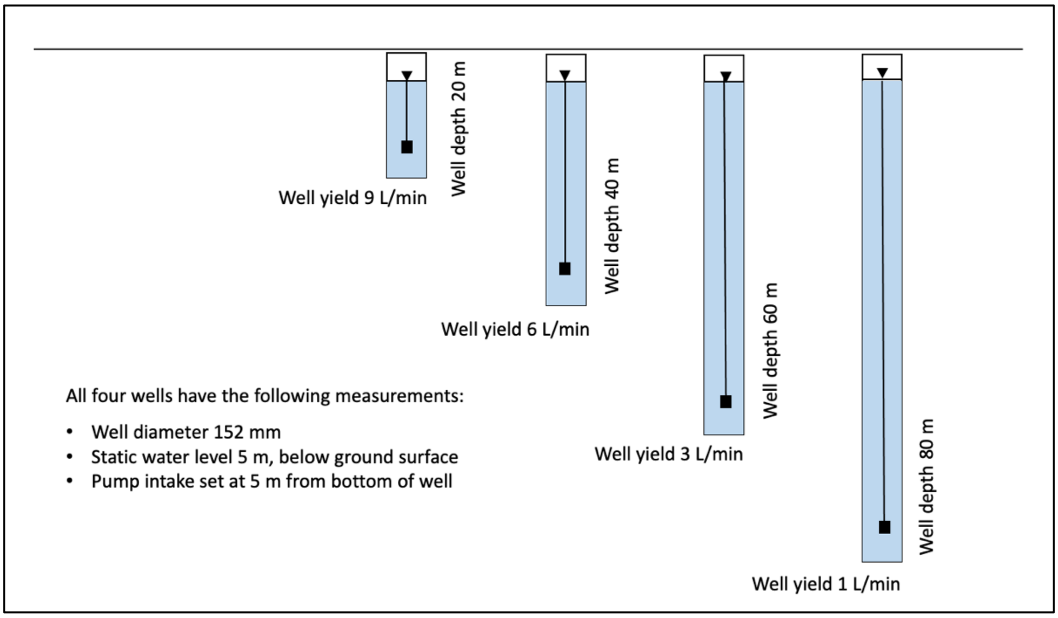

Figure Box 1-1 - Wells with various yields and depths that can meet domestic water quantity needs (modified from Nova Scotia Environment and Labour, 2004).

Table Box 1-1 - Water volume calculations for the wells in Figure Box 1-1.

Well Depth (m)	Well Yield (L/min)	Water Volume from 24-Hour Well Yield (L)	Water Volume from 2-Hour Well Yield (L)	Water Volume from Well Storage (L)	Total Water Volume Available from 2-Hour Well Yield and Well Storage (L)
20	9	12,960	1,080	181	1,261
40	6	8,640	720	544	1,264
60	3	4,320	360	907	1,267
80	1	1,440	120	1,270	1,390

Notes:

1. The target water supply volume of 1,200 L/day assumes a four-person household with each person using 300 L/day.
2. It is assumed that the entire water volume of 1,200 L/day will need to be supplied during a two-hour period to meet the peak demand. In addition, the well yield must be able to replenish this 1,200 L volume within 24 hours on an ongoing daily basis. To satisfy these requirements, the columns in this table named “Water Volume from 24-Hour Well Yield” and “Total Water Volume Available from 2-Hour Well Yield and Well Storage” must both meet or exceed the target volume of 1,200 L/day.
3. The “Water Volume from Well Storage” calculation assumes a 152 mm diameter well and that the available drawdown in the well is equal to the well depth minus 10 m (i.e., the static water level in the well is 5 m below ground surface and a 5 m allowance at the bottom of the well is used for a pump setting of 3 m off the bottom and a pump submergence of 2 m). The formula is as follows:
   Water Volume from Well Storage (L) =
   $(\text{Well Depth (m)} - 10 \text{ m})\ \pi\ r^2\ (1{,}000 \text{ L/m}^3) = (\text{Well Depth (m)} - 10)\ (3.146)\ (0.152/2)^2\ (1{,}000)$.

Return to the main text

Box 2 - Domestic Well Contamination Discovered by Health Effects

In Bangladesh and India, arsenic in groundwater was first discovered in domestic wells in the 1980s after patients were diagnosed with arsenic-induced skin lesions (Figure Box 2-1). The source of the arsenic was eventually discovered by analyzing the well water used by the patients. A subsequent regional well survey involving 200 villages with suspected arsenic contamination was carried out to determine the extent of the arsenic problem. Approximately 62 percent of the 33,000 wells sampled had arsenic concentrations greater than 100 μg/L (Smith et al., 2000). Since this discovery, Bangladesh has introduced programs to reduce arsenic exposure from well water, which primarily involve drilling deeper wells that avoid the high arsenic levels found in the local shallow aquifers (Kundu et al., 2016).

In Nova Scotia, Canada, arsenic contamination in groundwater was first discovered in 1976 after a patient at a local hospital was found to have chronic arsenic intoxication. The source of the arsenic was found to be the patient's domestic dug well. Historically, dug wells in Nova Scotia were sometimes constructed by lining the well walls with arsenopyrite-rich waste rock from gold mine sites. The arsenic concentration from the patient's dug well was 5,000 μg/L (Grantham and Jones, 1977), which is 500 times higher than the current Canadian drinking water guideline (10 μg/L). This discovery led to an investigation of arsenic levels in groundwater in former gold mining districts throughout the province. The investigations found that arsenic was not restricted to gold mining districts but was a province-wide problem associated with naturally occurring arsenic, particularly in metamorphic and plutonic bedrock aquifers. It is estimated that about 20 percent of domestic wells in the province exceed the drinking water quality guideline for arsenic, and it is now routine to analyze for arsenic in domestic well water in Nova Scotia.

Figure Box 2-1 - Skin lesions caused by arsenic in well water (photograph by World Health Organization (photograph from Smith et al., 2000).

A similar situation occurred in Nova Scotia, Canada, in 1978. In this case, previously unknown groundwater contamination was discovered by chance when a research project at Dalhousie University was studying the levels of various metals in the general population. The study found high levels of uranium in the hair samples collected from one of the study participants. Further investigations traced the source of the uranium to the domestic drilled well where the person obtained their drinking water (Grantham, 1986). As result of this discovery, regional well water surveys were carried out in the 1980s which found that naturally occurring uranium in groundwater is a province-wide problem, especially in plutonic and sedimentary bedrock aquifers. It is estimated that more than 6 percent of domestic wells in the province exceed the drinking water quality guideline for uranium (20 μg/L). It is now routine to analyze for uranium in domestic well water in Nova Scotia.

Return to where text linked to Box 2↥

Box 3 - Domestic Well Contamination Near a Waste Disposal Site

An example of a domestic well that has been contaminated by industrial activity is shown in Figure Box 3-1. This well is located adjacent to a construction and demolition debris disposal site in Nova Scotia, Canada. The site was used to store and transfer construction debris materials such as wallboard, concrete, and roofing shingles. The uranium concentration in this well increased from approximately 200 to 1,400 μg/L during the eight-year period of monitoring shown in Figure Box 3-1, which is 70 times greater than the Canadian drinking water guideline for uranium (20 μg/L).

In this case, there is no uranium in the leachate or waste materials at the site. However, it is suspected that leachate from the waste materials has migrated into the subsurface and caused naturally occurring uranium in the underlying bedrock aquifer to be mobilized (Letman et al., 2018). The leachate contains high levels of dissolved calcium, due to the dissolution of gypsum in waste wallboard, and this is suspected to have led to the formation of mobile calcium-uranyl-carbonate complexes. This example demonstrates how anthropogenic activities can cause unexpected contaminant mobilization that can affect domestic wells.

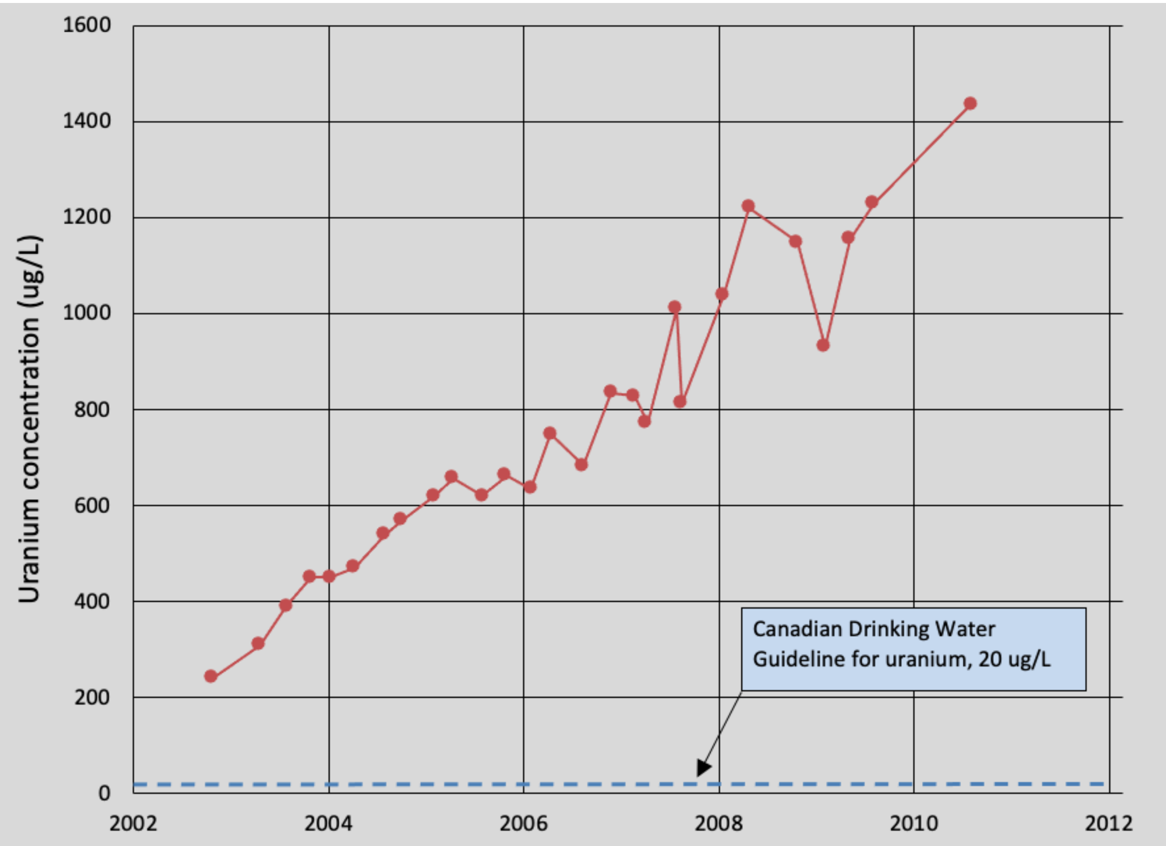

Figure Box 3-1 - Uranium concentration in a domestic well located adjacent to a construction demolition and debris disposal site (modified from Letman et al., 2018).

Return to where text linked to Box 3

13 Exercise Solutions

Solution Exercise 1

Determine if the well can supply the daily target water supply volume for the household by following the example calculations in Box 1. The target water supply volume is 860 L/day, based on four people using 215 L/day per person.

$$target\ water\ volume = 4\ person * \frac{215 \frac{L}{day}}{person} = 860\ L/day$$

Therefore, the well must be able to provide 860 L/day and must be able to provide this amount on both an ongoing daily basis and within a two-hour period to meet peak water demands. This can be achieved with a combination of well yield and water storage. The volume of water that can be supplied from the two-hour well yield and daily well yield is 240 L and 2,880 L, respectively.

$$2\ hour\ well\ yield = 2\ hr * 2\frac{L}{min} * 60\ min/hr = 240\ L$$

$$24\ hour\ well\ yield = 24\ hr * 2\frac{L}{min} * 60\ min/hr = 2{,}880\ L$$

The amount of available water stored in the well is calculated from the well depth (50 m), well diameter (152 mm), static water level (5 m), and pump setting allowance (5 m), and is calculated to be 726 L.

$$well\ storage\ volume\ = (well\ depth - static\ level - pump\ setting) * \pi r^2 =$$
$$(50\ m - 5\ m - 5\ m) * \pi \left(\frac{0.152\ m}{2}\right)^2 * 1{,}000\ L/m^3 = 726\ L$$

The total amount of water that this well can provide within a two-hour period is 966 L (i.e., by adding the two-hour well yield (240 L) and the well storage (726 L) together).

$$total\ water\ available\ in\ 2\ hour\ period = \ 2\ hour\ well\ yield + well\ storage$$
$$= 240\ L + 726 = 966\ L$$

It is concluded that the well can meet this household's needs because the target water supply of 860 L/day is exceeded by both the daily well yield (2,880 L/day) and the two-hour yield combined with well storage (966 L).

Return to Exercise 1↥

Solution Exercise 2

Search the internet to find the WHO arsenic drinking water guideline. For example, this WHO webpage↗ states that the current recommended limit for arsenic in drinking water is 10 μg/L. The arsenic concentration in the well exceeds this limit and, therefore, the water is not considered safe to drink. The well owner should either treat the water to reduce the arsenic level to below 10 μg/L (it is preferred to reduce arsenic levels as low as practical to minimize arsenic exposure) or use another source for drinking water that meets drinking water quality guidelines (e.g., bottled water, a different well, rainwater, treated surface water). To determine if the arsenic concentration in this well meets drinking water guidelines where you live, search the internet to find the drinking water guideline used in your jurisdiction.

Return to Exercise 2↥

Solution Exercise 3

Common reasons why well owners do not test their well water quality include:

- lack of concern;
- inconvenience of testing; and,
- cost of testing.

Well owners may also not be aware of the need for water quality testing or have the knowledge to carry out testing (e.g., where to get the sample bottles, what parameters to test the water for, where to get the water samples analyzed).

Examples of policies that can encourage domestic well owners to test their well include:

- mandatory testing when a new well is constructed; and,
- mandatory testing during a property sale.

Examples of initiatives that can address common barriers to water quality testing include:

- well owner education and outreach programs that help raise awareness about well water quality risks and provide information about how to test the water quality of a well (such as face-to-face community outreach activities and educational websites);
- making testing more convenient by providing well water sampling services, sample pick-up services, local sample drop-off sites, or mail-in sample options; and,
- providing free or subsidized water testing programs.

Return to Exercise 3↥

Solution Exercise 4

Several steps can be taken during the planning, construction, and operation of a well to protect it from contamination and ensure the water is safe to drink.

1. At the planning stage, it is important to identify potential contaminant sources (such as septic systems, oil tanks, farmyards, and manure spreading activities) and keep the well away from these sources and upgradient from them, if possible.
2. During well construction, it is important to follow local well construction regulations (if applicable), including the use of proper well construction materials, proper well design, and a licensed well contractor. Well construction features that help reduce the risk of contamination include adequate casing, annular seal, and a sanitary well cap.
3. Once the well is in operation, it should be regularly maintained (e.g., the casing and well cap should be routinely inspected to confirm they are in good condition), and the water should be regularly tested. Well owners should also maintain their septic system and keep contaminant sources away from their well. This includes ensuring that petroleum, paints, and household solvents are properly stored and kept away from the well, and lawn fertilizers, pesticides, and de-icing road salt are not applied near the well. If water treatment equipment is used, it should be maintained in accordance with the manufacturer's recommendations and tested regularly to confirm it is providing effective treatment.

Return to Exercise 4↑

14 About the Author

John Drage is a senior hydrogeologist with the Nova Scotia Geological Survey in Nova Scotia, Canada. He holds a Bachelor in Sciences in Geology from Dalhousie University and a Master of Science in Civil Engineering from the University of New Brunswick. John works on groundwater and geohazard projects and focuses on providing scientific advice to support the management and protection of groundwater in Nova Scotia. His geohazard work has included mapping and raising awareness about radon gas in indoor air and sinkholes in karst terrane. His groundwater work has included investigations of naturally occurring groundwater contaminants, such as arsenic, uranium, and radionuclides. John has worked to improve regional groundwater monitoring and has developed a real-time, community-based network to monitor groundwater levels using low-cost sensors in domestic wells. He has contributed to several books and journal articles and has worked as a consultant on geoscience and environmental projects in Canada, New Zealand, Australia, and the Philippines.

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