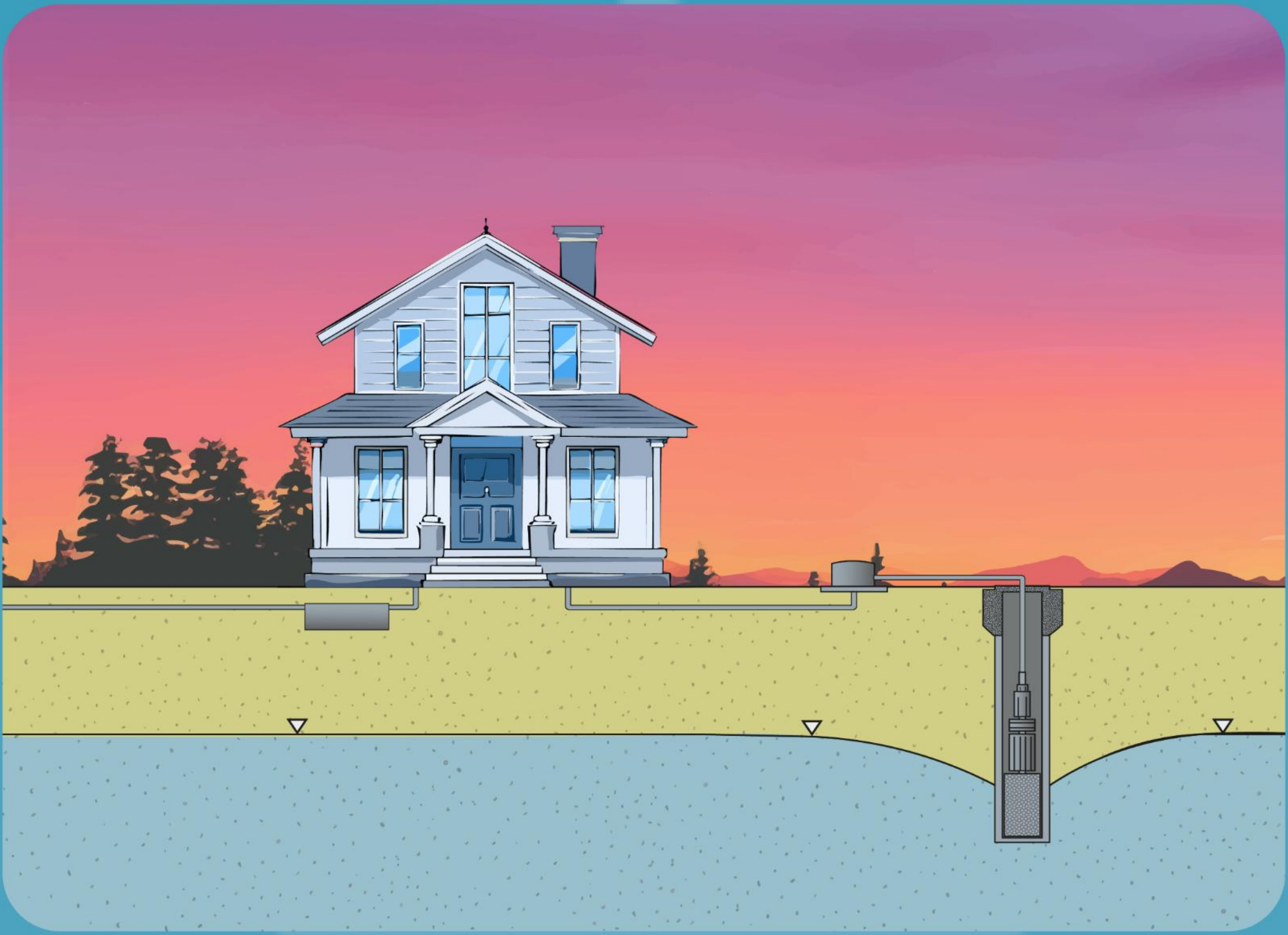

Best Practices for Owners of Domestic Wells in Alluvial Aquifers

Kristine Uhlman

THE GROUNDWATER PROJECT

Best Practices for
Owners of Domestic Wells
in Alluvial Aquifers

The Groundwater Project

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Best Practices for Owners of Domestic Wells in Alluvial Aquifers

The Groundwater Project
Guelph, Ontario, Canada

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Dedication

When I graduated from the University of Arizona, Department of Hydrology in 1974, the faculty treated me like a student, not like a girl. Their positive and professional treatment made me into a scientist! Thank you, Professors John W. Harshbarger, Eugene S. Simpson, Simon Ince, and Chester C. Kisiel.

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The Groundwater Project Foreword

The 2022 United Nations (UN) World Water Day theme "*Groundwater – Making the Invisible Visible*" was pivotal in raising global awareness about groundwater as an invaluable resource, and the year concluded with the UN Water Summit on Groundwater at the UNESCO headquarters. One of the key outcomes of the Summit was a call for governments and other stakeholders to scale up their efforts to better manage groundwater.

Groundwater makes up 99% of all liquid fresh water on Earth, underpinning its importance in providing drinking water to the world, sustaining food production, and maintaining healthy ecosystems. Many important global organizations have concluded that there is a freshwater crisis and given that nearly all freshwater is groundwater, the freshwater crisis is a groundwater crisis. During drought in many locales, groundwater is the only freshwater available, putting even more pressure on groundwater resources.

According to the World Health Organization and UNICEF (WHO/UNICEF, 2025↗), 2.1 billion people (1 in 4) live without safely managed drinking water and 3.4 billion people (4 in 10) live without safely managed sanitation. With groundwater directly supporting 8 of the 17 UN Sustainable Development Goals, groundwater is an invaluable resource. Safe and reliable access to groundwater directly supports the 2026 UN World Water Day (March 22) Theme "*Water and Gender Equality*" focusing on ensuring that women and girls have equal rights and leadership in water management.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, pioneers in advancing the understanding of groundwater by providing groundwater education to everyone. Recognizing that the world needs more highly skilled groundwater scientists to solve the water crisis, the GW-Project plays a pivotal role in creating the knowledge base for building the much-needed human capacity for the development and management of groundwater.

The GW-Project gained global recognition with publication of 64 original books, 94 translated books (in 59 languages), 7 interactive groundwater educational tools/modules, and over 50 high-quality educational videos, all made possible by a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines throughout 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project operates with the philosophy that high-quality groundwater education should be freely accessible for everyone, and to that end our publications are available free-of-charge on our website↗. We thank our corporate sponsors and private donors for making this possible. Please consider sponsoring the GW-Project so we can continue to provide groundwater education free of charge.

The Groundwater Project *Board of Directors*, January 2026

Foreword

There are approximately sixty million homes in the USA and Canada that receive their household water from private wells on the property. These are known as domestic wells because they are part of the property ownership. State and/or local regulations typically apply to the design, drilling, and construction of the well. However, following well construction, the state of the well and its safety for drinking water are the responsibility of the property owner. In contrast to the inspections that are required by government agencies when a house is built or when a kitchen is renovated, there are no inspections conducted when a private well is drilled.

Because all groundwater is in motion, the groundwater that flows to the well originates beyond the property. There are no requirements that prevent drilling a private well near contamination sources. The requirements for well design are the same even if the hydrogeologic conditions are exceptionally conducive to contamination or the well is at risk of drying out due to water levels declining in the area. Thus, the well owner needs to be knowledgeable about the well to avoid or adapt to deficiencies associated with the well that could cause harm to human health or result in a lack of sufficient water supply. The well owner needs to be vigilant with awareness of evidence that points to potentially harmful conditions.

This book is designed for owners of private wells in alluvial aquifers, to provide information they need to know for such vigilance. In each household relying on a private well, one person needs to take on the responsibility for this vigilance. Understanding the content of this book is a starting point. The author of this book has experience in hydrogeological consulting, and for two decades before retiring she was engaged by the State of Arizona, USA, to educate and liaison with well owners, especially private well owners. This book evolved from the many documents she prepared directed at the particular needs of well owners.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, January 2026

Preface

At the University of Arizona Hydrology field camp in 1973 in Safford, Arizona, USA, all the book learning, equations, and chemistry burst out of a well as crystal clear, cold water arching out of a turbine pump. In the middle of the dry desert, water! The sudden realization that water, so unseen at the surface, was held underground! Curiosity drove me to learn more. First employed by the US Geological Survey, I was handed the tools to learn, to discover, and to build. With this book, I share the knowledge I gained during my career with you to allow you to understand that yes, there are oceans of water beneath our feet, some of it good enough to drink!

Intuitively, one might not expect clean water to come out of a hole in the ground, but it does, and that water sustains us. This book offers guidance to help readers protect their water supply and maintain their well for generations of service. I provide information about what to expect in the chemistry of the water, how to sample and analyze the water, and how to remove any contaminants that are discovered.

During twenty-five years working in environmental remediation, I learned what can go wrong and how to fix errors of the past. Then, over the following twenty years at the University of Arizona, USA, I explained groundwater to students as well as the public, and I was met with the most amazing questions. What I have discovered from my consulting and teaching careers, and from finding answers to these questions, is here for readers of this book.

As you fill your water jug, this book can help you understand how that water originally fell out of the sky, seeped into the ground, and gathered into your aquifer; as well as how you can maintain and monitor your well to ensure long-term supply. Then, if necessary, how to best treat your water to meet drinking water standards. In this process, I hope you begin to share my enthusiasm for the science.

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I deeply appreciate the thorough and useful reviews of and contributions to this book by the following individuals:

- Dr. Hugh Simpson, Adjunct Professor, School of Environmental Design and Rural Development, University of Guelph, Canada;
- Dr. Jana Levison, Associate Professor, School of Engineering, University of Guelph, Canada;
- Dr. Steve Spayd, Adjunct Faculty, Environmental and Occupational Health Sciences Institute, Rutgers University, USA.

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I gratefully acknowledge graphic support provided by Lisa Angeles Watanabe, Vladimir Novokshchenov, and Janick Artiola. Individual photo credits are provided on each image, and those images obtained from other sources are indicated. This book follows similar writings I completed for both the University of Arizona, Tucson, USA, University of Texas at Austin, USA, and Texas A&M, College Station, USA. I appreciate the contributions of Susanna Eden.

The sources of figures and/or tables are cited in their captions. Where a citation does not appear, the figures and/or tables are original to this book.

1 Well Educated

This well-owner's guide of best management practices to sustain your water supply aims to assist you in learning more about a topic of the utmost importance—your drinking water. Gaining a better understanding about your well—its components and maintenance, geology, and water quality—will ultimately empower you, the well owner, to be able to better maintain and monitor your well and your water supply.

Carefully monitoring and keeping a detailed record of any maintenance done on your well and any water tests conducted can help you prevent future problems from occurring and ensure safe drinking water. For example, noting the rapid on/off cycling of your well pump may indicate a lowered water table or a problem with the pressure tank. Knowing which contaminants may be present in your well water will help you choose which water quality tests to request and the best water treatment, should it be needed.

This book addresses aquifers and wells, common well-water contaminants, drinking-water-quality standards, and the potential symptoms encountered from unsafe well water. Recommended water treatment options are also provided that may help you manage your well-water quality. As an introduction to an amazing well from the last century, Figure 1 shows a flowing artesian well in Texas, USA, depicted on a postcard.

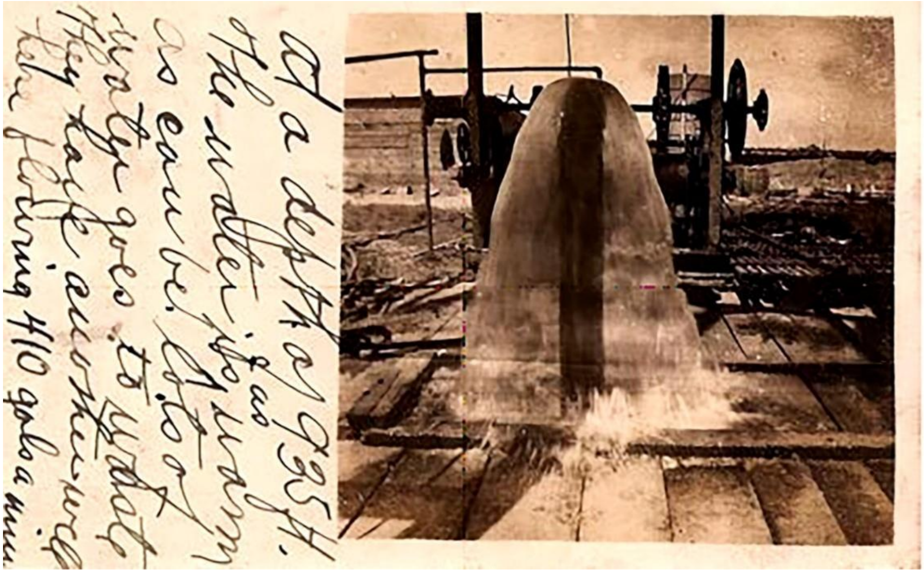

Figure 1- Flowing artesian ranch well in southwest USA (from the private collection of Dr. Robert Mace; originally published in Uhlman et al., 2012).

1.1 Aquifers and Wells

Understanding your aquifer and its geologic setting is important for managing your well. Section 2 introduces the reader to the geologic conditions that form aquifers across North America. Geology may contribute to some well water-quality concerns, such as naturally occurring elevated concentrations of arsenic, as well as other constituents. This

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book can help you identify whether such constituents might impact your well. Well operation, maintenance, and yield are the topics of Sections 3 and 4. These sections clarify the rules and regulations that guide the installation of a domestic water well, explain well system components, identify common maintenance concerns, and provide recommendations for the efficient operation of your well.

1.2 Your Well - Your Responsibility

As a private well owner, you are responsible for the upkeep of your well and the quality of water it produces. While a loan provider or real estate company may require a water quality test, there are no federal (USA and Canada) nor provincial (Canada) laws that require a well owner to have their private well tested, although several states in the USA have initiated water quality policies. Bowen and others (2019) list twenty-three of the fifty states as having some water quality policy related to domestic wells. They note that even in states with standards for water quality testing, testing is typically infrequent or not conducted at all. This means that while public water systems must meet certain water quality standards to provide safe, potable drinking water for their customers, well owners are solely responsible for testing their water and thereby protecting the health of anyone who drinks it.

1.3 Short List of Potential Contaminants in Well Water: Your Well and Your Health

Contaminants in well water may be present for a variety of reasons. Some may be present due to human sources; others may occur naturally. Some contaminants, such as dissolved metals and nitrates, may be present due to both human and natural sources. The following subsection presents a subset of common well contaminants, information about their sources, and possible health effects. It is important to remember that the presence of a contaminant in groundwater does not necessarily mean it will impact human health. The duration of exposure (i.e., how long you have been drinking, bathing, and/or cooking with the water), the concentration of the contaminant, your health, and many other “puzzle pieces” factor into whether a contaminant can make you ill. This short list of contaminants is further discussed in Sections 5 and 6, including sampling and analyzing your well water for these constituents.

1.3.1 Bacteria

Coliform bacteria can be found naturally in the environment. They are also present in the digestive systems of animals and humans. Most coliform bacteria are unlikely to cause illness; instead, they are used to indicate the presence of other bacteria, viruses, or parasites (protozoa) that could make you ill. The specific presence of *E. coli* in well water is usually an indicator of fecal or sewage contamination, and this is one coliform bacterium

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that can make you sick. In Canada, water can be tested for bacterial indicators without cost to the well owner.

1.3.2 Nitrates

Nitrates can occur naturally in groundwater and are usually found at concentrations that do not cause health problems. However, high levels of nitrates found in well water may be present due to contamination. This contamination may be from over-application or misuse of fertilizers, a leaking septic system (or one that is too close to the well), and animal waste. For infants and young children, nitrates can interfere with the body's ability to properly distribute oxygen and can cause a life-threatening situation called "Blue Baby Syndrome." This can cause the skin to become discolored to a pale gray or blue. At high enough concentrations, nitrate can affect the nervous system or even cause death.

1.3.3 Arsenic

Arsenic occurs naturally in the environment and can also be present in groundwater due to human activities. Concentrations may increase during drought. Long-term exposure to this element is correlated with skin problems and several different kinds of cancer.

1.3.4 Radon

Radon is an odorless, tasteless gas that is not visible. It forms when a radioactive metal, like radium, breaks down (decays) in rocks, and can be present in several different types of aquifers. The gas can dissolve into groundwater and could be present in drinking water from a private well. Radon gas can be released into the air of your home when the water is used for domestic purposes, such as showering and doing laundry. When inhaled, radon can increase the risk of lung cancer, and it is the primary cause of lung cancer among non-smokers.

1.4 More Information

It is useful for well owners to understand more about groundwater in general. Groundwater makes up 99% of Earth's liquid fresh water and is vital for the sustenance of rivers, lakes, wetlands, and ecological systems. However, few people see groundwater because it is hidden beneath the land surface. To overcome this "hiddenness", the Groundwater Project published a book that you may enjoy titled Groundwater in Our Water Cycle↗ by Poeter and others (2020). Additional Groundwater Project books that well owners may find interesting are Domestic Wells – Introduction and Overview↗ (Drage, 2022) and Public Health Risk Assessment and Risk Management for Safe Drinking Water↗ (Hrudey, 2024).

2 What is an Alluvial Aquifer?

Geology and climate determine how much groundwater is held in the subsurface. Rainfall and snowmelt seep into the ground and when the infiltrating water reaches groundwater it is called recharge. The recharged water is stored in a geologic formation. An aquifer is an underground geologic formation that is porous enough to hold water and is sufficiently permeable to produce, yield, or transmit, usable quantities of water to a well or spring. Permeability of the material is described by the term hydraulic conductivity, which when multiplied by the gradient of the groundwater levels indicates the flow rate. If a formation cannot store and transmit usable amounts of water, it cannot be considered an aquifer.

Knowledge of the local geology facilitates understanding how much water a well can yield, what the naturally occurring chemistry of the groundwater may be, and how vulnerable an aquifer may be to contamination. Climate conditions control how much water recharges the aquifer and how sustainable the aquifer may be during drought conditions. Typically, little or no recharge occurs in arid regions.

2.1 Aquifer Characteristics and Water Movement to Wells

Aquifers are formed from two broad types of geologic materials, or a combination of both: unconsolidated aquifer material and consolidated aquifer material with secondary porosity (Figure 2).

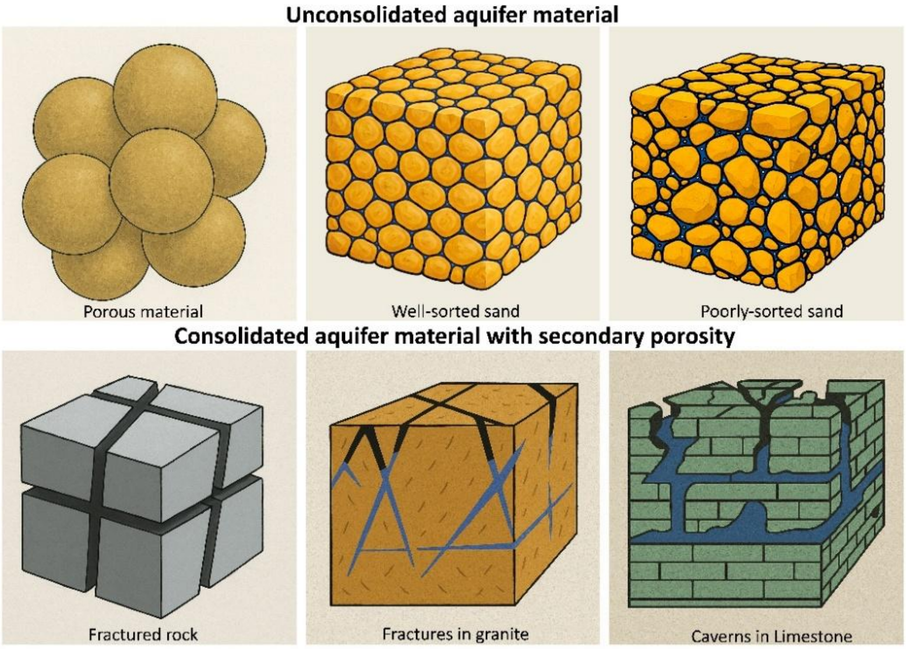

Figure 2 - Aquifers can be composed of unconsolidated materials, consolidated materials, or a combination of both, and the consolidated material may be fractured or cavernous. The interconnected spaces within the rock are called porosity, When that porosity is developed after the rock is formed—for example, by fracturing the rock—it is called secondary porosity, Alluvial aquifers are comprised of unconsolidated material. (modified from Heath, 1983).

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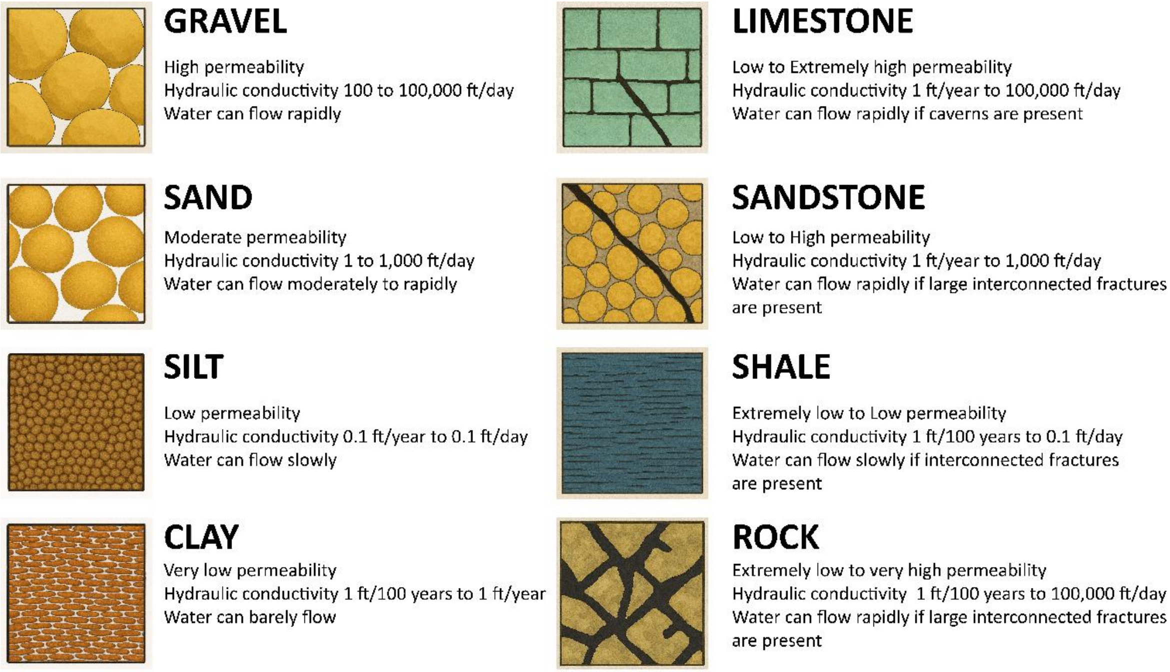
- Unconsolidated (loose) geologic materials include, for example, sands and gravels of river valleys, glacial deposits, dunes, and alluvial basins with varied composition like those in the North American Southwest (USA and Mexico). In unconsolidated aquifers, water is held in the spaces (pores) between grains of clay, silt, sand, and gravel.
- Consolidated (i.e., bound or cemented) or semi-consolidated rock materials include, for example, sandstone, shale, limestone, granite, and basalt. In consolidated aquifers, the water is primarily held in fractures and cracks in the rock. In many situations, a borehole/well in a consolidated rock aquifer does not need casing to prevent the rock from collapsing into the hole and does not need a well screen to prevent fine particles of the geologic material from entering the well.

This book focuses on domestic wells in unconsolidated material. Aquifers with different geologic characteristics have different porosity and hydraulic conductivity characteristics. The interconnected space within the grains or rock is termed porosity. When porosity is developed after the rock is formed, for example by faulting or fracturing, it is termed secondary porosity. The hydraulic conductivity of an aquifer is the capacity of the material (soil or rock) to transmit water. Variations in porosity and permeability within a single aquifer, and across aquifers, cause water to move at different speeds in different locations below ground.

Unconsolidated materials with large, well-connected pores have high porosity and permeability, while unconsolidated materials with small, poorly connected pores have low porosity and permeability. Consolidated materials with large, well-connected fractures or caverns have high porosity and permeability, while consolidated materials with small, poorly connected fractures and caverns have low porosity and permeability.

A semi-consolidated rock, such as sandstone, can hold a slope in a road cut better than unconsolidated material. Yet, unlike igneous rocks, sandstone holds water in both the primary and secondary porosity. The primary porosity of the rock may be very low but after faulting or fracturing the induced secondary porosity may allow water to flow rapidly through the aquifer, such as the sandstone in Figure 3.



GRAVEL
High permeability
Hydraulic conductivity 100 to 100,000 ft/day
Water can flow rapidly

LIMESTONE
Low to Extremely high permeability
Hydraulic conductivity 1 ft/year to 100,000 ft/day
Water can flow rapidly if caverns are present

SAND
Moderate permeability
Hydraulic conductivity 1 to 1,000 ft/day
Water can flow moderately to rapidly

SANDSTONE
Low to High permeability
Hydraulic conductivity 1 ft/year to 1,000 ft/day
Water can flow rapidly if large interconnected fractures are present

SILT
Low permeability
Hydraulic conductivity 0.1 ft/year to 0.1 ft/day
Water can flow slowly

SHALE
Extremely low to Low permeability
Hydraulic conductivity 1 ft/100 years to 0.1 ft/day
Water can flow slowly if interconnected fractures are present

CLAY
Very low permeability
Hydraulic conductivity 1 ft/100 years to 1 ft/year
Water can barely flow

ROCK
Extremely low to very high permeability
Hydraulic conductivity 1 ft/100 years to 100,000 ft/day
Water can flow rapidly if large interconnected fractures are present

Figure 3 - Hydraulic conductivity of different aquifer materials. Permeability is the ease with which water can move through an aquifer (modified from Artiola & Uhlman, 2009).

Aquifers can be categorized into two types:

- An *unconfined aquifer* (also known as a *water table aquifer*) occurs in geologic settings where water from rain and snow can seep through the soils and directly recharge the aquifer.
- A *confined (or artesian) aquifer* is overlain by a confining, low-permeability layer of geology, often called an aquitard. The low permeability prevents water from entering the aquifer directly and slows upward leakage from the aquifer such that pressure may be high enough to casue water to flow naturally from a well.

The upper boundary of an unconfined aquifer is the water table and is defined by the surface of the fully saturated geologic materials. Above the water table the geologic formation and soils are not saturated but will contain some moisture. This zone is called the unsaturated, or *vadose*, zone.

In a confined aquifer, water generally does not infiltrate into the aquifer from directly above, rather entering from the sides, as shown in Figure 4. The elevation of the recharge can generate high pressures in lower zones of the aquifer, resulting in an artesian well. If the pressure is great enough that water rises above the land surface when a well is installed, the well is referred to as a flowing artesian well, which is depicted in Figure 4 and Figure 5. Flowing wells can also occur in low areas without a confining layer.

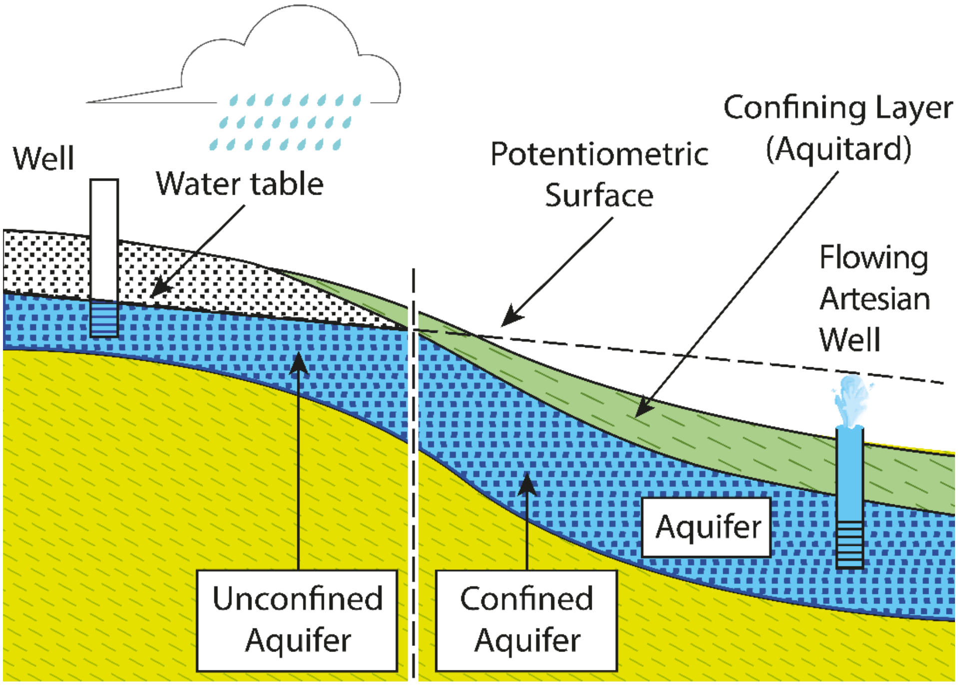


Figure 4 - Flowing artesian wells are found in a confined aquifer where the water level in the well is higher than the land surface. The dashed vertical line indicates the transition from unconfined to confined conditions. Because the confining layer has low permeability, flow through it is slow.

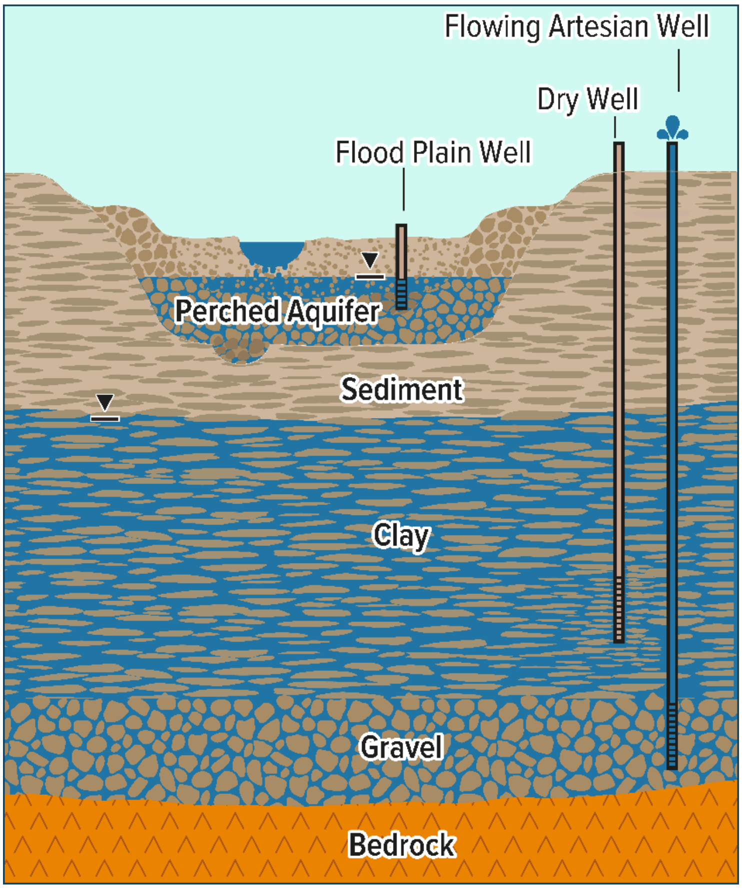


Figure 5 - Detail of a flood-plain aquifer and flowing artesian well. The dry well is within dense clay that does not allow water to flow into the well, whereas the gravel allows free flow of water into the flowing artesian well.

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The rate at which groundwater moves through an aquifer toward a well depends on the rate at which the well is pumped. When the well is pumped, the water level in the well declines causing a hydraulic gradient for water to flow from the aquifer to the well. As pumping continues, a cone of depression forms around the well either as a sloping water table in an unconfined aquifer or as a depression in the potentiometric surface in a confined aquifer. A steeper cone forms in thinner, less-permeable aquifers while a shallower cone forms in thicker, more-permeable aquifers. The cone is known as a *drawdown cone* or a *cone of depression* because pumping water from a well "draws down" or "depresses" the water table, as shown in Figure 6.

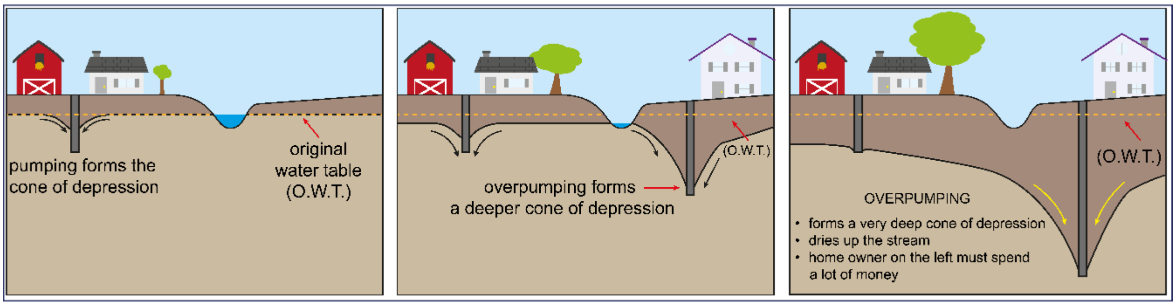

Figure 6 - Overlapping drawdown cones can lower the water table to the point where neighboring homeowner wells and streams go dry. In this example, the homeowner on the left must incur the expense of drilling a deeper well.

The rate of pumping needs to be within the range that the aquifer can provide, or the water level will decline to the elevation where the well becomes dry. The shape and size of the cone depend on the pumping rate, aquifer properties, and the direction of regional groundwater flow.

- In an unconsolidated aquifer, the cone of depression forms around the well, generally in an ever-expanding oval shape, skewed in the direction where regional flow approaches the well. The depth of the cone is dependent on the pumping rate and the aquifer's capacity to sustain the flow.
- In a highly permeable aquifer, the cone may extend for hundreds of feet but be only a few inches deep.

Several problems can arise from cones of depression formed by pumping.

- Water and contaminants in the cone around the well can eventually be captured and drawn into the well and water supply system.
- As depicted in Figure 6, if the cone extends beneath a river or stream, river water will flow through the riverbed into the aquifer and the river may go dry. As a result of pumping that began in the mid-twentieth century, many rivers in arid climates have gone dry.
- As regional water-table elevations drop in alluvial aquifers (described in Section 2.2), the land surface subsides, resulting in large cracks at the ground surface. Subsidence causes damage to infrastructure, particularly building foundations.

- If the cone extends beneath a source of pollution, such as a landfill, an agricultural field receiving excessive fertilizers or pesticides, or a leaky gas station storage tank, groundwater pumping may draw the contaminants into the well and your water supply.
- If a cone intercepts a neighboring cone of depression from a nearby well, both wells may go dry faster than if just one well were pumping.

If the water level in the well recovers slowly during times when the pump is turned off, the well may temporarily run dry when too much water is used rapidly, such as with heavy water uses over a weekend doing laundry. Using the water more uniformly throughout the week or month will help prevent this problem.

2.2 Alluvial Basins

Alluvial basins are formed when the earth's crust is stretched and broken by faults, causing the vertical displacement of large, consolidated blocks of bedrock which produces mountain ranges and basins (broad valleys). These basins are filled with alluvium that forms excellent unconsolidated aquifers. From mountain top to the valley basement, the average displacement may be as much as approximately 10,000 ft (3048 m) with the valleys filled by up to 7,000 ft (2134 m) of gravel, sand, and silt. Known as *basin fill* aquifers, the sediments or alluvial materials that fill these valleys originate from the adjacent mountains and typically consist of sands and gravels produced by the weathering of rock. The valleys are filled with materials produced by the actions of erosion and gravity transport as well as by washes and streams, as shown in Figure 7 and Figure 8. Larger sediments, such as boulders and gravel, tend to be deposited near their source along the basin boundaries, and finer-grained material, such as fine-grained silt and clay, is transported toward the valley center by wind and water.

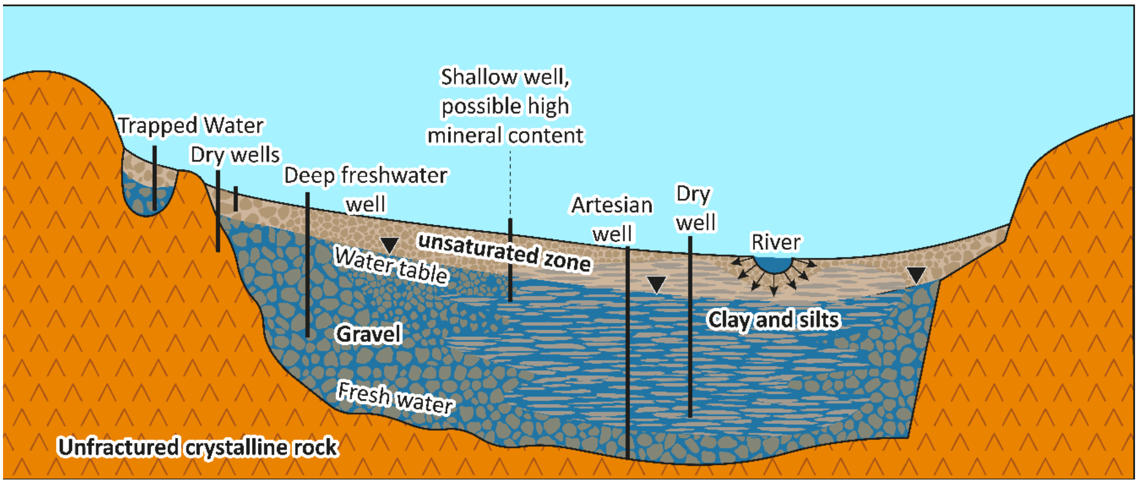

Figure 7 - In arid climates, gravity and erosion move unconsolidated sediment into valley basins, forming alluvial aquifers (modified from Artiola & Uhlman, 2009).

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Figure 8 - Typical alluvial basin sediment fill; the interior of your aquifer may look like this (modified from Artiola et al., 2017).

When water moves through soil and alluvium, it dissolves calcium and other minerals; these minerals may later be deposited further along the flow path as *caliche* in the pore spaces between grains. Through time, the unconsolidated sediments may become compacted and eventually transition into cemented consolidated rock as caliche fills the pore spaces. Cemented sediments become barriers to erosion and the movement of groundwater.

During the formation of alluvial basins, river drainage through the valley is often blocked, producing lakes in the valley basin during periods of wet climate, as shown in Figure 9. In these cases, sediment basin fill may include deposits of lake-bottom clay. During subsequent excessively arid climates, basin lakes evaporate, leaving layers of salt, gypsum, and other minerals.

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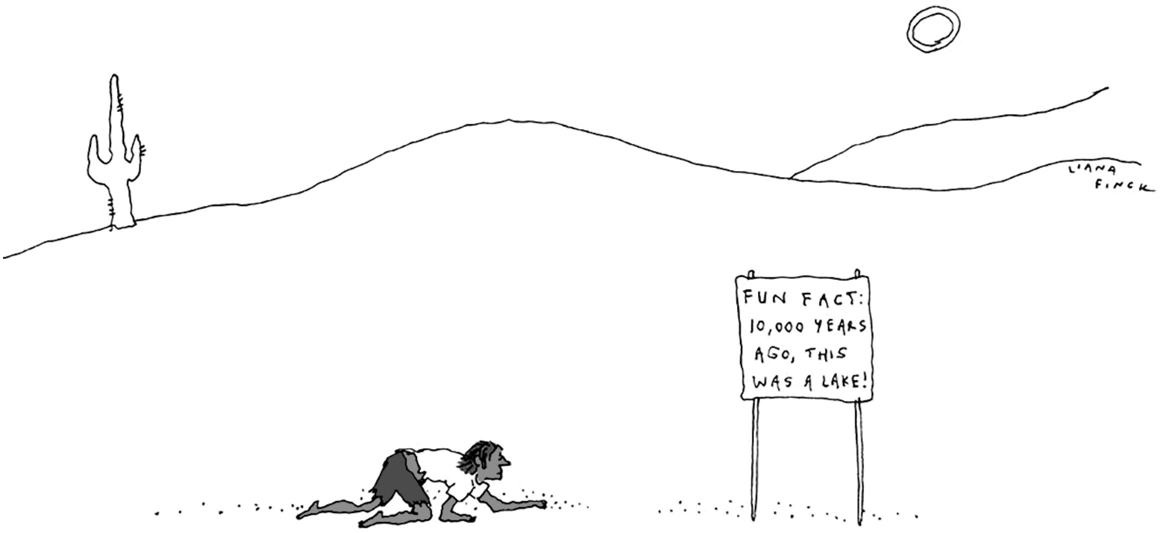

Figure 9 - Geologic clues reveal past climates; formation of lake clays and/or salt layers usually takes tens of thousands to millions of years (used with permission credit: Liana Finck/The New Yorker Collection/The Cartoon Bank).

Increased groundwater pumping from alluvial basins in major agricultural areas or groundwater-dependent urban areas lowers water table elevations and can result in land subsidence in some locations. In addition, because of dropping water tables and local geology, wells in these sediments may require drilling to greater depths to reach a water-bearing zone.

Groundwater is sometimes unexpectedly found in pockets of buried alluvial sand and gravel and lenses of ancient river gravel channels. In addition, the depth to water and the thickness of the water-saturated zone of the geologic formation and other related factors will control the ability of a well to yield sufficient volumes of water.

2.3 Aquifer Recharge

All water on earth is constantly moving and being recycled via a continuous process known as the water cycle, or hydrologic cycle. The hydrologic (water movement) cycle is driven by the energy of the sun and the force of gravity. Water moves by evaporation, condensation, precipitation, transpiration (consumption and evaporation from plants), infiltration, and runoff to rivers and streams. In arid and semi-arid climates, recharge to groundwater is estimated to be 2 to 3 percent of the average annual rainfall. For an arid climate with less than 10 inches of precipitation, this is less than 0.2 inches of recharge. In an alluvial aquifer with a 25 percent porosity, 0.2 inches of recharge would raise the water table 0.8 inches if water did not flow away from the recharge area. We typically measure water level to approximately 0.1 inches. In humid climates, depending on precipitation, existing soil moisture, and soil type, recharge is highly variable and could be as much as 15 in/year. As rainfall infiltrates into the ground across the seasons, the water table moves up and down, as shown in Figure 10. Plotting the measured groundwater elevation or depth to the water table from land surface in graph form is known as a *hydrograph*.

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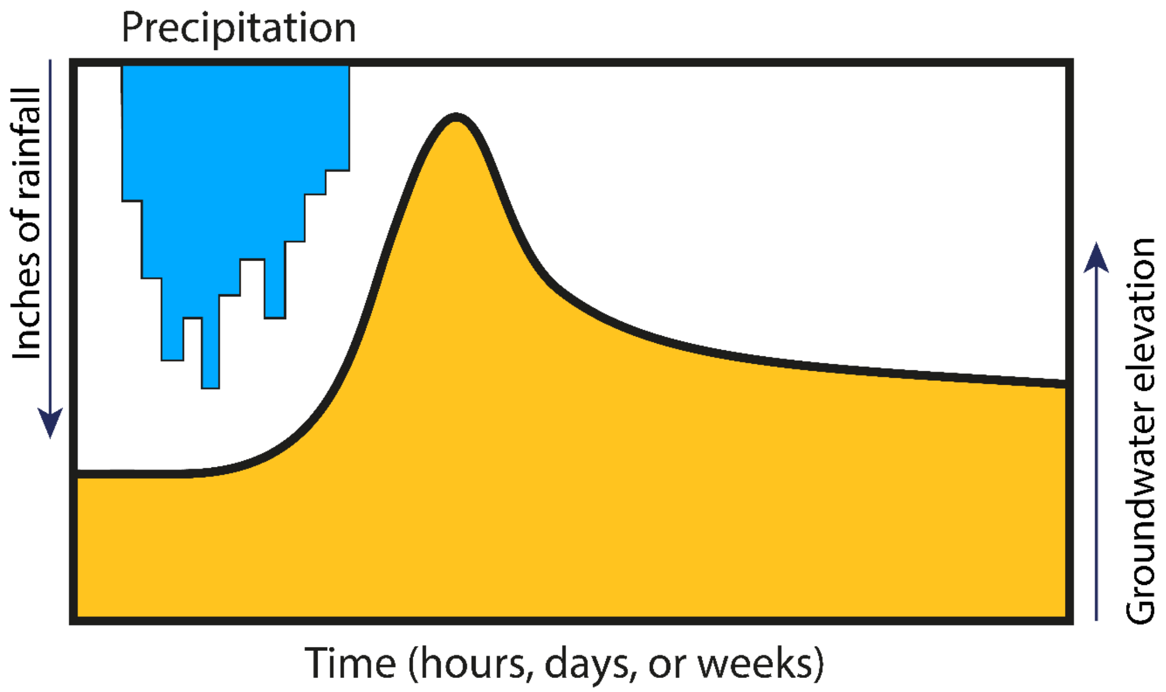

Figure 10 - A hydrograph shows the changes in water table elevation over time. There is a lag between the time when the rain falls and the time when the water table rises. The water that reaches the water table is called *recharge* (modified from Uhlman et al., 2012).

Several factors impact infiltration and percolation through the vadose zone (i.e., the zone of unsaturated soils and rocks). These factors include soil type and precedent moisture, climate, land use, topography, precipitation rate and type, available pore space, and aquifer type. Figure 11 depicts an example of groundwater recharge seasonality.

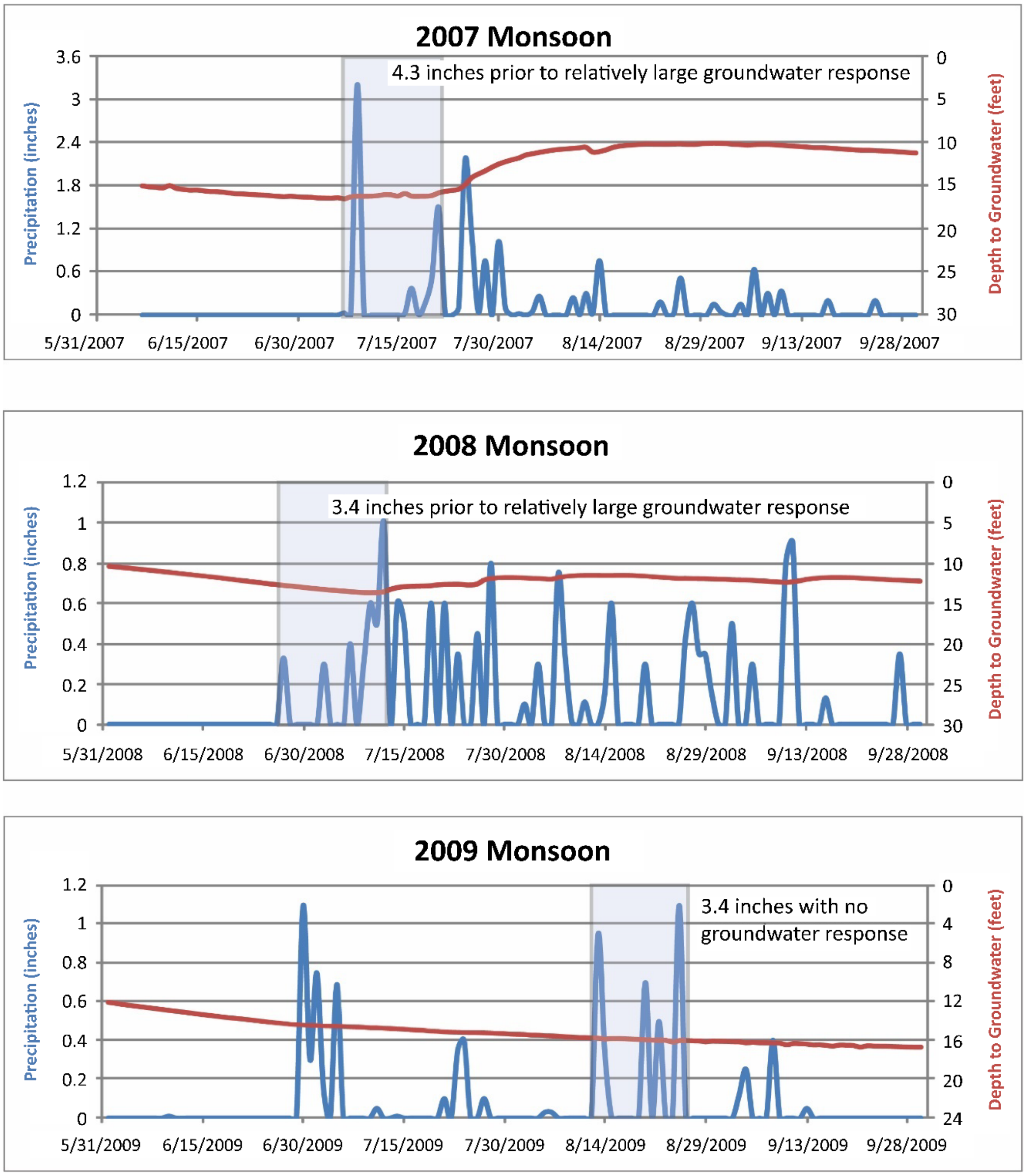

Figure 11 - This water well hydrograph (red line) in a region of generally low rainfall shows that groundwater elevation sometimes increases after monsoon rainfall (blue line). But when the rains are delayed, plants take up the water in soil moisture, and the water never recharges the aquifer. In 2007, the first 4.3 inches of rain of the monsoon season (after a long dry period) cause no increase in groundwater level because the rain replenishes soil moisture, but subsequent rain causes a rise of about 5 feet. Similarly, in 2008, groundwater levels decline during the first 3.4 inches of monsoonal rain, but subsequent rain causes a 1- to 3-foot increase in groundwater level. In 2009, each period of large precipitation is preceded by very small amounts of rain, so the large rain events replenish the soil moisture and provide water to plants, rather than causing increases in the groundwater level, 1 inch = 25.4 millimeters. 1 foot = 0.305 meters.

2.3.1 Soil Type

The movement of water through a soil depends on its depth, texture, and structure. Water drains more easily through large pores than through small pores. For example, water can infiltrate quickly through sandy soils because of their large particles and associated pore spaces, whereas clay soils and caliche slow water percolation and reduce the amount of recharge to an unconfined aquifer. Although sandy soils have large pores that allow for rapid movement of groundwater, they contain less water per unit volume than clay soils. For example, an aquifer made of sandy-gravely sediments and soils may contain about 30 percent water by volume, whereas a saturated clay soil or aquifer can have approximately 45 percent water by volume, but very little water moves through the clay because it cannot move easily through the small pores. Slightly acidic rain leaches calcium carbonate minerals from the soil and deposits them deeper in the soil, where the minerals can cement gravel, soil particles, and other minerals together to form a hard caliche layer. Caliche layers significantly reduce aquifer recharge rates if they are not fractured.

In mountainous areas, most aquifer recharge occurs along the mountain fronts because greater rainfall at higher elevations combined with coarser-grained materials on the basin margins allow the water to infiltrate rapidly. If all the pore spaces and fractures are filled with water, then recharge cannot occur, and the excess water flows over the land surface to rivers and streams. The water level in shallow wells near surface water, such as seasonally dry riverbeds, with a water table within a few feet of land surface, may exhibit dramatic seasonal variation in water level due to rapid infiltration through the streambed of recharge following precipitation.

2.3.2 Climate

Many semi-arid regional aquifers have not received significant volumes of recharge for hundreds to thousands of years. The US Geological Survey (USGS) has age-dated groundwater in the western USA (Figure 12). Age-dating is accomplished by analyzing dissolved carbon, hydrogen, and oxygen isotopes, and calculating the last time that water fell as precipitation prior to recharging the aquifer. These ages often correlate with the end of the Ice Age in North America, a period of long-term reduction in the temperature of the Earth’s surface and atmosphere, and increased precipitation resulting in the presence or expansion of glaciers across the mountains. As these glaciers melted, the fresh water recharged aquifers. Pumping this fossil groundwater is like withdrawing from a bank savings account without compounded interest.

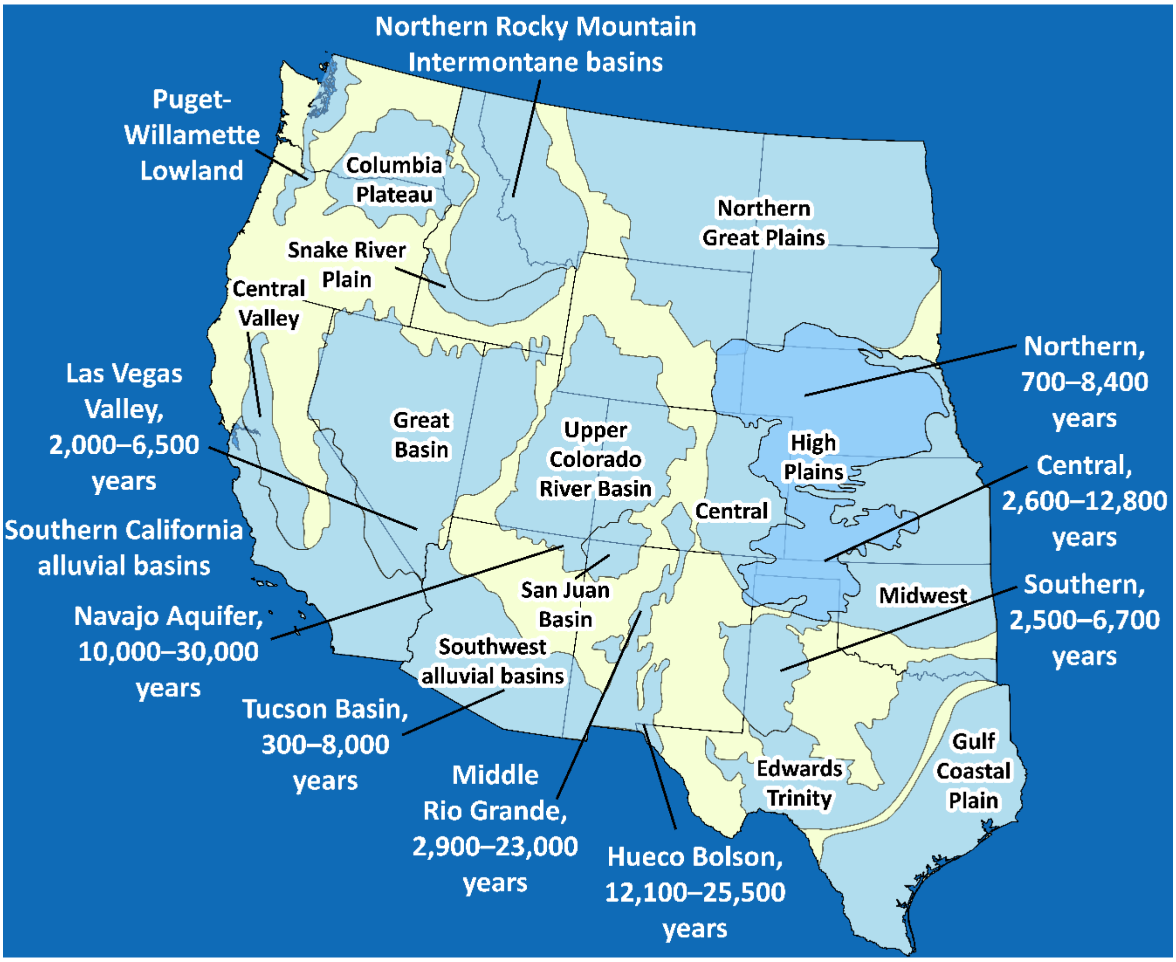

Figure 12 - Map showing groundwater ages in selected areas with significant groundwater resources in the western United States; yellow shading indicates areas without significant aquifers (modified from Mark Anderson, US Geological Survey, Tucson, AZ, personal communication, 2006).

Younger groundwater has been measured along recharge zones of mountain fronts, where runoff of mountain precipitation infiltrates the permeable sediments. Pumping from readily recharged aquifers is like withdrawing from a checking account with periodic deposits, relying on annual recharge due to rain and snow. The volume of recharge and the sustainability of the aquifer is dependent on climate as well as the size of the population relying on groundwater for water supply.

2.3.3 Land Use

Aquifer recharge does not occur through impermeable surfaces such as roofs, roadways, and parking lots. Increased residential and commercial development over an aquifer will decrease recharge while increasing runoff and flooding. Salt applied to roadways will enter the soil with recharge water, eventually reaching groundwater. Recharge can be increased in agricultural areas where imported water, such as from canals, is used to irrigate crops. Excess water (that not evaporated or taken up by plants) flushes the soil of salts as well as pesticides and fertilizers, transporting these constituents to the

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groundwater. Flood and furrow irrigation also leaches significant amounts of these chemicals below the root zone, eventually reaching the groundwater. Newer irrigation methods, such as drip irrigation, use less water while managing soil salt accumulation that is damaging to crops. Nonetheless, all forms of irrigation eventually impact groundwater quality.

Rivers and streams drain water to areas that often provide recharge to the underlying aquifer. Recharge in areas where surface water has accumulated in ponds or lakes is called focused recharge. Surface-water bodies or injection wells also can be used by communities to intentionally recharge groundwater with imported water or recycled treated municipal wastewater (Figure 13). This is known as water banking or aquifer storage and recovery. Recharge facilities that pond the water above an aquifer are designed to increase the rate at which water infiltrates to the subsurface. Tracking banked amounts of water allows for aquifer management and groundwater sustainability. Focused recharge has the potential for causing groundwater contamination. For example, stormwater-retention basins (dry ponds) accumulate urban stormwater runoff, which can contain contaminants that can percolate to the aquifer.

Figure 13 - One of several groundwater recharge basins in southern Arizona, USA, used to recharge the aquifer with imported Colorado River water.

3 Well Operation and Maintenance

3.1 Domestic Well Regulations

All domestic water wells, identified as being for private home use, must be registered and/or permitted by your local government. In the USA, domestic wells are classified as "exempt" wells. They are exempt from having to report their pumpage to the state, or to analyze and report water quality. These wells are regulated on the basis of installed pump size. Many states of the USA exempt wells under a specified flow rate (e.g., 35 gallons per minute (GPM)). In Ontario, Canada, the limit for exempt classification is use of less than 50,000 liters/day, or an approximate constant rate of 9 GPM. A well that is permitted to pump more than the exempt well status is classified as a "non-exempt" well and may have other uses, such as irrigation, public water supply, or mining. This classification, and the fact that some older well registrations do not list the use of the well, makes it difficult to determine precisely just how many private domestic water wells exist. Additional discussion of domestic well regulations is given in a related book, Domestic Wells – Introduction and Overview↗ by John Drage (2022).

3.1.1 Well Records

In all instances, your well installer and/or maintenance contractor should be aware of local issues and constraints on the installation or operation of a domestic water supply. An example of a domestic well configuration is shown in Figure 14. For a new well, your contractor will submit documentation to the appropriate government or jurisdiction agency. However, you are responsible for ensuring the information they provide is correct. For an existing well, documentation should be provided during property purchase and/or through the local jurisdiction. After well installation, an as-built description of your well includes important information such as aquifer geology, total well depth, screen length or length of open hole, pump setting, and measured pumping capacity of the well when installed. In some jurisdictions, minimal water sampling and analysis may be reported, but these test results may not include health-related contaminants, such as arsenic or nitrate.

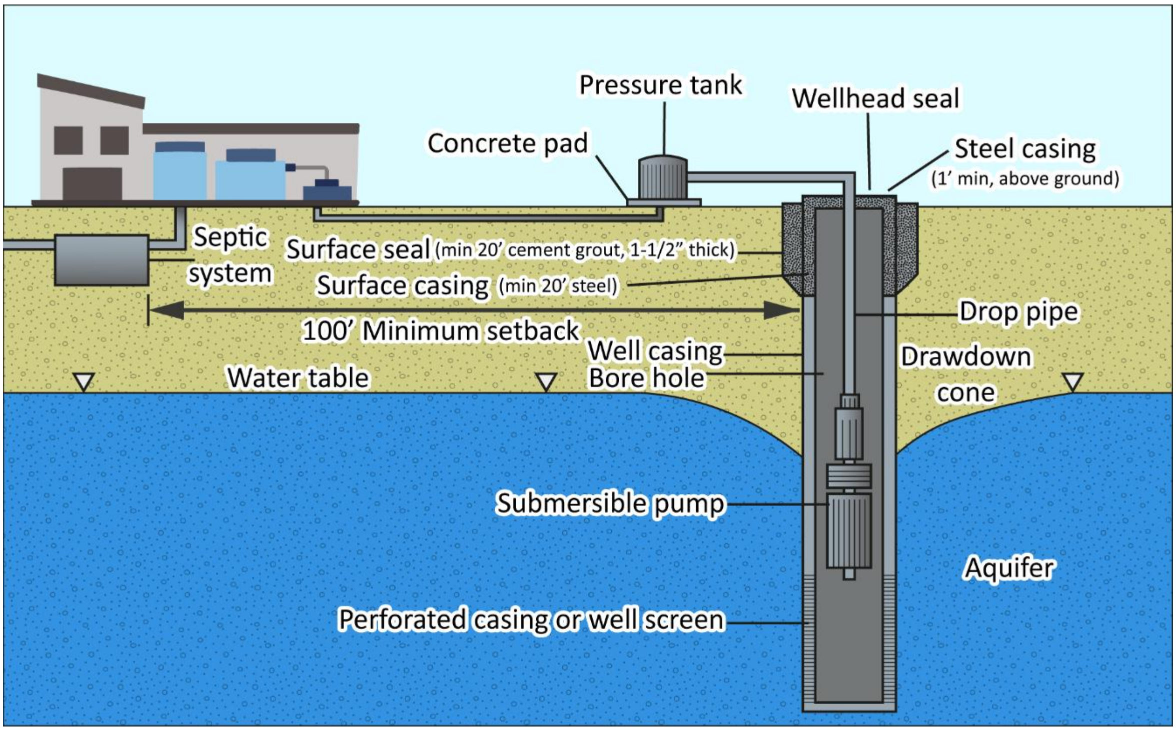

Figure 14 - A typical domestic well system. Your local government agency may have a slightly different configuration for wellhead pads and/or surface casing length. Your system may also include a storage tank, and a small pressure tank inside your house (modified from Uhlman & Artiola, 2009). 1 inch (") = 25.4 millimeters. 1 foot (') = 0.305 meters.

Private well owners are encouraged to verify the well's information that the local government agency has on file. It is especially important that private well owners keep their own records of well permits and logs; pump, controls, tanks, and treatment system operating manuals; and water testing results. No government agency oversees private water wells after they have been permitted and drilled, nor do they monitor water quality. It is the well owner's responsibility to test well-water quality. Analyze well water every year, such as on your birthday, so you will have another birthday (Exercise 1↴).

3.1.2 Initial Well Disinfection

Local regulations in most of the USA state that all wells destined to be used as a source of drinking water shall have the well-drilling contractor disinfect and, subsequently, sample the well for total and fecal coliforms before removing the drilling rig from the completed well. This bacteria sampling is the only occasion that water quality testing and disinfection of the well is routinely done by the well driller. Disinfection should also be conducted after any well maintenance or new pump installation. However, the well owner should not attempt this procedure because the disinfection chemicals can damage internal well plumbing; disinfection should always be conducted by a licensed well professional.

3.2 Well System Components

Local regulatory guidelines identify basic well components and required minimum dimensions; an example is shown in Figure 14. In addition to pumps, these include well

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casings, well caps, well screens, and storage tanks, as discussed below. Information on drilling wells, and additional information on well system components, is provided in Section 3 of a related book, Domestic Wells – Introduction and Overview↗ by John Drage (2022).

3.2.1 Well Casing

The well casing is a pipe placed in the borehole that extends to the bottom of an alluvial well (Figure 15). It is centered either with spacers or by backfilling the space between the casing and borehole. The casing keeps the well open and helps prevent the mixing of materials and groundwater from different zones of the aquifer. Within the casing is the drop pipe, which carries the electrical wiring to the submersible pump and the pumped water to the surface.

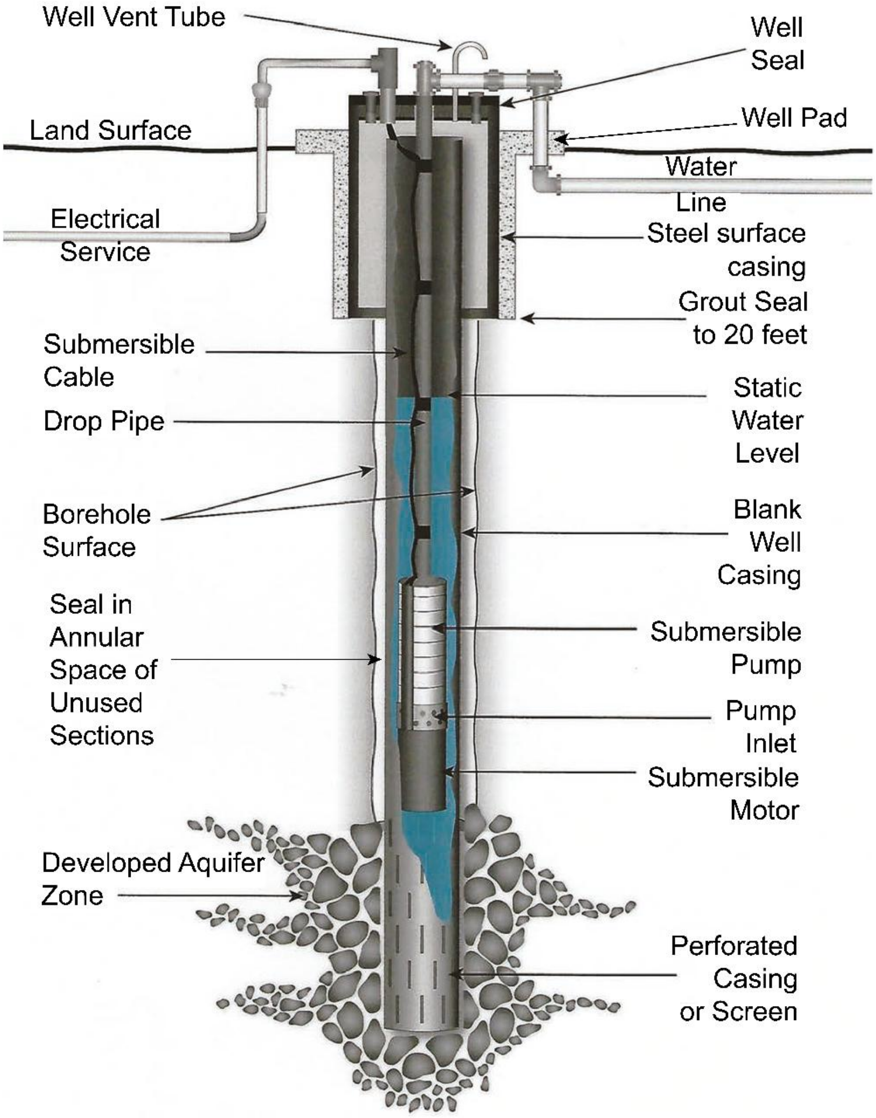

Figure 15 - Typical domestic water well in frost-free climates, with some plumbing installed above ground (after Artiola & Uhlman, 2017). In cold climates the water line is connected to the drop pipe below the frost line.

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A typical domestic water well will have a surface (also called a sanitary seal) casing in addition to the well casing (Figure 15). Most regulations require that the surface casing be constructed of steel and extend a minimum of 1 ft (0.35 m) above land surface. This casing usually extends to a minimum depth of 20 ft (6.1 m) below land surface and is cemented into the space between the borehole and the well casing (called the annulus), with a minimum of 20 ft (6.1 m) of cement grout. The cemented annular space should be at least 1-1/2 inches (3.81 cm) thick. This serves as part of the sanitary seal (discussed further in Section 3.2.2), which reduces the likelihood that ponded surface water around the wellhead will seep down into the aquifer. The well casing for domestic wells can vary from 4 to 8 in (10 to 20 cm) in diameter, depending on aquifer conditions, final depth of the well, and the type of pump to be installed. This casing may be constructed of carbon steel, plastic (usually ASTM Schedule 80 poly vinyl chloride (PVC)), or stainless steel. PVC is lightweight, resistant to corrosion, and relatively easy to install.

To minimize the risk of contaminating the well water with solvents, PVC casing sections should be threaded instead of joined by glue during construction of a new well. If PVC primer and solvent cement have been used, water tests in newer wells may indicate low levels of solvents in the water. However, over time, the solvent will flush out of the system. Many domestic water-well drillers currently use a PVC well casing with couplings that do not require glue. A strong advantage of this method is that the well casing can be removed quickly and reinstalled if problems arise during well installation.

In southern climates where frost is not common, wells are typically completed with above-ground plumbing and electrical connections that exit from the top of the well, as shown in Figure 15. The exterior plumbing can be wrapped with insulating materials for freeze protection, when dictated by winter weather temperatures. In northern climates, single casing wells, where the sanitary-seal casing is built into a pitless-adapter completion (Figure 16), are far more common than wells with surface casings because they avoid frost damage. In a pitless-adapter completion the plumbing entering the well casing is in the ground below the soil frost line as shown in Figure 16. The term "pitless" denotes that a below-ground well pit is not required to achieve a below-ground connection from the drop pipe to the water line.

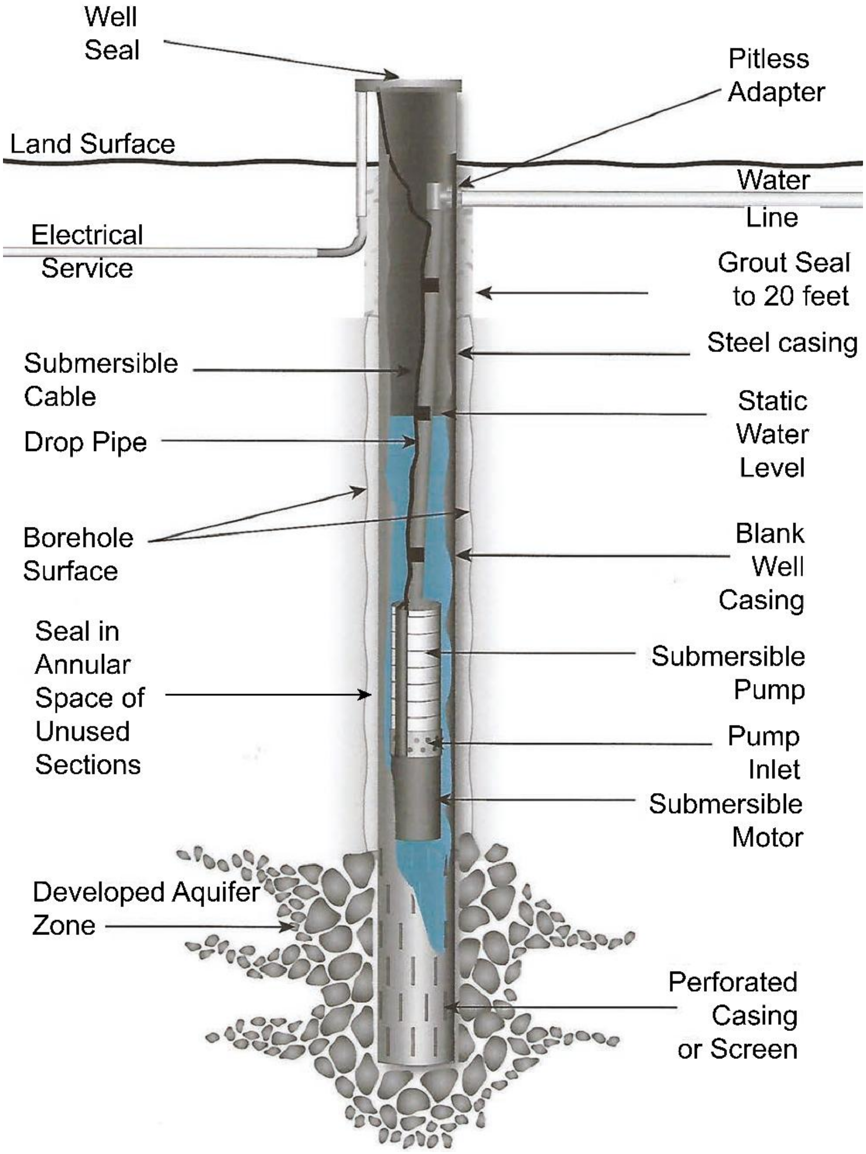

Figure 16 - Typical domestic water well for cold climates, with the water line connected directly to the drop pipe via a pitless-adaptor connection (after Artiola & Uhlman, 2017).

Many water-well drillers do not install pumping equipment; equipping of the well for domestic use is usually done by a water-well-pump installer. These installers do not drill wells and therefore are not licensed as a water-well drillers but are likely required to have a contractor's license.

3.2.2 Sanitary Seal

Sanitary seals prevent the infiltration of surface water into the annulus of the borehole, where in an unsealed well this water could flow to the water table. Wellhead sanitary seals feature a concrete apron that is sloped away from the well casing pipe. This keeps rodents from burrowing alongside the well casing and keeps rain and flood waters away from the wellhead. If a concrete apron is not present, the land surface near the wellhead should slope away from the surface casing. Coupled with the 20 ft (6.1 m) of

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grout, the intent of the sanitary surface seal is to prevent the infiltration of surface water into the well and down to the water table. If the driller did not adequately back-fill the annulus with cement/grout during initial installation, the sanitary seal may bridge and collapse, causing a serious failure to protect your water quality. Soil collapse around the casing or the concrete apron must be repaired to protect your drinking water.

Figure 17 shows a light gray sanitary grout placed around the surface casing during well construction. Older domestic wells drilled before local regulations were put into place were not required to have this sanitary surface seal and may not have protection unless they were deepened or modified in some way. Older wells may be constructed of concrete, fiberglass, and asbestos cement. Hand-dug wells may be cased with brick or stone.

Figure 17 - Photo of sanitary seal grout in the annular space around the surface casing of a well prior to the construction of the concrete apron.

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3.2.3 Caps

Well regulations typically state that every well with casing four inches (10 cm) in diameter or larger shall be equipped with a functional water-tight access port. The vent/access port in the well seal or pitless adapter is desirable because water wells interact with the atmosphere. Wells take air in as the water level is drawn down during pumping, and they push air out when the pump shuts off and the water level recovers. Some jurisdictions in regions of oil and gas production require venting to reduce the potential for methane gas to accumulate within the well. If the well is within a well house, that vent must extend beyond the roof line, to reduce accumulation of gas that may explode whenever the well turns on. Wells also breathe as atmospheric pressure changes occur due to passing weather fronts. Vents in water-well caps should be small enough so that insects, reptiles, or rodents cannot enter, as shown in Figure 18.

Figure 18 - Example of a well cap made of aluminum. The vent is shown by the arrow.

3.2.4 Well Screens

Well screens allow water to move into the well and help prevent sediment from entering the well, keeping out most of the surrounding sand and gravel. The most common screens used in domestic wells are made of slotted or perforated pipe constructed of stainless steel or PVC, as shown in Figure 19.

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Figure 19 – Examples of well screens, showing continuous wire-wrapped metal screens (left) and a slotted PVC screen (right). Screens serve to filter out sediment. The screen slot size is ordered by the driller to fit the aquifer geology. (reprinted by permission of Johnson Screens, a Weatherford Company).

Well screens are manufactured with specified opening shape and slot size to accommodate local geologic conditions. They are placed in the saturated part of the aquifer and may be damaged if the groundwater elevation drops. In addition, a dishonest well driller may intentionally install an incorrect screen or make his own with a hack saw through PVC. Screens that have openings larger than the geologic conditions warrant will allow the well to fill with sediment and will also destroy the pump. To check if your well screen is properly sized, check the sediment in the back of your toilet tank; gritty sand particles mean the pump will soon break down because the screen is allowing sediment to enter the well and is being drawn through the pump into your plumbing (Exercise 2↴).

3.2.5 Storage Tanks

The domestic well system may be configured to pump water into a storage tank before it enters the pressure tank (discussed later in this subsection) if the yield of the well is low, to assure water is available for times of peak use. Each has advantages and disadvantages.

Above-ground storage tanks are exposed to both hot sun and cold winter weather, storing the water at atmospheric temperature and pressure until it is needed. A storage tank is necessary for low yielding wells, to assure water is available for times of peak use. Tanks can be constructed of galvanized steel, mild steel, fiberglass, or polymer plastics. A plastic tank is shown in Figure 20. In the summer, the water in storage may warm to a temperature that can encourage microbial and algal growth. Because of this, above-ground tanks should be periodically cleaned and chlorinated. Below-ground storage tanks will reduce some of the problems associated with above ground tanks.

Figure 20 - Above-ground water storage tank and well house. If the well needs to be serviced in the well house, the roof must be removed to allow rig access.

In domestic windmill-based pumping systems, typical rates of extraction range from around 1 to 50 GPM (~4 to 200 liters per minute), and water pulled to the surface must be stored in a storage tank to assure a continuous supply to the water user (Figure 21).

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Wells can also be solar powered (Figure 22) but power supply may be intermittent due to cloud cover and time of day.

Figure 21 - Windmill-based well systems typically pump around 3 GPM, necessitating storage of water in tanks.

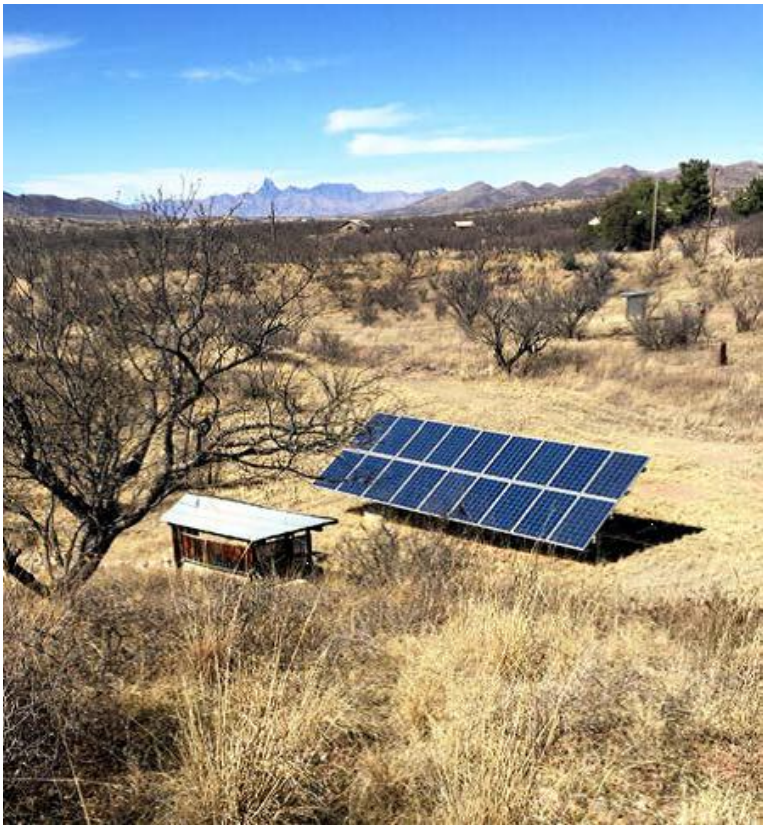

Figure 22 – Solar cells power a domestic well shown in the background.

In many domestic wells, the pumping capacity of the submersible pump and the yield of the well are such that groundwater is pumped directly into a captive air bladder pressure tank. This water system design, as shown in Figure 23, reduces the concern for bacterial contamination because the water comes directly out of the ground and goes directly into a pressure system without coming into contact with air. The captive air bladder tank sustains pressure throughout the household plumbing, including water treatment systems, and stores water for periods of heavy usage (Exercise 3↴).

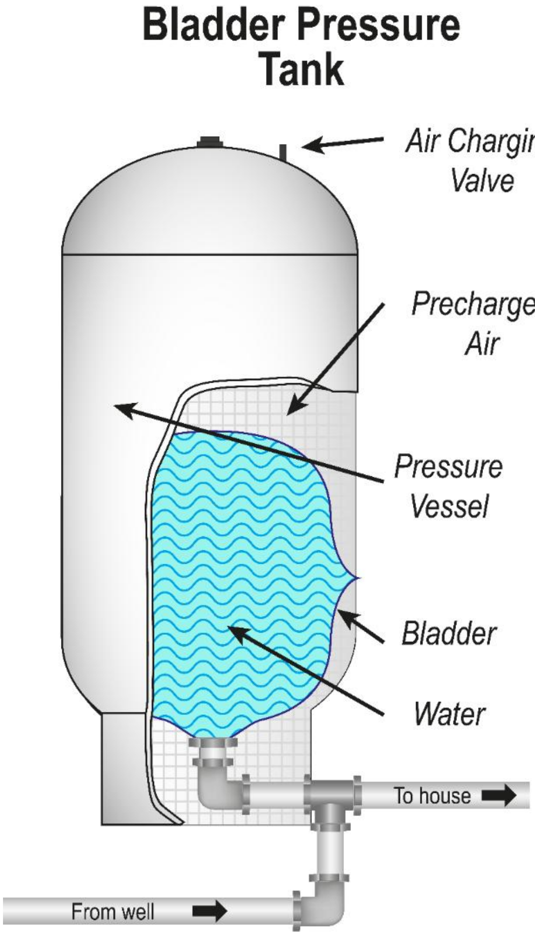

Figure 23 - Captive air bladder tank for a private domestic well system.

The tank pressure switch (Figure 24) is possibly the most important piece of the water delivery system that homeowners can readily observe, maintain, and to some extent adjust. Well owners should observe this switch to ensure that the small pipe stem that connects it to the exterior system is insulated and protected from freezing. A pressure switch must sense and respond to changes of water pressure. If the well is pumping sand, the grit will damage the air bladder and cause failure of the tank. Changing the pressure switch settings requires adjusting the air pressure inside the bladder tank to be 2 psi (about 6900 Pa) below the specified lower pressure on the pressure setting to avoid frequent cycling of the pump.

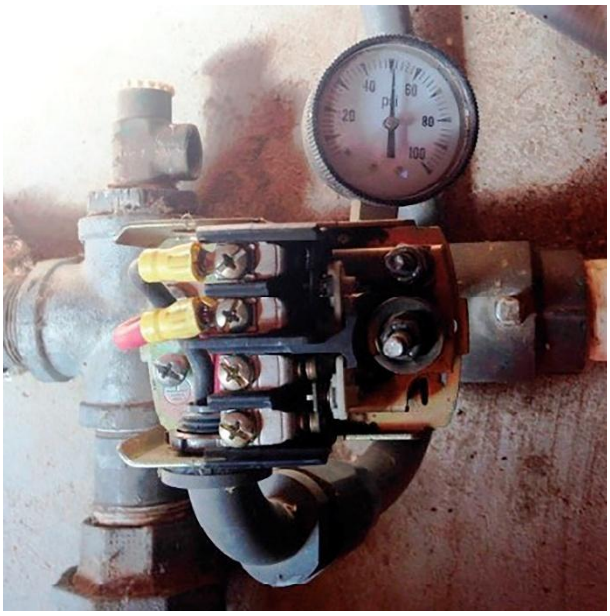

Figure 24 - Captive air bladder tank pressure switch.

Low yield wells may need storage tanks that can hold as much as 500 to 2,000 gallons of water, which is usually adequate for a single-family residence. If several homes share a single exempt well, then a storage tank of 5,000 gallons, two booster pumps (one for each home), and a pressure tank for each connection is a more typical design, as shown in Figure 25.

Figure 25 - A shared well system with above-ground storage and two bladder pressure tanks delivering water to two households.

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3.3 Managing Shared Wells

Wells that provide drinking water for community utility systems are regulated by state and federal law. These water systems serve at least 15 residential service connections year-round or at least 25 residents. Water supply systems with domestic wells that serve fewer than 15 service connections are non-regulated in the USA, are considered shared private wells, and are not required to comply with drinking water quality standards or reporting rules. If you are on a shared well system, you should enter into a legal contract agreement to:

- protect access to your water supply;
- stipulate costs and responsibilities for well maintenance;
- address the operation of the well and water distribution system (if the well is on another property, you may have limited access to the well unless stipulated in the contract; if the well is on your property, you may be held responsible for maintenance by default);
- set an annual fee and shared expenses; and
- require that the well water be tested annually to make sure it is safe to drink.

An example of a shared well agreement is provided by the Water Systems Council at the following link.

watersystemscouncil.org/download/wellcare_information_sheets/other_information_sheets/Shared_Well_Agreement.pdf↗

3.4 Well System Failure

All well systems are vulnerable to mechanical failure that can lead to pollution of the water supply. The water can become contaminated because of corroded pipes, broken sanitary surface seals, and standing water that seeps back into the aquifer along the outside of the well casing.

Pump or plumbing failure should always be addressed by a licensed well professional or contractor. High-quality pumps are typically engineered to last 20 to 30 years but can fail for several reasons, including the presence of sand or grit in the water. Figure 26 shows a pump that failed after being corroded by stray electrical currents. These currents can be caused by improper insulation of the wires or improper grounding. For the pump in Figure 26, water was forced through the hole formed by corrosion, causing the pump to fail.

Figure 26 - Stray electrical currents formed a hole in this submersible pump, causing the well to fail.

The most common cause of well system failure is a decline in groundwater elevation. If the water table drops below the well screen, air mixes with the pumped water causing turbulence and erosion in the aquifer with increased grit in the water. The first sign of system failure due to declining groundwater elevations is the buildup of sediment in tanks, pipes, and plumbing fixtures (Figure 27). If the well continues to pump gritty sands, the pump itself can be damaged and might have to be replaced. If the well runs dry regularly, consider installing a well pump protection switch that turns off pumping when water levels drop too low. However, if the pump cycles on-and-off rapidly, heat builds up that may melt the drop pipe, causing massive failure.

Figure 27 - Sand and precipitated manganese particles accumulated on the screen of an irrigation system (modified from Uhlman et al., 2012).

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3.5 Well Maintenance Tips

The amount of maintenance a homeowner can perform on their domestic water well may be somewhat limited due to the location of the well on the property and possibly due to unintentionally blocking well access by not considering what is required to pull and replace the pump at a future date. Figure 28 is a photo of a well inside a metal sculpture, preventing access.

Figure 28 - Photo of a well inside a non-removable metal sculpture, preventing access (modified from Artiola et al., 2017).

Well owners can better maintain their wells by implementing the following tips.

- Protect the well and electrical controls from direct sunlight, rain, and extreme cold conditions.
- Protect the wellhead and electrical controls from vandalism and unauthorized access.
- Inspect and document the working conditions of your well and water system equipment periodically to detect subtle changes of performance that might be taking place.
- Keep a permanent record of your well's performance. Install a well flow meter and record your monthly pumpage to detect a change in your water usage that might indicate a leak.
- Sample and analyze your drinking water quality annually on your birthday. A substantial change in water quality may indicate a failure of your well system.

- Annual well inspections and testing can be performed by well owners. If you are not comfortable with performing these tasks, a local licensed water-well contractor may be able to perform an annual well inspection for a small fee.
- Most domestic water wells can, and do, give their owners many years of good service providing sufficient good quality water. Like other real estate improvements, wells require minor routine maintenance and proper management.

4 Well Yield

The amount of water that a well can produce is called the well yield. All water wells begin a gradual decline in performance from the first day they are drilled and constructed.

4.1 Factors Causing Reduced Well Yield

There are four prime factors causing the slow decline in well performance: slime buildup (microbial growth) in the aquifer and well screen; scale formation (chemical precipitation) in the well screen; sediment buildup blocking the perforations in the well screen; and long-term decline of aquifer water levels. In extreme cases, the combined effect of slime and scale has been reported to reduce well yield by 75 percent within a year of well operation.

Microorganisms exist in the subsurface and groundwater before the borehole is drilled and the well is installed. Together, the introduction of water from another source during drilling; the introduction of oxygen, iron, and other elements during well construction; and nutrients in the groundwater; provide a suitable environment for bacteria to flourish and form biomass. The process of slime (also called biofilm) formation is initiated by a few bacteria, which then promotes the growth of more bacteria that clog wells and plumbing, as shown in Figure 29. An extreme example is shown in Figure 30. Bacterial slime can also cause serious health problems.

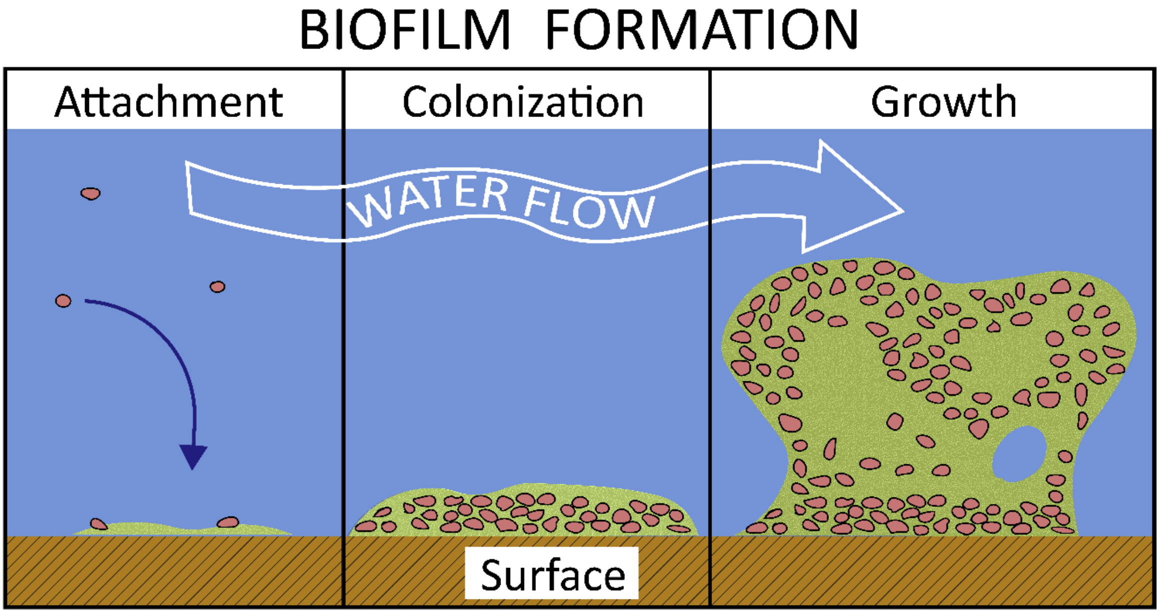

Figure 29 - Biofilms form from slime bacteria that feed on iron, manganese, and/or nitrate.

Figure 30 - Buildup of biological slime and mineral crust on a submersible pump inlet (photo provided by the National Groundwater Association, NGWA, for Artiola & Uhlman, 2017).

As groundwater enters the well, it quickly goes from being under hydrostatic pressure to atmospheric pressure. With the decline in pressure, entrapped gases are released and some minerals precipitate from the water, forming scale. Groundwater drawn into the well over long time periods brings with it trace amounts of clay, silt, and fine sand. Eventually these sediments build up in the well, get trapped in biomass growth, and accumulate on the well screen, eventually reducing the flow of water into the well, as shown in Figure 31.

Figure 31 - Scale formation on a well screen.

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Low-yield wells are susceptible to problems with water quality. In these wells, the water level typically changes often, and the pump is likely to cycle on and off frequently, which introduces oxygen into the aquifer. When exposed to oxygen, some minerals in the aquifer material dissolve into the groundwater and are contaminants. For example, if the aquifer contains arsenic minerals, contact with oxygenated water may increase the concentration of dissolved arsenic in the groundwater.

4.2 How to Improve Well Yield

To correct a low yield well, it is necessary to know the cause of the problem and the type of aquifer involved. The solutions may include 1) shock chlorination (to remove biomass growth); 2) scrubbing and redeveloping the well (to remove sediment clogging); hydraulic fracturing (to open clogged and develop new fractures); 3) carefully adding dry ice (creating powerful gas bubbles that scour the well and increase water flow, similar to a natural geyser - the pressure and agitation breaks up mineral scale and sediment, while the resulting carbonic acid dissolves carbonate buildup and reduces bacteria); and 4) deepening the well. These treatments must be done carefully to avoid casing damage.

4.2.1 Shock Chlorination

The best method for controlling the slow decline in well performance is to begin by making sure the well is fully disinfected when initially drilled, after the permanent pumping equipment has been installed. This requires that the pump installer, who may not be the well driller, shock chlorinate the well. Shock-chlorination introduces a strong chlorine solution into the well. Wells should also be shock-chlorinated after maintenance or when pumping equipment is replaced, and especially if the well-water testing results are positive for bacteria.

An operating well that is plugged with bacterial slime can be shock-chlorinated to kill the bacteria and improve its yield. It is important to hire a licensed and qualified water well contractor to shock-chlorinate the well instead of trying it yourself. Excessive well chlorination may dissolve any arsenic-bearing minerals present in the aquifer and mobilize arsenic in groundwater. In addition, excessive chlorination can damage plumbing in the well.

4.2.2 Redevelopment

Well yield can be increased by redevelopment of the well. Redevelopment consists of two steps: scrubbing the interior of the well screen and temporarily installing a high-capacity pump to force water flow into the well at a velocity greater than the well’s operation rate to remove fine sand accumulated within and near the well screen. Figure 32 depicts a cross section of a well that has been redeveloped. The process pulls fine grained sediment through the screen into the wellbore and then out of the well, leaving behind coarser-grained sediments, which allows water to flow more easily into the well. After redevelopment the well will operate more efficiently.

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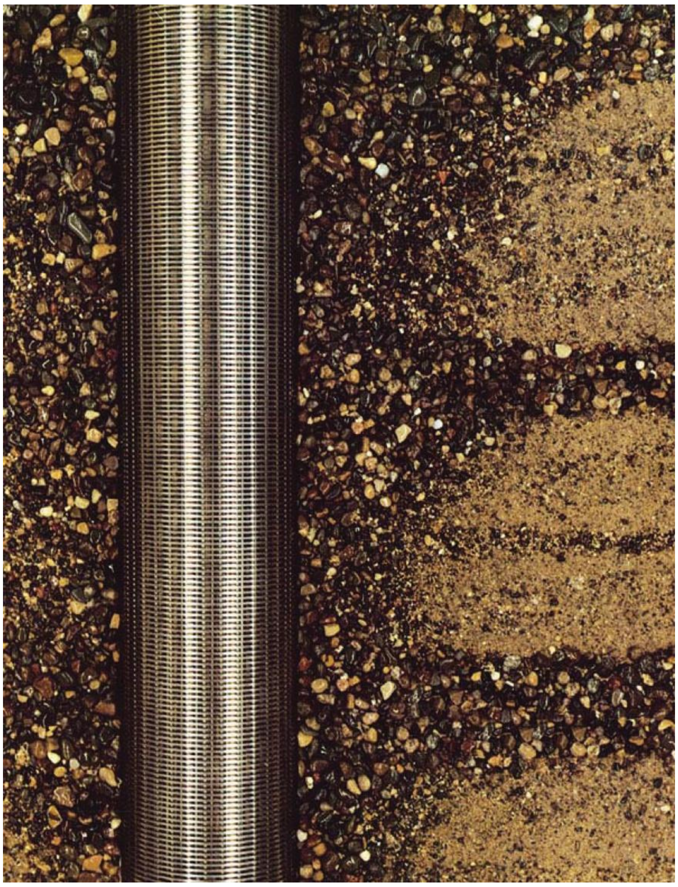


Figure 32 - Well redevelopment removes fine-grained sediment from directly adjacent to the well. As shown here, sediments adjacent to the screen are coarse whereas material further away still contains fine grains (modified from Uhlman et al., 2012).

4.2.3 Hydraulic Fracturing

Hydraulic fracturing, or *fracking*, was developed in oil and gas production, and is now also applied to water wells, to improve yield. Fracking is applicable only to open-borehole wells with no screens, drilled in dense consolidated, hard rock. It is not applicable to alluvial wells but is included here for completeness in presenting well improvement techniques. The process involves over-pressuring isolated short sections of an open borehole to crack and fracture the rock. For oil and gas wells, fine sand is pumped into the borehole to prop open the new fractures; this added step is not typical for water wells. Fracking is often used to increase yields in water wells constructed in shale. Hydraulic fracturing does not work in unconsolidated sediments because the pressure needed to fracture the rock is rapidly dissipated within the porous sediments. Hydraulic fracturing has also been used to increase yield of large, municipal wells in fractured consolidated sandstone formations but is not commonly used for domestic wells.

4.2.4 Carbon Dioxide

Some well owners have increased their well yield by dropping dry ice in the well. As the carbon dioxide gas bubbles are released from the dry ice, the water becomes more acidic, which dissolves parts of the carbonate-based scale and kills some of the bacteria.

The agitation of the bubbling dry ice in the well casing may also loosen some of the particulate scale. The agitation caused by dry ice can become violent, throwing columns of water high into the air. A well should never be capped or sealed when dry ice is used as an agitator because it can produce very high pressures.

Municipal water systems are beginning to use pressurized carbon dioxide gas to sanitize their well systems. The downside of using carbon dioxide is that it acidifies the water and thus can corrode metal plumbing.

Because microbial growth and chemical precipitation happen simultaneously while the well is being used, preventing or correcting bacterial slime growth and screen blockage requires a carefully planned periodic program of well rehabilitation. Any decline in the performance of the well may indicate the need for rehabilitation. If the cost for operating the well has been slowly increasing, it may be time to investigate the possibility of biofouling, sediment buildup, or a sustained drop in the water table. A trained professional with the proper equipment needs to be enlisted to remove and install pumps in wells and to safely handle the chemicals used to rehabilitate wells.

4.3 Managing Low Well Yield Caused by Drought

Water tables often decline seasonally or during severe droughts, and some low-yield aquifers that do not recharge quickly may be responding to a drought that started decades ago. The following steps can help protect your water supply during a drought.

- Monitor your pump for rapid cycling. One sign of lowered water tables is the rapid on-off cycling of the pump over short periods. This rapid cycling can burn out the motor, and the heat generated by a submersible pump can damage the drop-pipe if it is made of PVC. Allow the pump to rest while the water level recovers, or if possible, reduce the pumping rate.
- Listen to the pump. If pumping makes the sounds of sucking air, turn the pump off and allow it to rest while the water level recovers.
- If the pump is rapidly cycling, consider the installation of a pump/motor protection device, which monitors load and power conditions. Some systems monitor and diagnose motor load to prevent pump or motor failure due to conditions such as low-flow to wells, pump damage, clogging, or power surges.
- Check for sand in the toilet tank. When the water table is drawn down below the screen, the well may begin to produce sand. This is the fine sediment that is eroded out of the aquifer and drawn into the well. If you notice sand in the toilet tank, the well is in danger of going dry and the pump will likely be damaged. Call a pump contractor to evaluate and, as needed, repair the well.
- Watch for milky water. Water that appears milky at first and then clears after standing can be caused by the pump drawing air and may indicate that the water level in the

well has dropped. The milkiness is due to tiny bubbles, which when allowed to still, will clear up.

- Consider lowering the pump. Depending on the depth of the well, lowering the pump may be an option. Check with a licensed pump installer.
- Have the water tested. As the water table drops and pulls air into the aquifer, the chemistry of the water will change. Sometimes exposing the aquifer to oxygen causes an increase in dissolved arsenic concentrations. Send well water samples to an analytical lab for testing on a regular basis during and after a drought.
- Reduce pumping rate and increase storage capacity. Lowered pumping rates and increased storage capacity, such as with an above ground storage tank, may protect your water supply equipment and the groundwater resource.
- Schedule water use. If you have a shared well, work with your neighbors to schedule common or heavy water use. For example, if everyone in the neighborhood typically washes laundry on Saturday, the wells may begin to go dry on Sunday. Distribute heavy water use over the week to allow individual wells to recover and sustain the water supply in your neighborhood.
- Conserve water. Consider installing a well water meter to monitor and manage your water

5 Drinking Water Guidelines and Standards

In the USA with a few exceptions, wells registered with an exempt status are not subject to any federal, state, or provincial monitoring, nor are they required to meet minimum water quality standards. It is the responsibility of private domestic well owners to test their well water regularly to determine whether the water meets drinking water standards. Sections 5.1 and 5.2 familiarize private well owners with drinking water standards and encourage well water testing. Sections 5.3 through 5.5 discuss well water quality and common contaminants and pollutants found in groundwater.

The USEPA (United States Environmental Protection Agency) sets National Primary (and Secondary) Drinking Water Standards for public water utilities. This is done in collaboration with public water utilities, scientists and scientific health studies, state and local agencies, and the public. States of the USA and Canadian provinces, as well as Native American (USA) and First Nation (Canada) communities, often facilitate the implementation and enforcement of drinking water standards for public water utilities. The USA standards are published in the Code of Federal Regulations (Figure 33) and are listed in Box 1↴. Drinking water standards are always evolving as new and more sensitive analytical methods are developed, scientific information becomes available, and new priorities are set in response to changing concerns about potential health effects of contaminants found in water. Drinking water standards are set by considering the potential health impacts to the population exposed to a given contaminant using risk models. Also considered are the costs of monitoring and water treatment methods available to regulatory agencies and public water utilities. Additionally, public water utilities must treat their water to meet drinking water standards using only USEPA mandated or accepted water treatment methods.

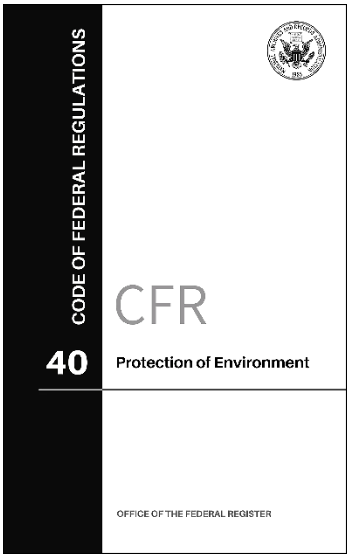


Figure 33 - United States Code of Federal Regulations: Title 40, Protection of the Environment, https://www.epa.gov/laws-regulations/regulations↗.

5.1 Primary Drinking Water Standards

National Primary Drinking Water Standards (NPDWS) are legally enforceable standards that consider primarily the potential human health effects using a risk assessment of the exposure (which is defined by the concentration of the chemical constituent and duration of the exposure) to a particular chemical with a known toxicity. The NPDWS include constituents that have a Maximum Contaminant Level (MCL) that may not be exceeded in drinking water delivered by public water utilities to consumers. If an MCL is exceeded, then the water quality poses an unacceptable health risk.

MCLs are set on the basis of different categories of chemicals: those chemicals that are not carcinogenic, versus those that the USEPA has determined are "known to be," "probably are" and "possibly are" carcinogenic. The USEPA also has set MCL public health goals (MCLGs) at zero in drinking water for a chemical known or suspected to be carcinogenic. However, present limitations in the laboratory analysis of chemicals and water treatment technologies make this goal impossible to attain.

There are about 115 contaminants with MCLs regulated by the USEPA, divided into four major categories: 1) inorganics, such as arsenic and chromium; 2) organics, such as pesticides, petroleum derivatives, and solvents; 3) radionuclides, such as uranium and radium; and 4) microbials, such as *Giardia*, and general microbial indicators, such as coliform bacteria.

If a well owner tests the well water and finds one or more MCLs exceeded, they should consider the water to be a health risk and treat it or seek an alternate source of drinking water (Exercise 4↴).

5.2 Secondary Drinking Water Standards

The USEPA has also established a set of National Secondary Drinking Water Standards for public water utilities; these are listed in Table 1. The USEPA does not enforce these standards, which are called Secondary Maximum Contaminant Levels (SMCLs). These standards are established only as guidelines to assist community water systems in managing their water for aesthetic considerations, such as taste, color, and odor. Exceeding any of the contaminants listed in Table 1 is not considered a health risk; therefore, public water systems are not required to treat these chemicals below SMCLs. However, water utilities often control these chemicals in their water supplies to reduce taste or odor-related consumer complaints.

If your well exceeds any SMCL listed in Table 1, but you find its taste and odor acceptable, there is no need to treat the water.

Table 1 - National Secondary Drinking Water Standards.

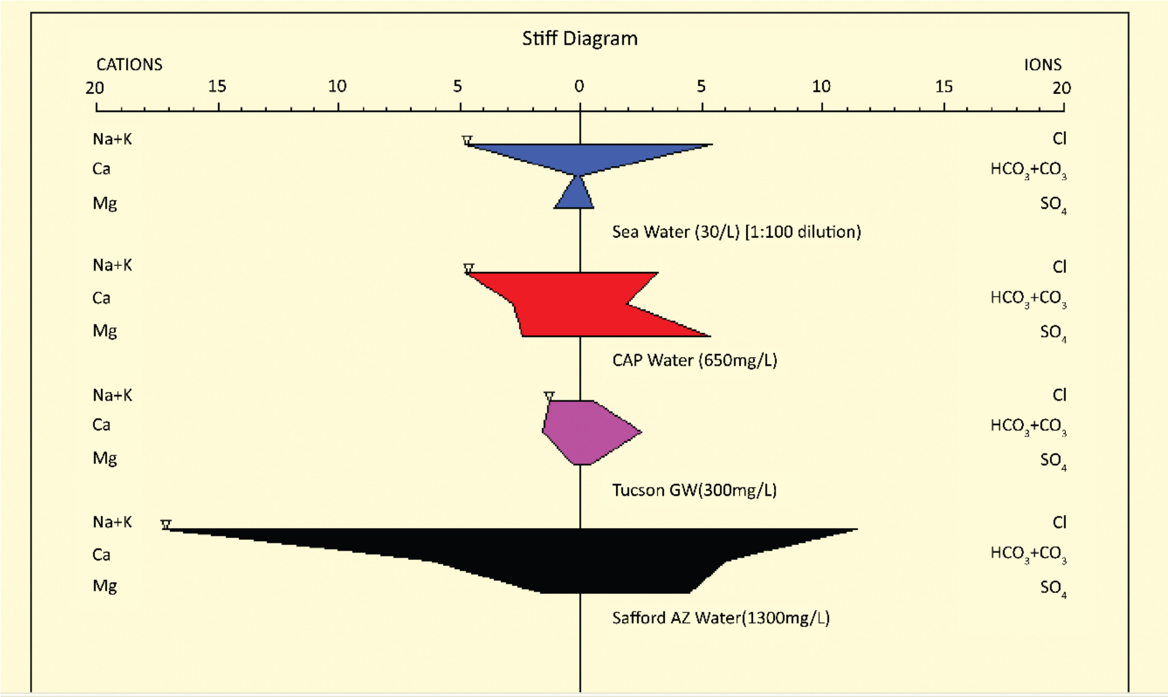
Contaminant	Secondary Standard	Primary Standard
Aluminium	0.05–0.2 mg/L	-
Chloride	250 mg/L	-
Color	15 (color units)	-
Copper	1.0 mg/L	MCL=1.3 mg/L
Corrosivity	Noncorrosive	-
Fluoride	2.0 mg/L	MCL=4.0 mg/L
Foaming Agents	0.5 mg/L	-
Iron	0.3 mg/L	-
Manganese	0.05 mg/L	-
Odor	3 threshold odor number	-
pH	6.5–8.5	-
Silver	0.10 mg/L	-
Sulfate	250 mg/L	-
Total Dissolved Solids	500 mg/L	-
Zinc	5 mg/L	-

5.3 Common Chemical Constituents in Groundwater

A nationwide study by the US Geological Survey found that more than 20 percent of the private household wells tested contained one or more contaminants at a concentration greater than is recommended by the USEPA (DeSimone et al., 2009). Most of the detected constituents are naturally occurring in groundwater and are considered contaminants when they exceed USEPA MCLs. In addition to elevated total dissolved solids (salts), the most common constituents found in groundwater in concentrations above drinking water standards are arsenic, nitrate, fluoride, and gross alpha radiation. These and other constituents that are commonly encountered in well water are discussed in the rest of this section. Further discussion of common contaminants in domestic wells is provided by John Drage (2022) in his Section 5 of the related book Domestic Wells – Introduction and Overview↗.

5.3.1 Salt - Total Dissolved Solids (TDS)

The level of dissolved minerals and salts in water is known as total dissolved solids (TDS). TDS is reported as a single value, typically in milligrams per liter (mg/L). TDS is often referred to as a measure of salinity because it reflects the concentration of salts dissolved in the water. The most common mineral in high-TDS water is sodium chloride ($NaCl$). The following seven constituents make up about 95 percent of TDS in groundwater: bicarbonate, calcium, chloride, magnesium, potassium, sodium, and sulfate. These chemicals usually originate from the presence of common minerals like limestone, dolomite, gypsum, and salt in or near aquifers. Road salt applied during winter storms is a common source. Figure 34 depicts the mineral concentration of several water sources, as compared to sea water diluted 100 times for testing. There are other minor chemicals found in water like nitrate, fluoride, boron, selenium, and trace elements like iron, manganese, and arsenic. These constituents have very minor contributions to the overall TDS of the water but are important to the quality of the well water.



Sample	Color	Na	K	Cl	Ca	HCO_3	CO_3	Mg	SO_4
Sea Water (30/L) [1:100 dilution)	🟦	107.60	3.99	193.50	4.11	1.42	0	12.90	27.10
CAP Water (650mg/L)	🟥	106	6	113	56	110	2	29	257
Tucson GW(300mg/L)	🟪	29	2	20	32	150	1	3	21
Safford AZ Water(1300mg/L)	⬛	395	3	406	125	361	1	19	217

Figure 34 - Mineral concentrations of sodium chloride (Na + Cl), calcium (Ca), and magnesium (Mg) in three municipal water sources compared to sea water diluted 100 times (modified from Artiola et al., 2017). A Stiff Diagram plots concentrations of cations and ions, typically derived from dissolved minerals, on a horizontal scale, depicting geometric shapes that allow the reader to quickly understand the variation in mineral contents. For example, here the Tucson water has low mineral concentration, while the water in Safford has high sodium.

Drinking water with more than 500 mg/L TDS (Table 1) is not necessarily unsafe, unless elevated levels of nitrate, arsenic, and other toxic chemicals are also present. However, it may taste salty, clog pipes and water heaters, and stain laundry or plumbing fixtures depending on the chemical composition.

Salty water can stunt the growth of crops and landscape plants. If your water has a high TDS, have it tested to determine the specific minerals in the water supply. Then match the treatment method to the minerals in the water or select the appropriate salt-tolerant plant species. For example, groundwater high in bicarbonate (HCO_3) tends to precipitate calcium and magnesium and form a hard crust on the soil. These precipitates may eventually form a caliche layer on or below the soil surface. Water high in sulfate is less likely to precipitate, but when this water evaporates it will form gypsum in the soil.

The mineral composition of water may affect its taste. For example, water with a TDS of 500 mg/L composed primarily of table salt (NaCl) feels slippery, tastes slightly salty, and, on the hardness scale, is considered soft water. Water with the same TDS value but having roughly equal proportions of table salt, gypsum, and calcite (calcium carbonate) tastes less salty and feels less slippery because of its greater water hardness.

5.3.2 Arsenic

Long-term exposure to arsenic-contaminated drinking water increases the risk of cancer and damage to skin and to the nervous and circulatory systems. Exposure to arsenic has also been associated with fetal developmental effects, heart disease, and diabetes. In response to these and other potential health effects from arsenic in drinking water, in 2001 the USEPA lowered the Maximum Contaminant Level (MCL) for total arsenic in drinking water from 50 to 10 micrograms per liter (μg/L) and required all public water utilities to meet this new standard by 2006. Although this was more than 20 years ago, many rural water companies have not financially recovered from implementing treatment to meet this standard.

Several significant geologic sources of arsenic exist, including volcanic magma, which, when pushed upward into existing bedrock, hardens into veins containing copper, silver, gold, and arsenic ores. Regions of granite bedrock with valuable gold ore often contain elevated concentrations of arsenic. Alluvial aquifers containing eroded granitic bedrock may contain arsenic.

Because the solubility of arsenic in water is a function of residence time in the aquifer and its mineral form, changes in the pH, oxygen content, and geochemistry of the aquifer water may increase or decrease arsenic concentrations in the water. An example is the introduction of atmospheric oxygen as groundwater elevations drop due to drought.

5.3.3 Nitrate

Nitrate can be naturally occurring in arid soils, but high concentrations of nitrate in groundwater are usually due to either agricultural practices (excessive fertilizer use and/or poor irrigation methods) or failing septic systems that allow contaminated waters to drain into the aquifer. Nitrate is undetectable without testing because it is colorless, odorless, and tasteless. However, when it originates from septic fields or agricultural activities, nitrate may be associated with higher-than-normal TDS, soluble organic matter, pathogens, and herbicides that can change water taste and color. Although nitrate is released into the environment in large quantities, it is a nutrient taken up by plants and other organisms that can then reduce its concentration. In low-oxygen environments, nitrate can also change to ammonia or nitrogen gas, dissipating into the atmosphere.

The USEPA MCL for nitrate (reported by the analytical laboratory as Nitrate-N) in a public water supply is 10 mg/L or parts-per-million (ppm). This standard is based on the risk of acute health effects, specifically the risk of methemoglobinemia, which can be life-threatening for infants and young children, and is referred to as "blue baby syndrome", in which blood lacks the ability to carry sufficient oxygen to the individual body cells.

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In areas with historic or current agricultural activities and/or those served by individual septic systems and domestic wells, nitrate contamination may be prevalent. Large expanses of irrigated cropland are the most significant contributor to elevated nitrate concentrations.

5.3.4 Lithium

Lithium is categorized as a critical mineral, defined as a non-fuel mineral essential to the economic and national security of the USA, and essential in the making of batteries. Your cell phone battery and other batteries all rely on lithium to operate. Naturally occurring lithium may be found in sedimentary aquifers as well as in volcanic ash.

Lithium is used medicinally for treating mental health issues because it is a mood moderator. Lithium is not regulated in the USA but the nonregulatory health-based screening level proposed by the USEPA is 10 ppb (Lindsey, et al, 2021). Symptoms of toxicity that have been reported include tremor, nausea and diarrhea, vision changes, and confusion. In addition, several studies in the USA, Japan, and the United Kingdom have found a significant correlation between concentration and public safety (e.g., low criminality and low suicide prevalence) in regions with high lithium, and high levels of criminality in regions with low lithium. If you are currently prescribed lithium for health reasons, you may want to analyze your well water to reduce the chance of imbibing too much. There are no regulatory standards for lithium in drinking water.

5.3.5 Fluoride

Fluoride is a common element that is concentrated in volcanic ash, soils, and sediments that contain minerals rich in fluorine like carbonates, clays, and fluorite (CaF_2). Fluoride minerals may also be present in granite. Most of the elevated concentrations are associated with confined aquifers because groundwater held in confined aquifers usually has not had the opportunity to mix with recently recharged water high in dissolved oxygen. The low-oxygen environment and long resident time allows for fluoride naturally present in the geologic materials to dissolve into groundwater. In high-oxygen environments, fluoride minerals tend to remain bound to their geologic source.

Although it can be harmful at high concentrations, fluoride is essential for strong teeth and bones and is essential for the development of tooth enamel. Many municipal water-supply systems add fluoride to the water to support dental health. However, excessive fluoride concentrations in drinking water can discolor teeth and cause skeletal fluorosis. The maximum contaminant level for fluoride is 4.0 mg/L, and the secondary maximum contaminant level is 2.0 mg/L, a level at which tooth discoloration can occur.

5.3.6 Dissolved Iron and Manganese

Iron and manganese are found in nearly all groundwater. While the USEPA does not have a primary standard for manganese in drinking water, Health Canada has established a maximum acceptable concentration for total manganese in drinking water of

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0.12 mg/L (120 μg/L) to protect against neurotoxic effects, particularly in infants and children.

The presence of high levels of iron, manganese, and sulfides in well water may be due to low oxygen content and the presence of naturally occurring iron or manganese minerals. When this groundwater is pumped and exposed to air it produces reddish-brown (iron) or brownish black (manganese) particles, deposits, and stains and can also adversely affect the taste of water. Precipitated manganese particles can clog an irrigation system as shown in Figure 27. While abnormal levels of iron and manganese can give unpleasant rust or metallic taste, odor, and color to water, they are not considered a health risk.

When drawn from the tap, well water containing iron may initially be clear, but soon very small particles of iron form. Called colloidal iron, these particles settle very slowly, turning the water reddish brown and causing stains on concrete, glassware, laundry, porcelain, sinks, and plumbing fixtures. Similarly, manganese usually dissolves clear in water, but some colloidal manganese may tint the water black, causing brownish black stains. Detergents do not remove these stains. Chlorine bleach may even intensify the stains and produce water tinted purple.

5.3.7 Radioactive Elements

Radioactivity is the release of energy from within atoms in the form of atomic particles (alpha and beta) and gamma radiation. Certain atoms are inherently unstable and spontaneously break down (decay) to form more stable atoms. For example, the potassium-40 isotope decays very slowly (half-life of 1.23 billion years) but eventually becomes calcium and the gaseous element argon. Because potassium is a significant component of clay minerals, clay, bricks, and pottery are slightly radioactive. Plants grown in clay soils are also slightly radioactive as are animals who eat these plants.

Any element that decays by emitting radioactive particles or gamma radiation is known as a radionuclide. As radionuclides decay, they produce daughter products (for example, potassium decays to argon) that may be shorter lived and possibly more radioactive. Of particular concern is naturally occurring uranium, which decays to thorium and other radionuclides that can accumulate to harmful levels in drinking water.

Radioactive minerals containing the radionuclides uranium and its daughter product thorium-230 (4.5 billion and 75,000 years half-life, respectively) can be found in granite, including in granitic sediments in unconsolidated aquifers. These elements decay, eventually becoming a new element called radium (half-life of 1,620 years), which then decays to the element radon gas (half-life of 3.8 days). The MCL for uranium is 30 micrograms per liter (μg/L). The MCL for the sum of the isotopes radium-226 and radium-228 is 5 picocuries per liter (pCi/L).

"Gross alpha" is a measurement of the amount of alpha particle radioactivity in water and is due to the decay of uranium, radium, and their daughter radionuclides. Gross alpha is a measurement of overall radioactivity from alpha particles. Therefore, gross alpha

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does not tell us which radionuclides are in the water, but simply that alpha emitting radionuclides are present. The most common alpha emitters are uranium and radium. Elevated gross alpha concentrations in groundwater are natural and common in granitic bedrock aquifers or in alluvial aquifers composed of eroded granite. The MCL for gross alpha measured in picocuries (pCi) is 15 pCi/L, and all radionuclides are carcinogenic.

5.3.8 Radon Gas

Radon is an odorless, colorless, tasteless gas that dissolves in groundwater and may migrate upward through the soil, eventually dissipating into the atmosphere. If there is dissolved radon gas in your well water, every flush of the toilet or use of the shower releases the gas. If radon gas is trapped within a structure, such as a bathroom or basement, the concentration of the gas may exceed health standards. The USEPA estimates that 1 in 15 homes contain a high level of the gas (USEPA, 2025). Radon is considered to be the second leading cause of lung cancer in the country after tobacco smoking. The USEPA action level for radon is 4 pCi/L. If radon is at or above this level, the agency recommends taking action to reduce its concentration.

5.3.9 Other Constituents

Water that comes into contact with the natural environment always has minute amounts of dissolved minerals at low concentrations that are not known to be a health threat. However, the mineral-rich geology in mining districts can result in elevated levels of copper, zinc, and sulfate because they are occasionally found in groundwater.

Elevated levels of other naturally occurring constituents can be found in domestic well water, and for this reason, a baseline water analysis needs to be done to test for these constituents. Naturally occurring hexavalent chromium (Cr(VI) also called Chrome 6 and known to cause cancer), selenium, and boron occur in evaporite deposits, and these elements have also been detected in agricultural drainage waters. Elevated levels of sulfates can be found in groundwater impacted by mining activities and can also come from aquifers rich in gypsum usually found in evaporitic basins.

There are no water quality standards yet for boron, although the World Health Organization (WHO) has a recommended a level of 0.5 mg/L. Copper, silver, zinc, chromium, selenium, and sulfate have known health impacts or established drinking water standards (Box 1).

5.3.10 Hardness

Hardness is a measure of calcium, magnesium, and other minerals in water. For example, groundwater from a limestone aquifer is typically hard because of the calcium and magnesium dissolved from the rock into the water. Hard water requires more soap for laundry and washing and causes scale to build up in dishwashers, washing machines, water heaters, and plumbing fixtures.

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There are no primary or secondary standards for water hardness, but the National Research Council states that drinking hard water generally contributes a small amount toward the total dietary needs for calcium and magnesium.

The hardness of water is reported as an equivalent amount of calcium carbonate ($CaCO_3$) in mg/L or grains/gallon (Table 2). Unfortunately, the use of a sodium-chloride-based water softener salt will increase the concentration of salt in your septic system, potentially resulting in damage to the soils in the drain field and the failure of the system. If your water must be softened, consider using a potassium chloride-based salt, and a properly set up demand-based water softener that will limit your use of salt.

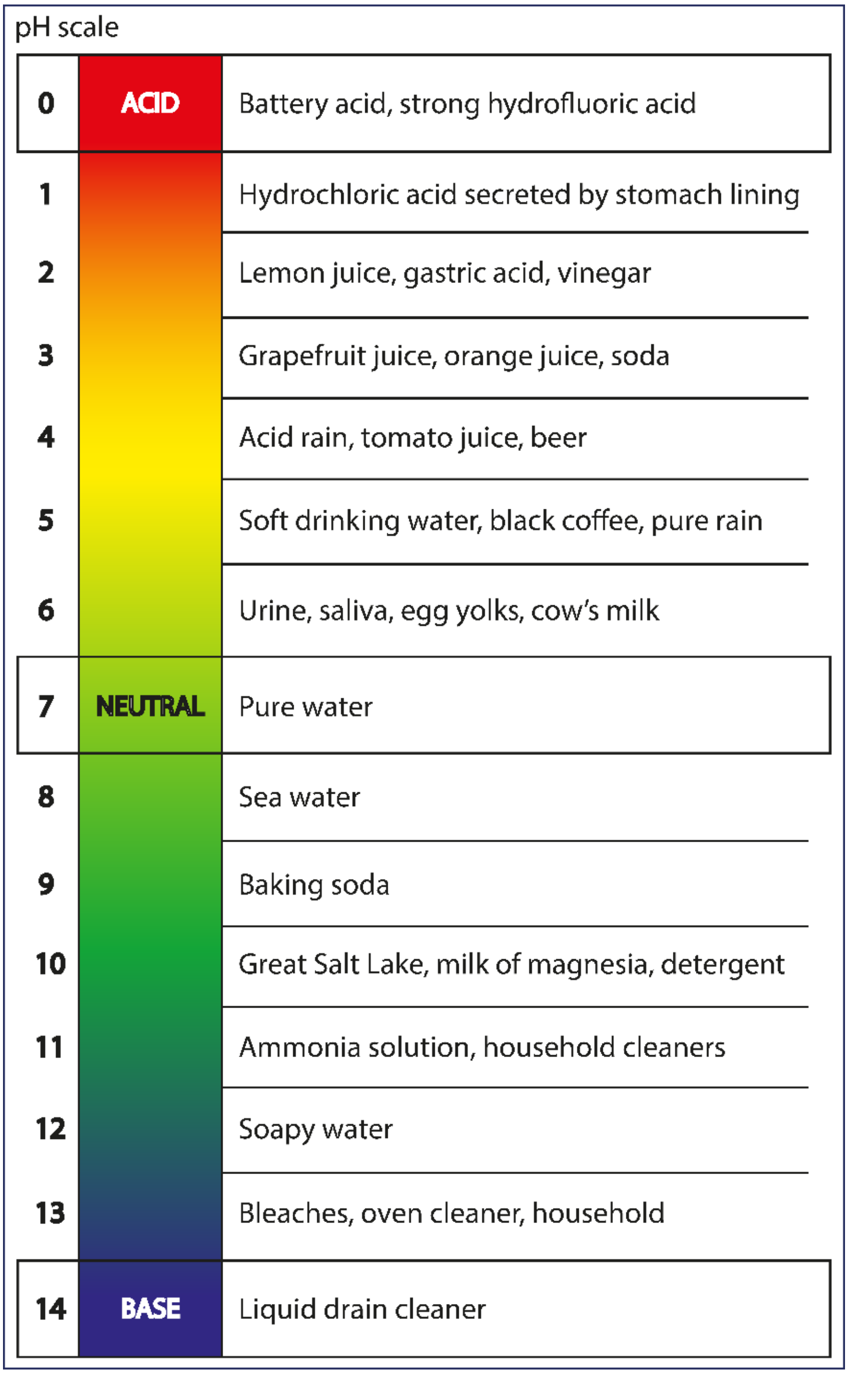
Table 2 - Water Hardness Scale

Grains Per Gallon	Milligrams per Liter (mg/L) or Parts per Million (ppm) of $CaCO_3$	Classification
Less than 1.0	Less than 17.1	Soft
1.0–3.5	17.1–60	Slightly Hard
3.5–7.0	60–120	Moderately Hard
7.0–10.5	120–180	Hard
Over 10.5	Over 180	Very Hard

Conversion: 17.1 mg/L of $CaCO_3$=1 grain per gallon (gpg)

5.3.11 Acidic or Basic Water: pH

The pH of groundwater is defined as the concentration of hydrogen ions. pH of 7 is considered neutral; as water becomes more acidic, its pH falls below 7; and as water becomes more basic, its pH rises above 7 (Figure 35). pH is important because it impacts the ability of mineral constituents to dissolve into the water. pH is a measure of acidity in water and should not be confused with alkalinity, which is the ability of water to neutralize acids and resist changes in pH. Many groundwater sources are alkaline and contain high levels of bicarbonates. The presence of some minerals, for example arsenic or fluoride, can cause water to become more basic, a characteristic that is often correlated with alkaline water. pH is important in controlling pipe corrosion and some taste problems. Metallic taste for example may be due to excessive levels of metals (such as zinc and copper) that are present due to low water pH that corrodes metal pipes. The recommended pH range for drinking water is 6.5 to 8.5; Figure 35 compares the pH of various liquids to water. Water with a pH value above 8.5 is usually too high in TDS to be potable.



pH scale

0	ACID	Battery acid, strong hydrofluoric acid
1		Hydrochloric acid secreted by stomach lining
2		Lemon juice, gastric acid, vinegar
3		Grapefruit juice, orange juice, soda
4		Acid rain, tomato juice, beer
5		Soft drinking water, black coffee, pure rain
6		Urine, saliva, egg yolks, cow's milk
7	NEUTRAL	Pure water
8		Sea water
9		Baking soda
10		Great Salt Lake, milk of magnesia, detergent
11		Ammonia solution, household cleaners
12		Soapy water
13		Bleaches, oven cleaner, household
14	BASE	Liquid drain cleaner

Figure 35 - pH scale and corresponding fluids (modified from Artiola et al., 2017).

5.3.12 Taste

Several factors influence water taste, including TDS levels, pH, organic matter, and the types and proportions of minerals. For example, water with 500 mg/L of sodium salts will have a slightly salty taste and feel slippery, but water of equal TDS but composed of gypsum, calcium, and bicarbonate would taste less salty. Salty taste can be reduced by lowering the water TDS.

5.4 Organic Matter

Color, odor, foam content, and taste of water are affected by the presence of natural organic matter (NOM). NOM is usually found at much higher concentrations in surface water than groundwater, but even deep, old groundwater may have measurable levels of NOM. Most NOM is derived from vegetation, such as leaves, that fall in the surface water and decay. If well water contains organic matter, it is usually derived from vegetation such as leaves or roots in the well. These constituents can impart taste and color to the water, like when tea leaves are brewed. Wells with water levels that respond quickly to rainstorms and floods may also have elevated levels of NOM, sediments, and other unwanted contaminants, following rapid recharge of stormwater to the aquifer.

5.4.1 Rotten Eggs (Hydrogen Sulfide Odor)

The decay of organic matter in the aquifer may generate hydrogen sulfide gas, which smells like rotten eggs. Although colorless, hydrogen sulfide is perceptible by the human nose at concentrations as low as 0.47 μg/L (equivalent to 0.47 parts per billion) in air. The gas may corrode pipes as well as create black stains on silverware and plumbing fixtures. Iron and sulfur-reducing bacteria can thrive in low oxygen environments rich in organic matter such as slow-moving groundwater and in warm storage tanks, water heaters, and water treatment tanks.

Corrosive hydrogen sulfide gas can also be produced by bacteria in aquifers that contain pyrite (iron sulfide) minerals, are rich in sulfate, or are near oil and gas production where natural gas is seeping into the aquifer.

5.4.2 Iron and Manganese Slime

When red-iron or black-manganese deposits have the consistency of slime, this indicates the presence of iron and manganese bacteria in the water that form biofilms on surfaces (Figure 29). These slimy deposits are soft and can be found in toilet tanks and can quickly clog water and well systems as they tend to grow faster than hard mineral deposits.

5.5 Anthropogenic Contaminants

Anthropogenic contaminants are found in water because of human activities that release or discharge industrial and agricultural chemicals into the environment. They also can be derived from land use activities such as the flushing of oils and grease off roadways. The volumes released vary widely and their fate and transport within the environment depend on their chemical and physical properties, as well as how each aquifer's geological material interacts with their presence. Some contaminants are harmless or are not known to be toxic; others degrade into harmless chemicals. Some contaminants can accumulate in our tissue and organs and become a danger to our health. Nitrate, previously discussed, is a good example of a chemical that is both natural and anthropogenic and is often released

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into the environment at concentrations that can be harmful to human and aquatic environments.

The odor threshold (the concentration at which the human nose can detect an odor) of some natural and industrial chemicals is lower than the detection capacity of a testing laboratory. This means that sometimes we can be alerted to the presence of contaminants in water by their smell. However, one should not only rely on the sense of smell to determine the possible presence of contaminants in well water.

5.5.1 Trichloroethylene (TCE) and Other Industrial Solvents

The solvent trichloroethylene (TCE), an industrial degreaser, is found in the groundwater at thousands of environmental remediation sites across the USA and Canada. This human-made chemical is so soluble in water that one pound of it can turn 24 million gallons of water unfit to drink. It has an MCL of 5 ppb—2,000 times lower than nitrate (Box 1). Because TCE increases the risk of cancer, the USEPA has set its MCLG to zero.

TCE-contaminated groundwater is difficult and expensive to remediate, partly because under anaerobic conditions this chemical commonly degrades to additional harmful chemicals, resulting in the presence of multiple contaminants. TCE in its free-phase (undissolved) liquid form is nearly 1.5 times denser than water, and it sinks to the bottom of aquifers.

Anthropogenic chemicals in groundwater commonly originate from industrial sites and landfills but also can come from other less expected sources. Environmental contamination sites are often first discovered because private well owners notice unusual odors or taste in their well water. Groundwater contamination from an environmental site usually decreases farther away from the source (such as a landfill or leaking underground gasoline storage tank), and the contaminant usually moves downgradient. In some cases, the contaminant plumes can be miles long.

5.5.2 MTBE and PFAS

The gasoline additive MTBE (Methyl tertiary-butyl ether) was used to reduce air pollution by boosting octane while replacing lead in gasoline starting in the late 1970s. However, the fate of this chemical in the soil and water environment was not fully tested before its use. MTBE is very mobile, soluble, and stable (slow to degrade) in water, which has resulted in the contamination of numerous groundwater supplies from leaky underground storage tanks. Although some states like California and New Jersey, USA, regulate MTBE in drinking water, to date the USEPA has not set an MCL for this chemical in potable water.

PFAS stands for per- and polyfluoroalkyl substances and there are several unique chemical formulations included within the general PFAS label. These are a group of man-made chemicals that are resistant to grease, oil, water, and heat and are used to coat non-stick cookware. They are also contained in firefighting foam used in fire training pits at

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military bases, as well as in firefighting. PFAS are found near airports, military bases, and across urban areas. Once these chemicals reach groundwater, they are dispersed throughout the aquifer. They are also known as "forever chemicals" because they are resistant to degradation in the environment and are both difficult and expensive to remove from water. The USEPA has recently (April 2024) set an MCL for several PFAS chemicals in drinking water (Box 1).

5.5.3 Pathogens

Groundwater can be contaminated with organisms such as intestinal (enteric) waterborne pathogens that can cause diseases. An enteric pathogen can impact the digestive system and cause vomiting and/or diarrhea. In rural areas, this contamination is often the result of failing septic systems and poor wellhead protection. Contaminated groundwater represents approximately 40 percent of all the waterborne disease cases documented in the USA every year (USCDC, 2024).

Organisms that can contaminate groundwater include human-waste derived viruses such as adenoviruses, rotaviruses, Hepatitis A, and norovirus; enteric bacteria such as *E. coli* O157:H7, *Salmonella, Campylobacter, Pseudomonas, Helicobacter, Aeromonas, Vibrio cholerae,* and *Shigella*; protozoan pathogens such as *Cryptosporidium* and *Giardia*; and an amoeba called *Naegleria fowleri*. These organisms present a human health risk when ingested in contaminated water. Typical symptoms associated with an infection include acute gastroenteritis, severe cramping, abdominal pain, dehydration, and diarrhea.

The *Naegleria fowleri* organism thrives in warm water and in slow flowing or stagnant water systems such as storage tanks and has been found in water pipelines in Australia. This amoeba usually infects humans by traveling through the nose to the brain and spinal cord causing a painful death.

All the above-mentioned organisms are a risk to human health, but viruses are considered more of a threat to groundwater because they are much smaller than bacteria or parasites and can leach farther down the vadose zone and into aquifers. Viruses can be more persistent in the environment than many bacteria requiring stronger disinfection methods to inactivate them.

5.5.4 Emerging Contaminants

Emerging contaminants include chemicals that can be detected at lower levels with new or improved analytical methods. New instruments and techniques routinely detect concentrations or contaminants previously not expected to occur in our water supply. Very small concentrations (part-per-trillion and lower) of chemicals such as: artificial sweeteners; caffeine; fabric fire retardants (PFAS); antibiotics and common medications such as ibuprofen; the mosquito repellent DEET; and chemicals originating from products such as Teflon®, ScotchGard®, and Gore-Tex®, are now found in our wastewaters and drinking water supplies. Artificial sweeteners are becoming the most detected contaminant

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in drinking water due to seepage from septic systems and discharge from water treatment facilities.

Chemicals that can affect the human endocrine system—called endocrine disruptors—are of increasing concern and are found in pharmaceuticals and personal care products (PCPs), steroids, and human hormones. These are passed through our bodies and are transported to the environment. According to the USEPA↗, endocrine disruptors include therapeutic and veterinary drugs, fragrances, cosmetics, sunscreens, diagnostic agents, and vitamins—each ending up in our drinking water.

National surveys have shown that many of these chemicals are not fully removed during treatment of municipal wastewaters. New and more aggressive wastewater treatment approaches are being developed but have yet to become economically available to the homeowner. Thus, reclaimed wastewaters discharged into the environment are affecting the quality of other water sources. Although limited information exists about emerging contaminants in septic systems, we know that some of these contaminants have the potential to reach groundwater when discharged through septic systems.

Drinking water standards for emerging contaminants evolve slowly. An example is perchlorate, which is known to persist in water for many years, and which can be naturally occurring. This chemical is water soluble, mobile, hard to degrade, a major component of rocket propellants, munitions, and fireworks. It may also be found in fertilizers and bleach. It has been detected in western USA water supplies, such as in the Colorado River, and it is found naturally in brackish groundwaters. This chemical can affect the endocrine system (thyroid function), and according to the USEPA, is a likely human carcinogen. Some states have health-based goals for perchlorate in drinking water public water supplies, although the USEPA has yet to set a national MCL.

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6 Testing Well Water Quality

Water testing is usually not required to register a pre-existing domestic well or after drilling a new one. A few states require water quality testing when a property using a well is sold and many lending institutions may require limited well water testing (e.g., bacteria contamination check) before authorizing a loan for purchasing land or a home with a water well. Therefore, it is the responsibility of the well owner to test the well water after drilling completion and regularly thereafter. In deciding which parameters to test, it is helpful to gather as much information as possible about the groundwater quality from previous owners, neighbors, local water utilities, and state agencies. It is also important to be familiar with local geology and nearby past or present land use activities, since these factors usually determine the quality of your well water and which contaminants are likely to be present. Information on these topics is provided in the previous section on Drinking Water Standards and Guidelines.

It is important to prioritize water quality information, because testing for all possible contaminants can cost in excess of $4,000 USD per sample, with PFAS alone ranging between $400 to $600 per sample. A baseline analysis for nitrate, bacteria, arsenic, fluoride, and other constituents that may be naturally occurring in your aquifer should be done and repeated specifically for arsenic whenever the well is serviced. You need not repeat the entire list of initial tests every year. However, total and fecal coliform (*E. coli*), and nitrate should be tested annually as they are early indicators of water quality changes in an aquifer. Ongoing visual and odor inspection of your well water is recommended; be aware of any changes in health of household members and visitors. Box 2↴ provides a list of symptoms related to poor water quality, possible causes, and treatment devices. The possible causes can guide you to an appropriate well test method to determine the source of the water problem.

6.1 Sampling Your Well Water

Water samples may be collected at the wellhead, pressure tank, or inside your house at the point of use—usually your kitchen faucet. To test the aquifer water quality, collect a water sample as close to the wellhead as possible after the well has been purged several times. A typical domestic well will be purged at the end of the day if there has been substantial water use, such as doing several laundry loads and/or watering the garden.

Water sampling beyond the wellhead and inside the house is complicated by the presence of storage and/or pressure tanks and water heaters that can impact the water quality over time with lasting residual effects. If the water quality at the wellhead is acceptable, then any contamination (detected at the kitchen faucet, for example) may require further testing at several points inside the house to determine the contaminant source. Lead is not likely to be found in groundwater, and if present, is likely due to lead

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pipes or the use of lead-based solder in your plumbing. Sampling for lead should be at the faucet (Exercise 5↴) (Exercise 6↴).

6.1.1 Water Analysis using a Certified Laboratory

Well owners can collect water samples following the guidelines provided by a laboratory and the laboratory will provide the containers/bottles. Sampling instructions should be followed carefully to avoid improper handling that can result in sample contamination biasing the results.

The laboratory should be certified. Obtain a list of certified laboratories from your local government agency. Certification means that the method of analysis is standardized across all laboratories.

6.1.2 Home Water Test Kits

There several types of water testing kits including portable meters to measure pH, TDS, and other water quality parameters. These kits, while inexpensive, often lack the sensitivity and accuracy of modern laboratory methods and instruments. They are usually designed to perform a single test using a test strip with a color scale (Figure 36).

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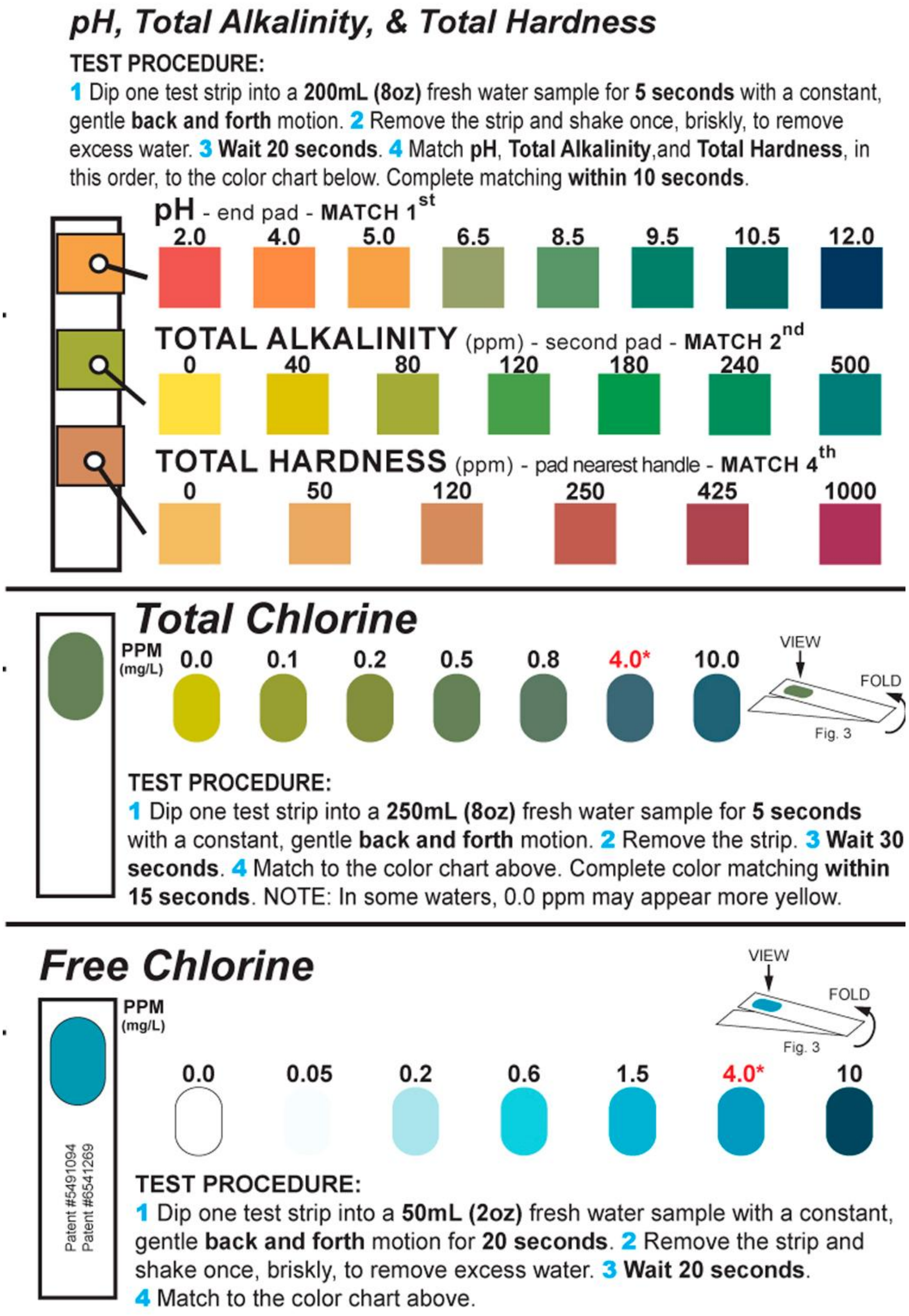

pH, Total Alkalinity, & Total Hardness

TEST PROCEDURE:

1 Dip one test strip into a **200mL (8oz)** fresh water sample for **5 seconds** with a constant, gentle **back and forth** motion. **2** Remove the strip and shake once, briskly, to remove excess water. **3 Wait 20 seconds**. **4** Match **pH**, **Total Alkalinity**,and **Total Hardness**, in this order, to the color chart below. Complete matching **within 10 seconds**.

pH - end pad - **MATCH 1st**

2.0 4.0 5.0 6.5 8.5 9.5 10.5 12.0

TOTAL ALKALINITY (ppm) - second pad - **MATCH 2nd**

0 40 80 120 180 240 500

TOTAL HARDNESS (ppm) - pad nearest handle - **MATCH 4th**

0 50 120 250 425 1000

Total Chlorine

PPM (mg/L) 0.0 0.1 0.2 0.5 0.8 4.0* 10.0

TEST PROCEDURE:

1 Dip one test strip into a **250mL (8oz)** fresh water sample for **5 seconds** with a constant, gentle **back and forth** motion. **2** Remove the strip. **3 Wait 30 seconds**. **4** Match to the color chart above. Complete color matching **within 15 seconds**. NOTE: In some waters, 0.0 ppm may appear more yellow.

Free Chlorine

PPM (mg/L)

0.0 0.05 0.2 0.6 1.5 4.0* 10

TEST PROCEDURE:

1 Dip one test strip into a **50mL (2oz)** fresh water sample with a constant, gentle **back and forth** motion for **20 seconds**. **2** Remove the strip and shake once, briskly, to remove excess water. **3 Wait 20 seconds**.
4 Match to the color chart above.

Figure 36 - Instruction sheet from a home water-testing kit. These kits typically rely on a color change on a test strip to determine the concentration of a contaminant.

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Other tests use a combination of two or more chemicals added to the water to obtain a color change that is measured against a color scale to determine a contaminant detection range. Compared to USEPA-approved methods used in laboratories, testing kits have several limitations.

- Contaminant detection range is limited and can only read values at discrete intervals, lacking precision.
- Procedures or shortcuts may not be approved for accuracy.
- Results may be influenced by the presence of other constituents, such as unusual levels of dissolved iron and organic matter.
- In-home tests are often less accurate when measuring contaminant levels that are at or near the drinking water standards.

On the other hand, these kits can be useful.

- They can offer an early warning of the presence of high levels of a contaminant in water.
- They can provide routine verification of well water quality in conjunction with less frequent analyses performed by certified laboratories.
- They are inexpensive and easy to use. If they are from a reputable company, they will be USEPA certified or approved. Never use test strips or test kit chemicals past the expiration date posted on the box.

Water testing kits are available from independent companies such as Hach, Lamotte, EMD Millipore, and Waterworks, and from resellers such as Ben Meadows (no endorsements implied).

6.2 Interpretating Water Analysis Results

Your laboratory report should include your sample results in the appropriate units, including:

- milligrams per liter (mg/L), or parts per million (ppm);
- micrograms per liter (μg/L) or parts per billion (ppb);
- nanograms per liter (ng/L) or parts per trillion (ppt); and
- picocuries per liter (pCi/L).

The table of results should have columns listing the drinking water standards for comparison with your results and a laboratory data quality control that includes sample detection limits. Some sample values may be reported as "BDL" meaning "below detection limit" or "ND" meaning "non detect." In either case, the laboratory reported sample detection limit should be less than the drinking water MCL. For example, your well water sample may have arsenic reported as BDL in the laboratory report. The report also lists the detection limit for arsenic as 1 ppb. This means that your sample meets the drinking water standard of 10 ppb because the arsenic concentration in your sample is BDL and therefore less than 1 ppb.

Compare all the results to the MCL standards and Health Based Advisories in Box 1. Any water quality constituent that is above the primary MCL may be a threat to human health or make the water unfit to drink.

Contact the laboratory for clarification of special terms or abbreviations if needed. If you are concerned about any health-related issues related to your water quality, contact your local government agency and/or discuss the concern with your health care provider. Seek assistance from independent water quality/treatment specialists and reputable equipment vendors before deciding on expensive water treatment options. If your well water exceeds one or more quality standards, use an alternate source of water for drinking and cooking while exploring water treatment remedies.

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7 Water Treatment Options

Domestic well owners have access to several water treatment options but choosing which one to implement can be difficult as the optimal system depends on the type and concentration of the contaminant(s). Selecting a water treatment option can also be confusing, often due to incomplete or misleading information about the effectiveness of treatments provided by vendors, who wish to sell their product. The consumer may not realize that, besides the initial purchase price, there are additional installation, routine maintenance, and testing costs not always anticipated or explained. Some water treatment systems may be installed and maintained by well owners, but complex systems will require professional assistance.

There are several methods to treat water, starting with filters to remove sediment particles. More complex water treatment systems add or remove chemicals or contaminants to/from the water and change the water's chemical composition. Water treatment methods scientifically proven to treat water safely and accepted by the USEPA and organizations like the National Sanitation Foundation (NSF) or the Water Quality Association (WQA) are described in the following sections, and include: particle and micro filtration; reverse osmosis; ion exchange; activated charcoal (ultrafiltration); chemical filters (permanganate, alkaline, iron); distillation; and disinfection (including heat, chlorine, and UV light-based methods). Other methods not covered in this book but used in large scale water treatment operations include the use of iron and aluminum-based flocculants and anion/cation exchange resins.

Home water treatment systems are usually set up to treat some, or all, of the water entering the house. A point-of-use system may be installed on the kitchen faucet or under the sink to treat water used for cooking and drinking. A point-of-entry system, such as a particle filter, may be installed as the water comes into the house, and treat all the water used in the house. Some treatment systems, such as water softeners, need only treat water within the hot water plumbing system to prevent scale formation in the water heater and pipes.

Figure 37 provides a guide for the initial selection of water filtration systems based on contaminant type and sediment particle size. This guide does not include chemical, disinfection, or distillation treatment methods.

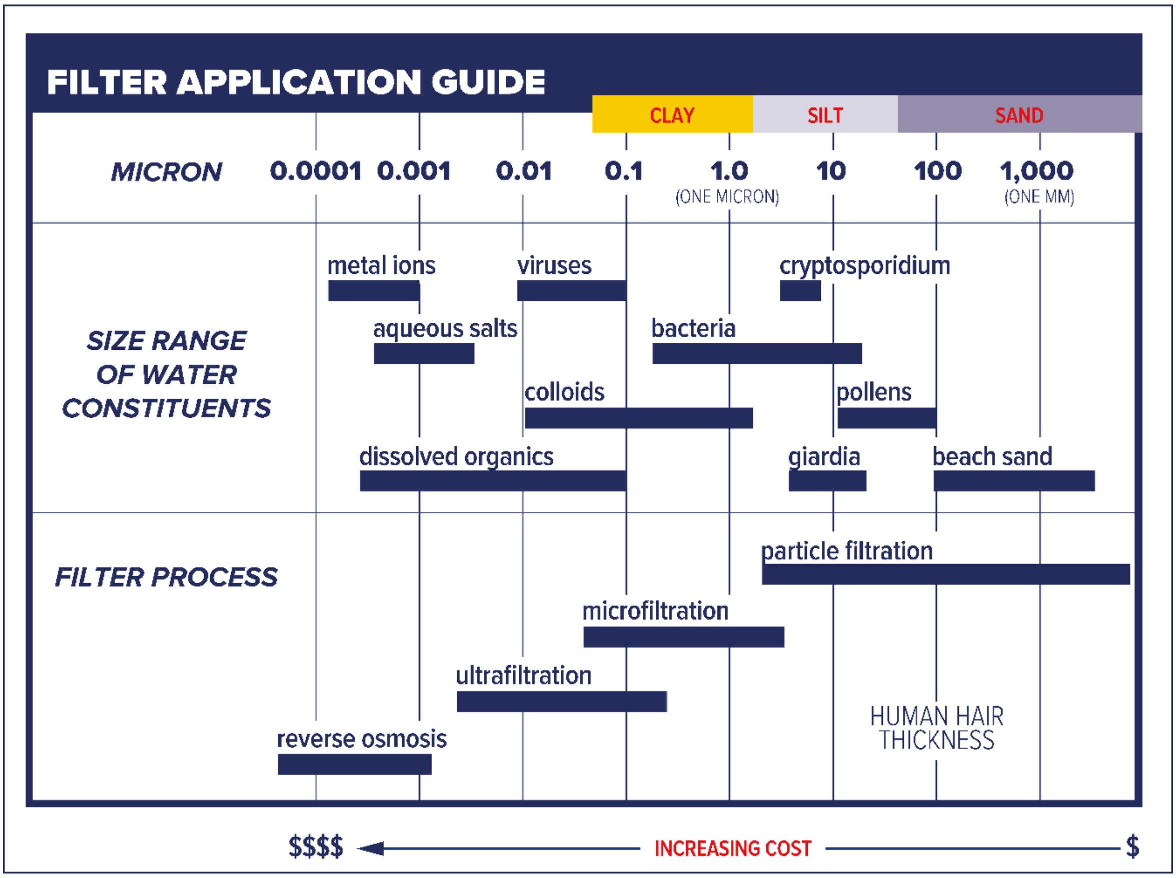
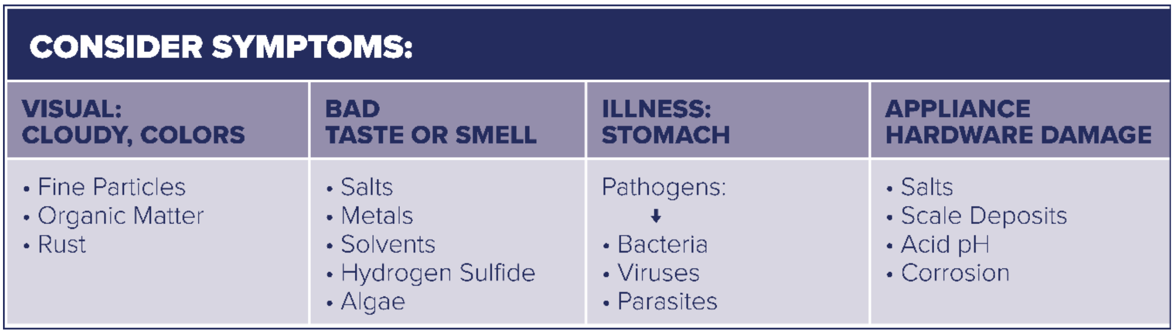


Figure 37 - Filtration guide showing size ranges of clay, silt, and sand particles, and of common water constituents, as well as size ranges over which different filtration methods are effective (modified from Uhlman et al., 2012).

Well owners may select water treatment options based on one, or more, of the four general symptoms shown in Figure 38. These symptoms are indicative of water quality problems that cause nuisances, health issues, and damage, usually requiring some form of water treatment. But other more serious health-threatening contaminants may be present in well water such as arsenic, nitrate, radionuclides, PFAS, volatile organics, and pesticides that cannot be seen, tasted, or smelled.



CONSIDER SYMPTOMS:

VISUAL: CLOUDY, COLORS	BAD TASTE OR SMELL	ILLNESS: STOMACH	APPLIANCE HARDWARE DAMAGE
• Fine Particles • Organic Matter • Rust	• Salts • Metals • Solvents • Hydrogen Sulfide • Algae	Pathogens: ↓ • Bacteria • Viruses • Parasites	• Salts • Scale Deposits • Acid pH • Corrosion

Figure 38 - Symptoms that suggest you may need water treatment. Box 2 provides a more comprehensive table of symptoms, causes, and treatments (modified from Uhlman et al., 2021).

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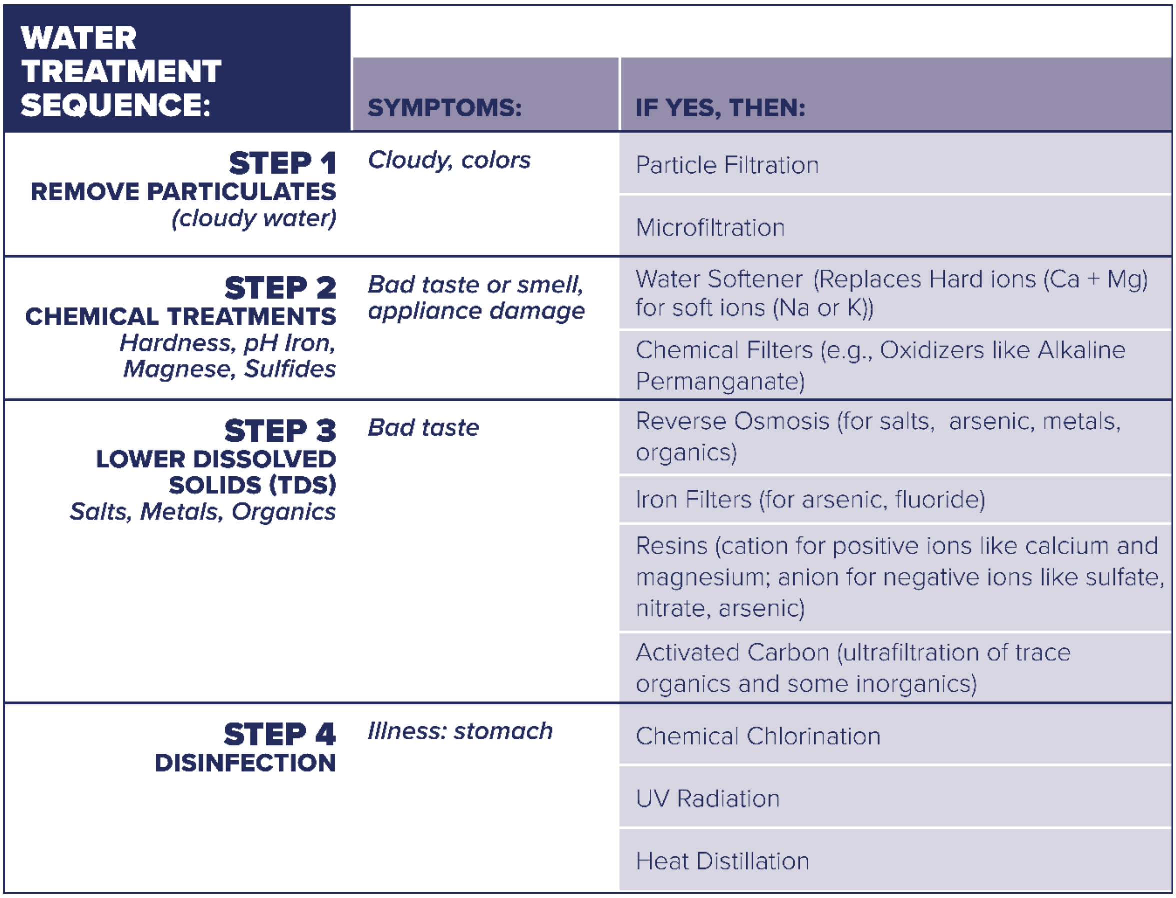
7.1 Treatments

To assist in well-water treatment selection, Figure 39 shows a decision tree with steps 1 through 4, each with options depending on the quality of the water. In most cases only one treatment step will be needed, but in others two or more steps may be needed and should be implemented in order. For example, the water may need to be filtered prior to chemical treatment. Aside from selecting treatment based on symptoms, it is important to test and measure the concentration of the contaminant to properly size the treatment system. After installation of the system, a follow-up water test should be done to evaluate efficiency of contaminant removal. For example, arsenic-treatment systems may remove only 80 percent of the contaminant, so if the groundwater concentration is very high you might need two arsenic-treatment systems in-line to assure safe water.



WATER TREATMENT SEQUENCE:	**SYMPTOMS:**	**IF YES, THEN:**
STEP 1 **REMOVE PARTICULATES** *(cloudy water)*	*Cloudy, colors*	Particle Filtration
		Microfiltration
STEP 2 **CHEMICAL TREATMENTS** *Hardness, pH Iron, Magnese, Sulfides*	*Bad taste or smell, appliance damage*	Water Softener (Replaces Hard ions (Ca + Mg) for soft ions (Na or K))
		Chemical Filters (e.g., Oxidizers like Alkaline Permanganate)
STEP 3 **LOWER DISSOLVED SOLIDS (TDS)** *Salts, Metals, Organics*	*Bad taste*	Reverse Osmosis (for salts, arsenic, metals, organics)
		Iron Filters (for arsenic, fluoride)
		Resins (cation for positive ions like calcium and magnesium; anion for negative ions like sulfate, nitrate, arsenic)
		Activated Carbon (ultrafiltration of trace organics and some inorganics)
STEP 4 **DISINFECTION**	*Illness: stomach*	Chemical Chlorination
		UV Radiation
		Heat Distillation

Figure 39 - Recommended sequence for installation of treatment systems (modified from Uhlman et al., 2012).

7.1.1 Particle Filtration

Natural filtration occurs as water infiltrates through the soils to the aquifer through a combination of physical, chemical, and biological processes within the environment. Well-water filters, such as gravity-fed sand filters, combine several layers of granular material (often progressing from coarse to fine sizes in the direction of flow) to reproduce this natural process. These filters are capable of filtering soil particles and some types of

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pathogens when the filter is properly designed and maintained. An example of a simple filtering system is shown in Figure 40. Sand filters can be scaled to filter large volumes of well water but require periodic maintenance and monitoring to assure constant flows and water quality. Particle sand filters can also be effective in reducing the levels of bacteria and viruses in water. Closed system (pressurized) sand filters are used in swimming pools to remove lime scale residues, but these are typically not used for drinking water treatment.

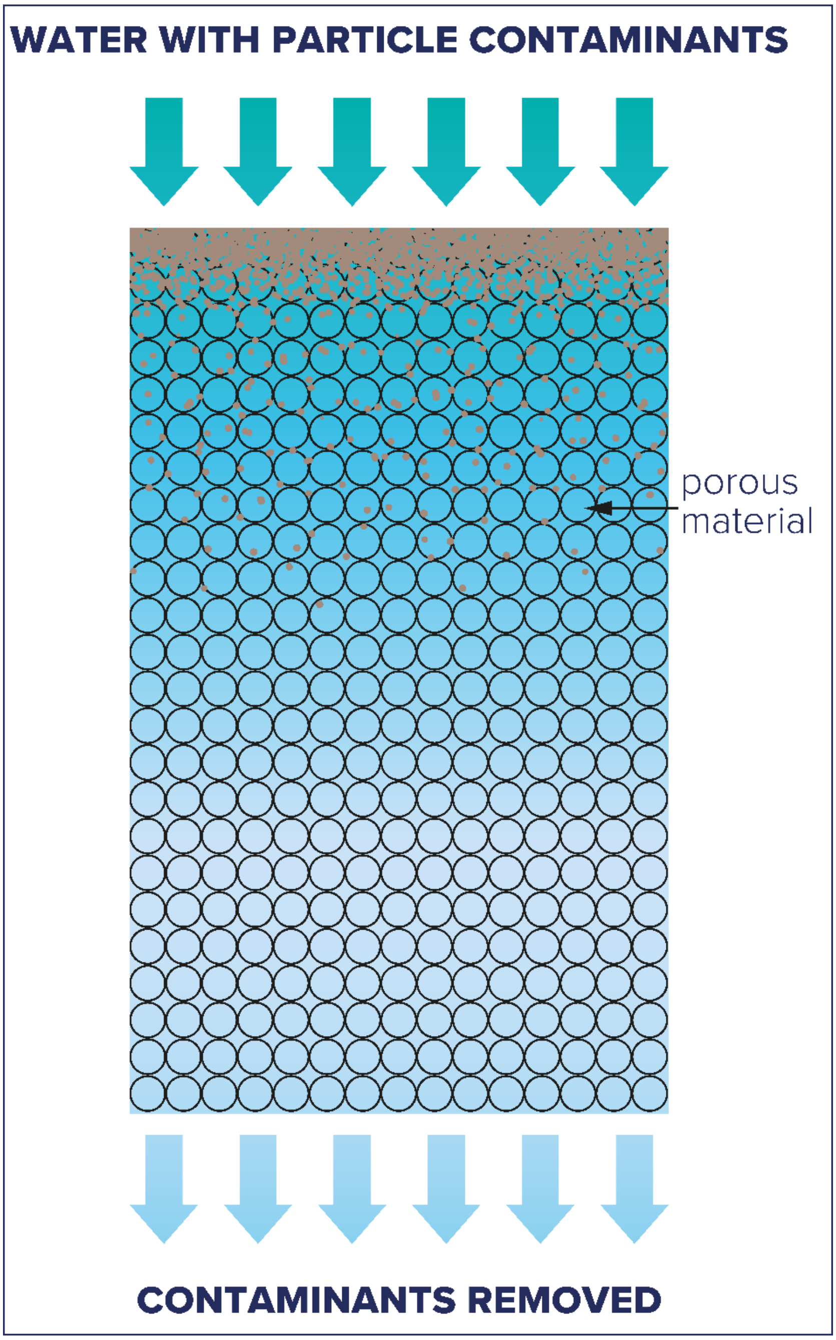

Figure 40 - Particle filtration process. When activated carbon is the porous media, contaminants are captured within the carbon. The filter must be removed and replaced as often as recommended by the manufacturer because bacteria may begin to grow within the filter, and/or contaminants will break through into your water supply (modified from Uhlman et al., 2012).

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Some filters have a thick filter medium mostly made from synthetic polymeric material fibers spun in different patterns to produce different size openings (Figure 41). Absolute particle size filters have a cut-off point above which no particle will pass through.

Figure 41 - Example particle filters (photo courtesy of US Filter, Plymouth Products Division and Water Conditioning & Purifications).

When possible, filters should be located indoors to avoid extreme temperature changes and cleaned or replaced regularly to prevent the formation of unwanted biofilms that can quickly clog fiber filters.

Micro filters are typically rated using an absolute size cut-off, usually 1 micron or less (Filter Application Guide, Figure 37). These are used to filter out pathogens like *Giardia* and *Cryptosporidium* bacteria, some types of viruses, as well as fine soil and plant matter. These filters are not recommended for outdoor use and require frequent back flushing to prevent membrane fouling. They should be used in sequence after particle filtration to prevent clogging. Back flushing requires pushing water through the filter in the direction opposite to that used to filter your water and letting the outflow go to waste; it does not mean turning the filter upside down and reinstalling, as that will release contaminants into your drinking water.

7.1.2 Activated Carbon

The popular activated-carbon method of home water treatment is a form of ultrafiltration. Activated carbon filters lower the levels of dissolved organic contaminants in water, but the mechanism of removal is a combination of physical and chemical processes. Activated charcoal filters contain cylinders of finely ground and compacted,

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chemically treated, coconut shell (or other hardwood) charcoal; an example is shown in Figure 42.

Figure 42 - Activated carbon point-of-use treatment system installed on a faucet; the carbon media is shown in the photo insert.

Carbon filters are commonly used to reduce the levels of residual chlorine taste in municipal water systems but are also efficient in reducing odors, pesticides, solvents, and emerging contaminants from well water. Some activated carbon filters may also reduce the levels of radon gas and some metals like lead from water. Carbon filters will not remove or lower the levels of salts like sodium or calcium, nitrates, or chlorides from water, and will only remove a small percentage of arsenic. Activated carbon filters will not soften or disinfect water.

Particle-free water should be passed through carbon filters to avoid reduced efficiency and clogging, thus particle filtration may be necessary prior to water entering the carbon filter. Point-of-use filters may be used in faucet attachments or in under-the-sink filter adaptors with a separate faucet. When treating potable water, these filters may lower already very low contaminant levels or dampen a temporary surge of some contaminants. If the water has levels of contaminants consistently above drinking water standards, these filters must be professionally sized and installed, and the water needs to be tested regularly.

7.1.3 Reverse Osmosis

Although best known for their use in industrial scale desalination, reverse osmosis systems are commonly chosen to reduce water salinity levels (TDS), as well as arsenic, nitrate, and other contaminants in well water. Reverse osmosis can also reduce the levels of many types of organic contaminants. The core of the system consists of a semi-porous

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membrane that filters out many types of soluble constituents, depending on its manufacturing specifications. Figure 43 shows a cut-out drawing of a reverse osmosis treatment system.

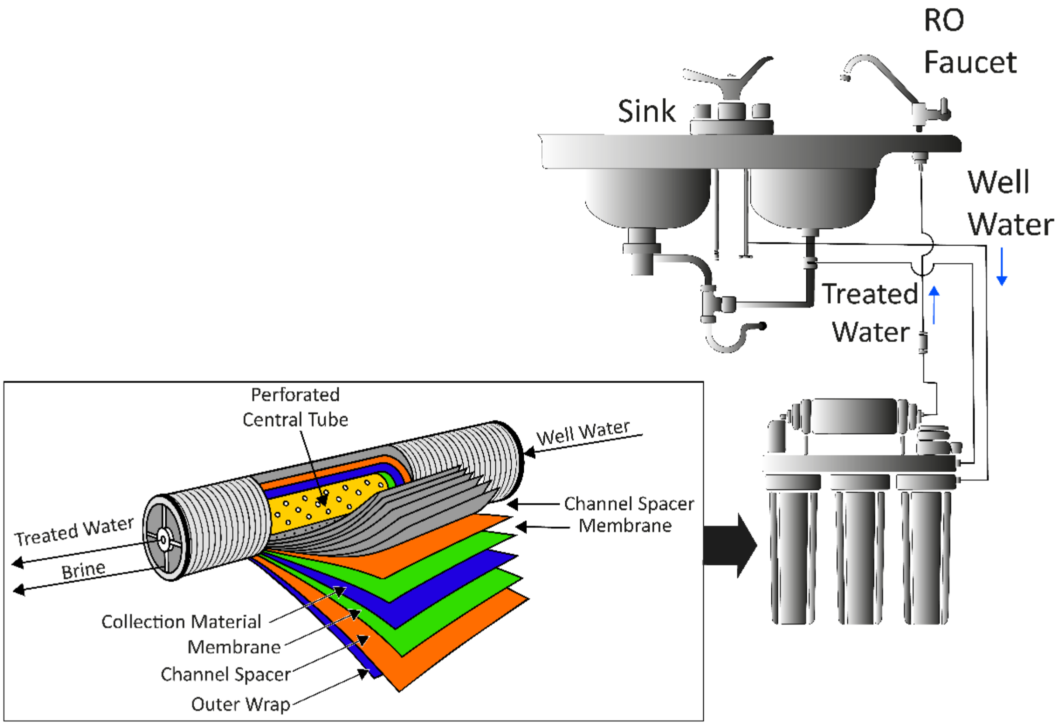

Figure 43 - A home reverse osmosis system, installed under a sink (modified from Uhlman et al., 2012). When the reverse osmosis (RO) faucet is open, well water that would normally flow to the double sink faucet is directed to the RO unit under the sink and then to the RO faucet so the user can choose to draw treated water if needed for the intended use.

The reverse osmosis process is a complex combination of sieving (filtering by size exclusion) and chemical reactions that occur at the surface of the membrane. Membranes are rated according to their ability to exclude or retain certain types of ions; thus, the filtering efficiencies vary with constituent and membrane type. Some pollutants may be prevented from passing 50 percent of the time while others more than 95 percent of the time. Because the filtering efficiencies of these membranes can also be affected by the overall water quality, testing should be done after the reverse osmosis treatment to establish system efficiency. This is particularly important when using reverse osmosis systems to treat constituents that are consistently above drinking water standards in well water. Although reverse osmosis systems can filter particles, bacteria, and viruses, they are not recommended for particle filtration or water disinfection.

As with all filter media, microbial biofilms can develop, which can plug and shorten the life of these membranes, especially when not used regularly. Well owners that do not, or cannot, disinfect their household water should routinely test their reverse osmosis systems and change the membrane cartridges at recommended intervals, or more frequently, depending on use.

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Installing a reverse osmosis system will increase the household water use because they require more frequent flushing to control membrane fouling. Therefore, reverse osmosis systems produce large volumes of concentrated wastewater. For example, one gallon of potable water produces on the order of 3 to 8 gallons of concentrated brine wastewater, depending on the reverse osmosis system and initial salinity and hardness of the well water. To prevent an increase in the wastewater load of the septic system, well owners can divert the backflow concentrate of their reverse osmosis unit to safely irrigate salt-tolerant native plants and trees. If the salty reverse osmosis wastewater is allowed into your septic leach field, the soils may be damaged, possibly causing the eventual failure of your system.

7.1.4 Water Softeners

Water softeners use cation exchange resins (beads) to replace calcium and magnesium (hardness minerals) as well as iron, manganese, radium, and other cations (i.e., positively charged ions) in the water with sodium or potassium ions. They do not remove most other contaminants found in water. The units typically consist of two tanks, one for the resin and the other for the effluent brine solution (Figure 44). Modern water softeners are automated with timed cycles that regenerate the resin with sodium chloride or potassium chloride based on water hardness and household water consumption. This process is usually done at night and can be water intensive, typically using more than 50 gallons per cycle.

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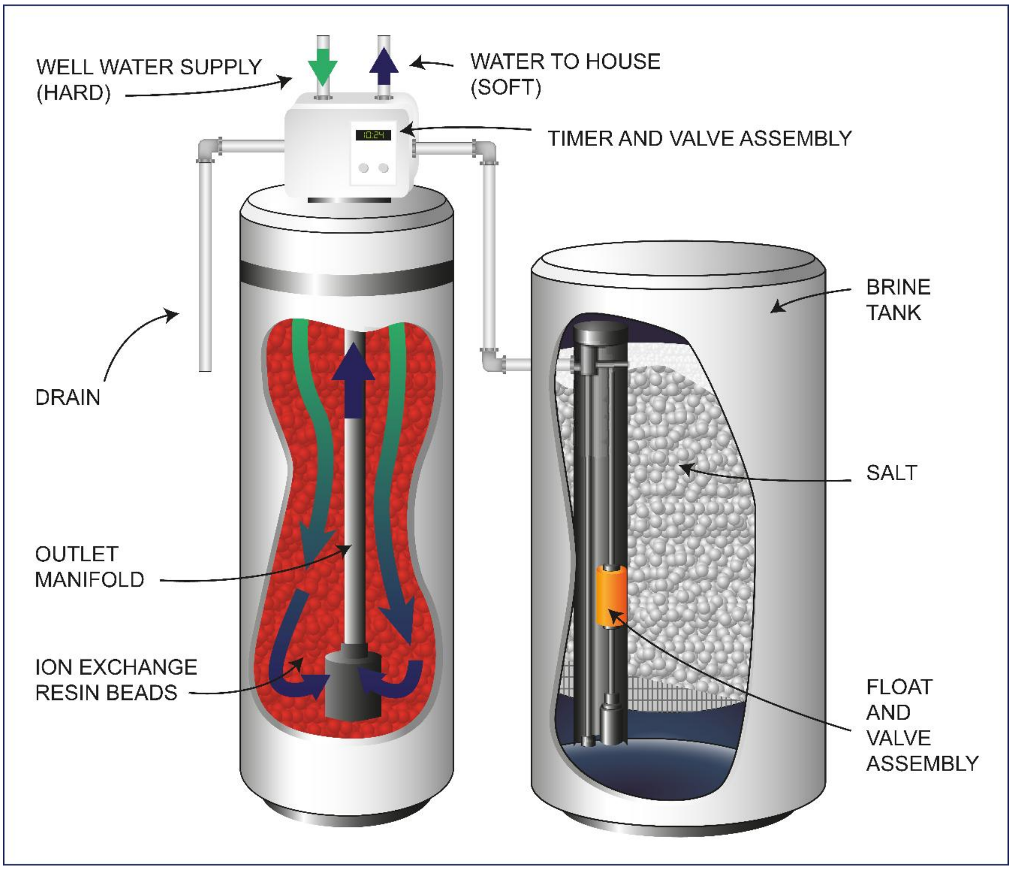

Figure 44 - A water softener. (modified from Uhlman et al., 2012).

Installing a water softener will increase household water use and the wastewater load to the septic system. Do not use water softened with sodium on household plants, vegetable garden plants, or landscaping because the sodium will build up in the soil inhibiting healthy growth and ultimately killing the plants.

Saline soft water may degrade the performance of septic fields and increase the chance of groundwater contamination. The wastewater (effluent from the brine tank) will contain concentrated salts. For that reason, use of sodium (Na) based systems is not recommended as this salt will damage your septic system. Potassium-based (chemical symbol K) systems are strongly recommended as they do less harm to the environment. Many communities prohibit the use of sodium-based water softeners because they degrade the quality of reclaimed wastewater and add to the amount of sodium salts entering the environment.

7.1.5 Distillation

Steam distillation effectively removes inorganic contaminants including suspended matter, salts, metals, and arsenic from water. It also removes most non-volatile organic contaminants. Volatile constituents, such as solvents, may not be removed unless the unit has a venting system or an activated carbon post filter, as shown in Figure 45. Distilled water is corrosive and has a flat to sweet taste. Distilled water should not be used on plants because it lacks minerals and nutrients vital to plant health, so it will inhibit growth and ultimately cause the plants to die.

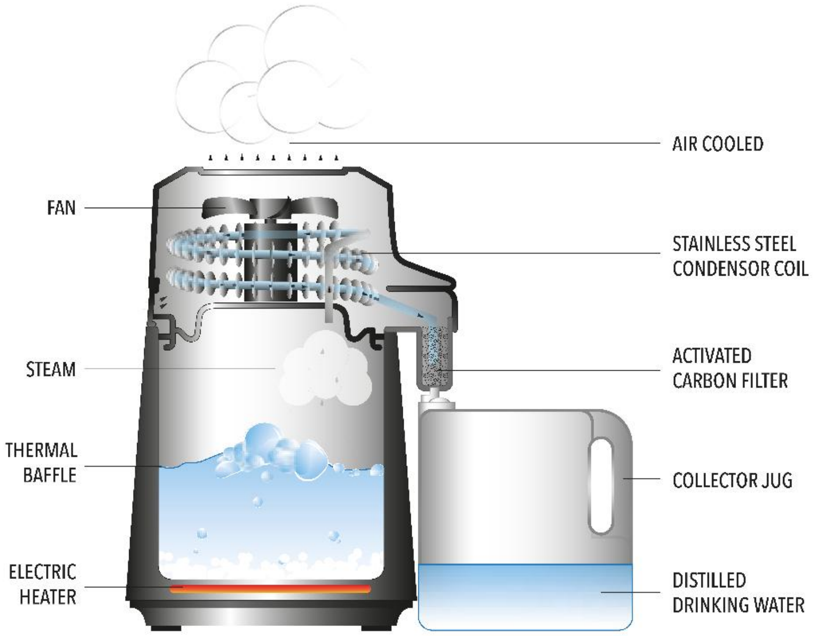

Figure 45 - Water distillation with a venting system and an activated carbon post filter.

Steam distillation also kills pathogens, effectively disinfecting the water. The steam distillation process is energy intensive and tabletop consumer units can use as much electricity as a toaster oven that is left on 24/7. The daily energy consumption increases with water salinity and gallons of water produced. Consumers that plan extended or exclusive use of distilled water in their diets should consult with their physician as drinking distilled water can alter blood chemistry.

7.2 Chemical Filters

7.2.1 Alkaline Filters and Aeration

Well water that is too acidic or contains abnormal levels of iron, manganese, and sulfides can be treated with an alkaline filter to raise the water pH. After the pH is adjusted, the water is passed through a manganese (green sand medium) filter to precipitate iron and manganese and to convert sulfides to sulfate. Well water that is also low in oxygen needs aeration to facilitate the oxidation and precipitation of iron and manganese. Aeration consists of bubbling air into the bottom of the water storage tank. Strong chemicals (oxidants such as hypochlorite) can be used to complete the oxidation process.

Aeration also can be used to remove dissolved hydrogen sulfide gas—which has a rotten-egg odor—from well water. Professional installation of aeration equipment is recommended. Another source of hydrogen sulfide gas is a water heater with an electric anode made of magnesium. The magnesium reacts with the sulfate in the water, producing the gas. If you detect the rotten egg odor from hot- but not cold-water faucets, the source is likely the water heater. To reduce gas production, a licensed plumber can replace the magnesium anode with a zinc anode, but the change may void the water heater warranty.

Well water that has high levels of iron, manganese, and/or sulfides should be tested to determine the filter types and sizes required to treat the desired volume of household water. Balancing the required water pH changes and oxygen demand for the removal of iron and manganese from water can be difficult and usually requires professional assistance.

7.2.2 Iron Based Filters for Arsenic Removal

For lowering arsenic levels in well water, iron filters may offer a simpler alternative to the more complex reverse osmosis systems. Because some iron minerals readily adsorb arsenic from water, these filters are usually composed of tightly packed iron, or iron-coated particles (beads), as shown in Figure 46. These filters are installed in-line and do not use electricity or extra water. Iron filters do not lower the levels of salts (TDS) or soften water. However, besides arsenic, they may also trap fluoride and selenium.

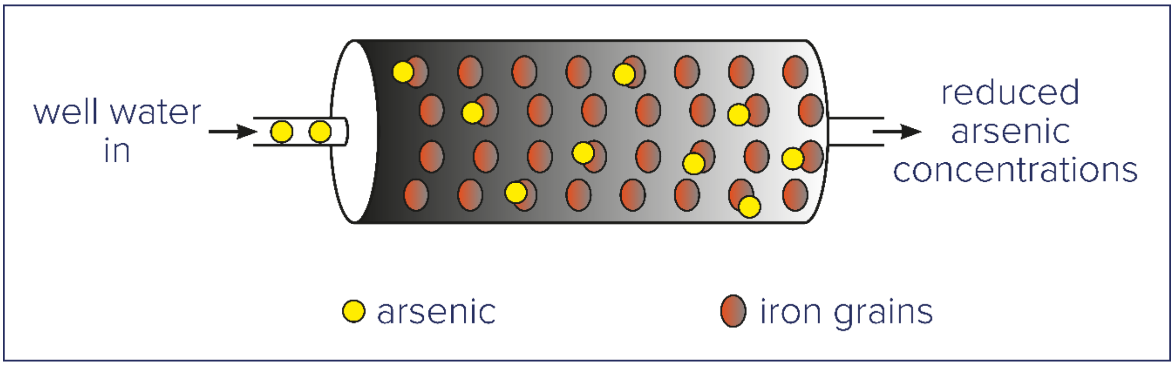

Figure 46 - Schematic of an iron filter system with arsenic adsorping (chemically sticking) to iron grains to reduce arsenic concentrations (modified from Uhlman et al., 2012).

The presence of other common ions such as silica, bicarbonate, and chloride may affect the performance of the filter, reducing its capacity to absorb arsenic significantly. Consumer-sized iron filters are not recommended to treat water with arsenic concentrations above 100 ppb. Presently, it is best to use whole-house, professionally sized, professionally installed (at the point of water entry to the house), and tested water-treatment systems.

7.3 Disinfection Methods

7.3.1 Chlorination

Public water utilities commonly use chlorine-based chemicals to disinfect potable water. These chemicals destroy or inactivate most waterborne pathogens, with some exceptions—some viruses and parasites. The most common chemicals used are chlorine and chlorine dioxide gases, which are hazardous chemicals and too dangerous for home use. However, liquids and solids that contain sodium or calcium hypochlorite can be used for household disinfection. Ultraviolet (UV) light (Section 7.3.2) can also be used to disinfect well water instead of chlorine.

Water chlorination systems for home use are typically automatic with a flow-dependent automatic shut-off. These systems should be professionally sized and installed because they usually require a holding tank containing hazardous liquid chlorine, as shown schematically on Figure 47. As with other forms of chemical treatment, water should be sediment-free before chlorine disinfection because when chlorine is in contact with organic matter present in the water, it often produces toxic disinfection by-products that can be harmful to your health. Chlorine-treated water should be tested and, if needed, filtered through an activated carbon system to reduce toxicity.

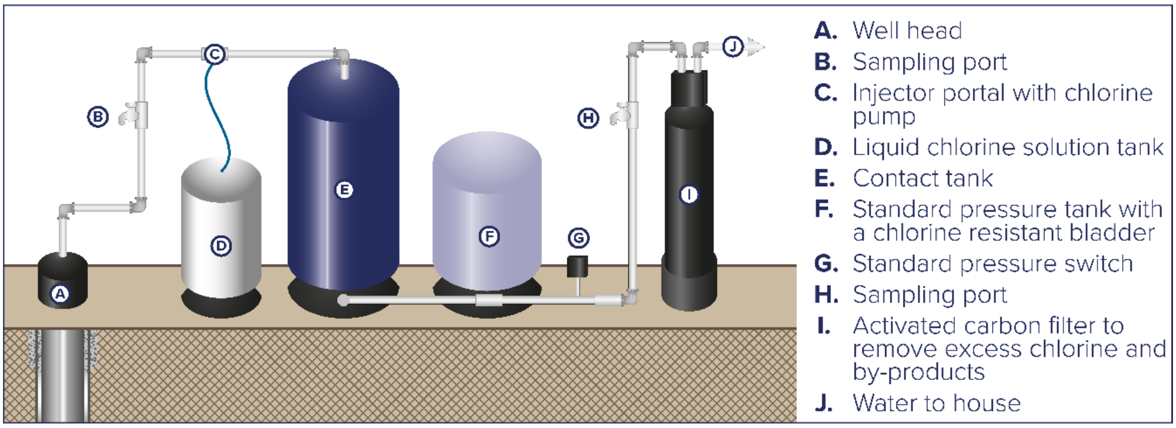

Figure 47 - Chlorine treatment system, which requires professional sizing and installation if considered for home use (modified from Uhlman et al., 2012).

7.3.2 Ultraviolet Radiation

Ultraviolet (UV) light may be used to disinfect particle-free, clear water using flow-through glass tubes with an enclosed UV light source. UV light is damaging to living organisms and viruses that contain RNA and DNA material, stopping their ability to reproduce or infect other cells. Waterborne organisms like bacteria, viruses, and even some parasites may be quickly inactivated when exposed to a concentrated source of UV light.

UV light disinfection systems are simple and relatively maintenance-free (except for replacing the UV light bulb according to the manufacturer's instructions), as shown in Figure 48. The system efficiency depends on the design and UV light-source type and power, the water flow rate, and the amounts and types of pathogens and other microorganisms present in the water source. If the well water is contaminated, pre and post water testing for waterborne pathogens should be done to determine the disinfecting power of the UV light system.

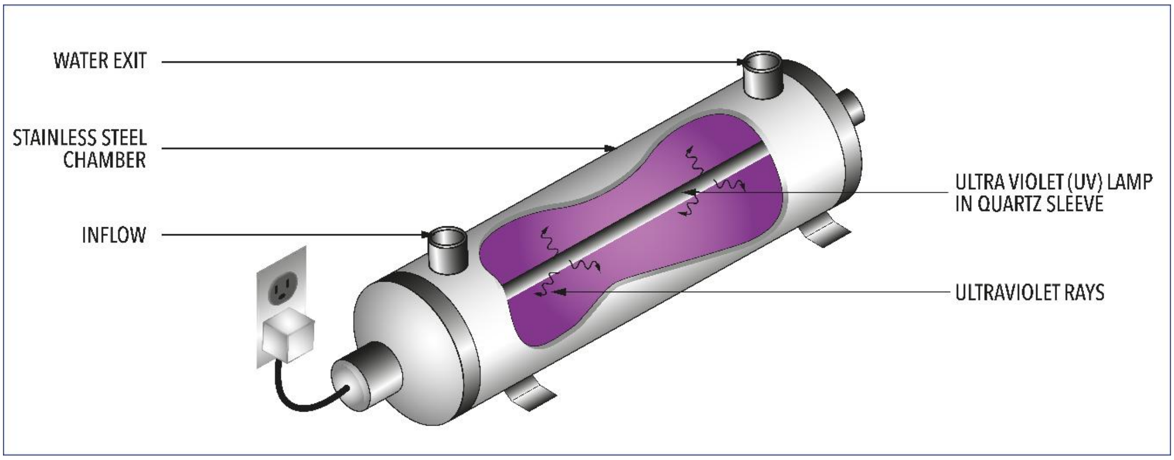

Figure 48 - Ultraviolet light disinfection systems for domestic well use are simple and relatively maintenance free; however, the water must be clear of cloudiness and sediment before entering the system (modified from Uhlman et al., 2012).

7.3.3 Other Disinfection Methods

In emergency situations, water may be boiled vigorously for at least two minutes to kill all organisms. Household chemicals, such as bleach or iodine, may be used to disinfect but should not be relied on for continuous treatment. For example, disinfection can be achieved by adding six drops of household bleach per gallon of clear water and allowing the solution to stand for 30 minutes. If the water is colored or turbid, or if after 30 minutes the water does *not* have a faint smell of bleach after treatment, double the amount of bleach.

7.4 Alternative Sources of Drinking Water

Well owners can use bottled water for drinking when their well water is heavily contaminated, treatment options are too expensive or unavailable, and there are no other available water sources. There is no reason to think that bottled water is safer than municipal tap water (from public water utilities); in fact, in most countries, municipal water is regulated to high-quality standards, while typically bottled water is not required to meet the same rigorous standards. The major advantage of bottled water is its portability and that it has no residual disinfection chemicals because it is usually disinfected using UV radiation and bottled in sterile containers. Bottled water should be kept in a cool, dark place and consumed quickly. It should not be stored for months, because plastic bottles may degrade over time and contaminate the water with plastic residues.

Alternatives to bottled water could be sharing water from a neighbor's well if it is known to be uncontaminated, installing a storage tank and having water delivered by a bulk-water delivery company, and harvesting rain, although in most locales the volume and frequency of precipitation cannot provide a reliable supply.

8 Protecting Your Well Water Quality

Well water can be contaminated by anthropogenic, rather than natural, sources as shown in Figure 49. The figure depicts subsurface transport of common contaminants that can be found near a domestic well. Five common causes of contamination in domestic wells:

- well installation/repair/maintainance practices;
- leaky wellheads, where ponded surface water seeps into the well;
- septic system leach fields or septic failure;
- other land use activities near the well; and/or
- events such as floods or fires.

This section discusses practices to protect your well-water quality from these contaminant sources, and revisits shock chlorination as a method to disinfect a well. Lastly, it presents proper well abandonment methods to prevent an unused well from becoming a conduit for aquifer contamination. Section 6 of the related book Domestic Wells – Introduction and Overview↗ by John Drage (2022) provides additional discussion of domestic well vulnerability to contamination.

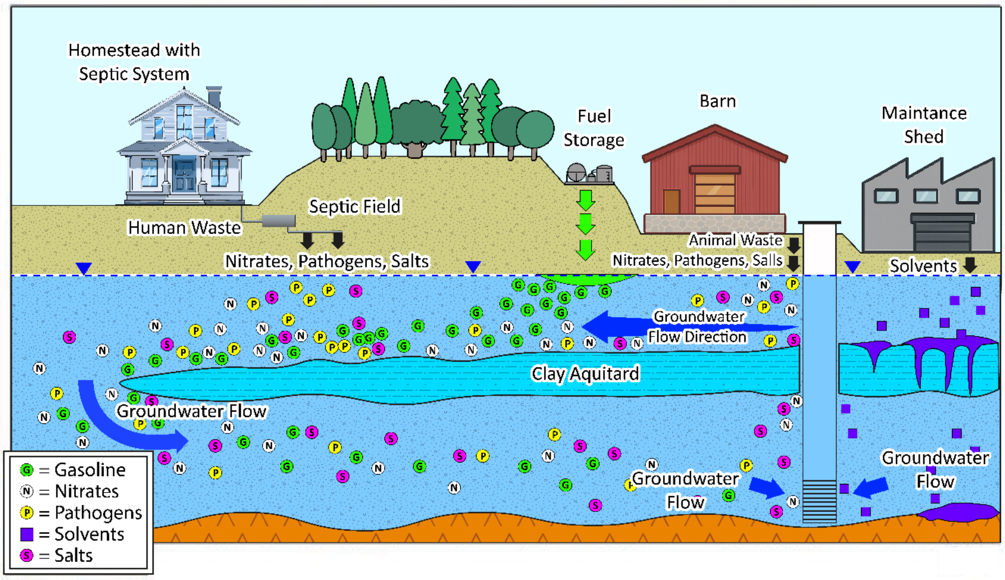

Figure 49 - The sources of drinking water contamination that often exist near domestic wellheads, including septic leach fields and land use activities.

8.1 Well Installation and Maintenance

Although licensed well drillers and pump installers are trained to prevent contaminants from entering a well, bacteria can still enter during well construction or routine maintenance. Follow these steps to prevent or reduce bacteria in your well water.

- Check your plumbing, water storage, and treatment systems on a regular basis and look for algae, slime, or discolored filtering media. If bioslime is present, have the

system components scrubbed and rinsed with chlorine bleach, and the filter media replaced.
- Test the water for bacteria after any well maintenance. Coliform bacteria can be introduced when the pump or drop pipe is laid on the ground when it is pulled out of the well during maintenance. Some types of harmful coliforms and organisms, such as amoebae, can be retained or grow in bioslime that develops naturally inside the well.
- If excessive slime develops that can plug up well screens and pump intakes, have the well's interior physically scrubbed and then shock chlorinated. Shock chlorination, well cleaning, and well and pump maintenance should be done by a licensed professional.
- If you notice an oily sheen or fuel odor, have the water tested for total petroleum hydrocarbons (TPH) and volatile organic compounds. Pump maintenance may introduce oils and grease into the well that can foul the water or provide a source of nutrition for naturally occurring bacteria. Purging the well immediately after maintenance is recommended to reduce the potential for this to occur.
- If you notice ponding of water or flooding near the wellhead, have the well water tested for bacteria.
- Make sure that all faucets with hose connections are equipped with backflow prevention devices, such as check valves. Without these devices, for example, a hose left in a kiddie pool may allow drainage back into the well if left unattended.

8.2 Wellhead Protection

Because each well provides a direct route to the aquifer, you will need to take special precautions to protect the wellhead (Figure 50 and Figure 51). Once groundwater or your well is contaminated, it is very difficult to restore. Most groundwater remediation or water treatment options are costly. The well-protective (surface) casing should be at least 1 ft (.35 m) above the ground and be surrounded by a 4-in (10.2 cm) thick concrete pad for at least 2 ft (0.61 m) in all horizontal directions. Older wells may not have been installed with a concrete pad. Updating your wellhead with this added protection is recommended. This configuration protects the well from flooding or ponded water and reduces the potential for contaminants to seep down into the aquifer around the well casing. If you suspect any well casing or pump failure, have a licensed well driller or pump installer inspect the system (Exercise 7↴). Only a licensed well driller can repair well casing. A pump installer is licensed as a contractor and can only install and remove a pump. Older wells, especially those made of black iron or steel, can corrode and break, allowing contaminants to enter the well.

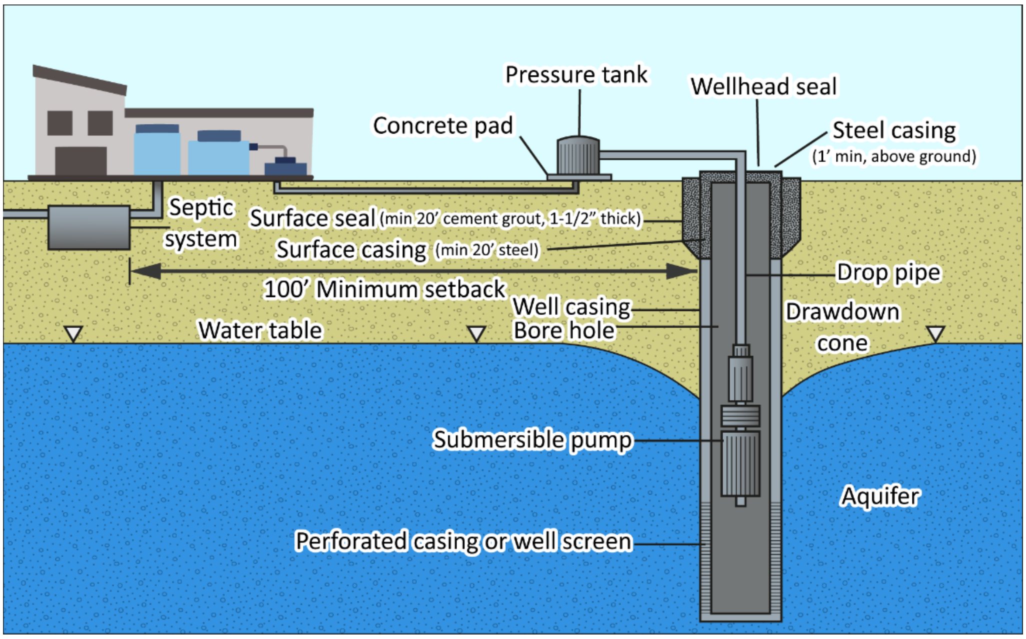

Figure 50 - An example of minimum well construction standards. Such standards are administered by your local jurisdiction and should protect the aquifer and well from surface water ponding around the wellhead (modified from Uhlman & Artiola, 2009). 1 foot (1') ~ 0.3 m. 1 inch (") ~ 2.54 cm.

Figure 51 - Wellhead with pad in a well house. If this well needs to be serviced, the roof of the well house will need to be removed to allow space for an overhead crane or winch to remove pipes and the pump from the well. Also, the two bottles of chemicals should *not* be stored in the well house, and the well owner should not self-chlorinate their well (photo credit: G. Schindel).

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Some types of chemicals such as fuels and solvents pose major threats to groundwater quality. Some can cause serious illness or death if consumed. Liquids that do not readily or fully dissolve in water are called non-aqueous phase liquids (NAPLs). NAPLs may be lighter than water or dense and heavier than water.

- Light NAPLs (LNAPLs) will float on the water table like oil floats over vinegar in some salad dressings. Examples of LNAPLs are petroleum-based fuels such as gasoline, motor oil, diesel, and home heating fuels. These fuels will pool on the water table and release toxic chemicals such as benzene into the groundwater, as shown in Figure 49.
- Dense NAPLs (DNAPLs) are heavier than water and sink, displacing groundwater and leaving a trail of small liquid blobs trapped in the pore spaces of the aquifer that dissolve slowly and can contaminate large volumes of groundwater. Typical DNAPLs are degreasers and solvents, such as those used to clean an oil stain on a driveway. They are extremely difficult to remediate and can permanently contaminate the aquifer. Several cancers and childhood leukemia have been linked to parts-per-billion concentrations of chemical degreasers and solvents in groundwater.

Follow these steps to protect your well water from chemical contamination:

- Do not store or use chemicals near the wellhead.
- Do not mix pesticides or store gasoline within 150 ft (45.7 m) of a well.
- If your well is in a storage shed or well house, do not store potential contaminants such as fuels, pesticides, or fertilizers in the structure.

Following these additional guidelines will help prevent other types of contamination of your well water.

- Inspect the wellhead on a regular basis and address any breakage or soil disturbance by burrowing animals or insects. The well owner can repair and maintain the wellhead pad; casing repairs require a licensed well driller.
- Locate pet and livestock enclosures at least 150 ft (45.7 m) away and downslope of the wellhead. Pet waste from dog runs and yards can contaminate groundwater.
- Build livestock corrals at least 150 ft (45.7 m) away and downslope of a wellhead, and direct stormwater runoff away from the wellhead. Runoff from livestock pens and pastures can contaminate groundwater with bacteria, nitrates, and veterinary drugs.
- Line and cover compost stacks to prevent leachate waste from seeping into the ground or running off and entering the soil.

8.3 Household Wastewater Management

Septic systems must be maintained regularly to reduce the chances of polluting the aquifer and causing health problems. To operate and maintain an onsite septic system effectively, first understand how it works and what affects it.

The most common onsite wastewater treatment system is a conventional septic system, as shown in Figure 52. The system treats wastewater in the tank and in the drain field.

- Wastewater flows through pipes from the house to the septic tank, which is a watertight container where solids are separated from liquid wastes.
- In the septic tank, microorganisms begin to consume the solids, nutrients, and organic matter in the wastewater.
- The wastewater, which typically contains salts, soluble organic matter, nitrate, and some trace contaminants, then moves through perforated pipes to a bed of gravel or similar material.
- From the gravel bed, the wastewater moves into the soil, where soil microorganisms further consume organic matter, contaminants, and nitrates.
- The water evaporates, is used by plants, and/or percholates down to the aquifer.

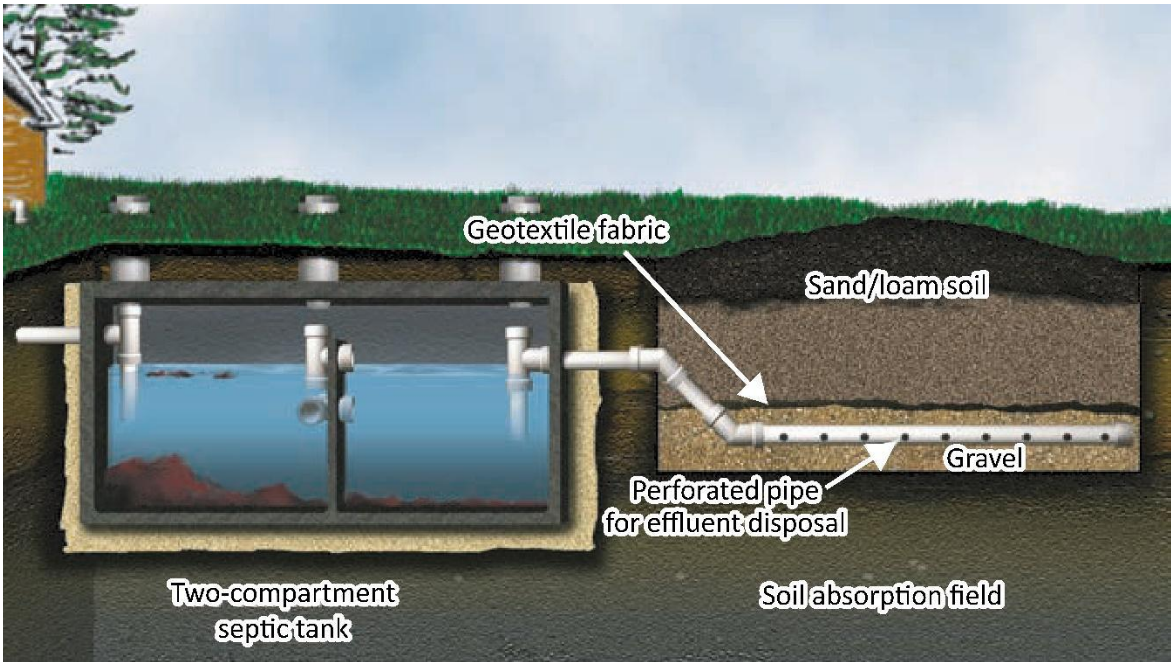

Figure 52 - A septic system and soil absorption leach field system.

All systems need routine maintenance because the system will malfunction if not adequately maintained. Different types of onsite wastewater treatment systems require different maintenance practices. Adhering to the following guidelines will keep your system operating properly and avoid contaminating your drinking water.

- Locate the septic tank and drain or leach field at least 100 ft (30.5 m) from your well. It is always best if your well is located uphill from your and your neighbors' septic systems, if possible. If installing a new well, be aware of the location of your neighbors' septic system locations to protect your own water supply.
- Do not excessively use in-sink garbage disposals, which may overwhelm your system.

- Divert stormwater runoff coming from driveways and roofs away from the soil treatment area and wellhead. If the leach field is saturated the system has failed.
- Do not dump grease or medications down the drain or into a toilet. Do not use the toilet as a trash can. Prescription medications and non-biodegradable artificial sweeteners have been found in groundwater downgradient from a failing septic system.
- If you are undergoing chemotherapy, ask your doctor about appropriate waste disposal methods to avoid discharging toxic drugs into the environment.
- Do not use chemicals to clean the septic system. They can interfere with the biological action in the tank, add toxic chemicals to groundwater, and clog the drain field by flushing sludge and scum into the field. Some septic cleaners contain solvents and degreasers and are banned in several states.
- Have the septic tank pumped every two to three years.
- Do not cover the drain field with an impervious surface such as a driveway or parking area.
- Do not drive heavy equipment over the components of a wastewater treatment system.
- Because septic systems do not remove nitrogen compounds efficiently (a common component in human waste), have the well water tested for nitrate every year. One of the most common pollutants found in domestic drinking water wells is nitrate.
- Conserve water in the home to reduce the amount of water that the wastewater treatment system must process. Excessive amounts of water can overload the system and cause it to fail.

Other problems to watch for include the following.

- Roots from trees and other vegetation may clog and damage the system.
- Some drinking water treatment systems, such as reverse osmosis and water softeners, discharge waste brine and can increase the septic field load significantly. This increased volume of water may saturate your system, leading to failure.
- Spent brine discharge from reverse osmosis and water softeners will increase the concentrations of salt in the soil, which could change the soil structure causing the system to fail. This brine may increase the amount of salt and untreated waste entering the aquifer.

8.4 Shock Chlorination of Water Wells

When a water system is contaminated with bacteria the well can be disinfected by shock chlorination (as discussed in Section 4.2.1 in the context of improving well yield). This process introduces very high concentrations of liquid chlorine directly into the well and plumbing system. Chlorine is highly toxic to bacteria and animals. Commercial bleach, commonly used to disinfect wells, can release harmful vapors and damage skin when full-strength exposure occurs or when mixed with acids.

To reduce your risk of exposure to hazardous chemicals and to protect your pump and system components, have a licensed water well driller or pump installer conduct the procedure. Corrosion of downhole plumbing and pumps can occur from excessive use of chlorine. To avoid expensive repair and replacement of equipment, the licensed contractor should take the responsibility of protecting your investment.

Implement shock chlorination when the water system will not be in use for at least 12 to 24 hours. In addition to the well, water treatment equipment—including water heaters, softeners, filters, and pressure tanks—may need disinfection. During and immediately after the disinfection process, the water from the system will be unsuitable for consumption. You will need to flush the water system until all traces of chlorine are removed and the well water has been tested. Do not allow the water to be used for drinking until test results confirm the water is safe. Do not drain a water system that has been shock chlorinated to your onsite wastewater system.

Multiple shock chlorination procedures may not be enough to resolve the problem. In those situations, a licensed well driller or pump installer will need to remove the pump and plumbing from the well and scrub the interior with brushes and chemicals made for this purpose.

When chlorine chemicals are introduced into a well, some of the chemical may enter the aquifer. When the geologic material of the aquifer is exposed to chlorine, other constituents, such as arsenic, if present in the geology, may dissolve and enter the water supply. Always test your water after shock chlorination to ensure safety (Exercise 8↴).

8.5 Plugging Abandoned Water Wells

An abandoned well that is no longer used must be properly plugged by a licensed well driller. If not adequately plugged, the landowner may be liable for groundwater contamination or injury that results from lack of proper abandonment. An abandoned well that is not adequately plugged is a direct channel from the ground surface to the aquifer below. Contaminants that enter the well move directly into the aquifer and may threaten human health and the environment. Inadequate plugging also puts other wells in the same aquifer at risk for contamination, particularly those close to the abandoned well.

Plugging and appropriate abandonment of a well is accomplished by filling or sealing the well to prevent the well, including the annular space outside the casing, from being a channel that allows the vertical movement of water and contaminants. Specific materials and depths of fill are required, based on the aquifer and the well depth. Only a licensed professional can abandon a well.

9 Exercises

Exercise 1

Do you have a copy of your well report? The report should include well depth, initial depth to water, testing of potential well yield and basic chemistry, and the geology of the aquifer. The well log includes the geology encountered and the as-built construction diagram, including screen and casing size, and the material used to construct the well.

Solution to Exercise 1↴

Return to where text linked to Exercise 1↥

Exercise 2

Do you have grit or sand in your toilet tank?

Solution to Exercise 2↴

Return to where text linked to Exercise 2↥

Exercise 3

Have you lost water pressure?

Solution to Exercise 3↴

Return to where text linked to Exercise 3↥

Exercise 4

Do you have the baseline water chemistry for your well and any additional, recent water chemistry reports?

Solution to Exercise 4↴

Return to where text linked to Exercise 4↥

Exercise 5

Does your water look cloudy or have an unpleasant odor?

Solution to Exercise 5↴

Return to where text linked to Exercise 5↥

Exercise 6

Has your home or well head been flooded?

Solution to Exercise 6↴

Return to where text linked to Exercise 6↥

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Exercise 7

Is your cold water unusually warm? Shallow unconfined groundwater maintains the average annual air temperature, so in the winter it should be comparably cool, and in the summer, it should be comparably warm, but high temperatures greater than these seasonal changes are cause for concern.

Solution to Exercise 7⤵

Return to where text linked to Exercise 7⤴

Exercise 8

Has your water analysis failed for bacteria contamination?

Solution to Exercise 8⤵

Return to where text linked to Exercise 8⤴

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10 Glossary

Acute	A rapid onset of an illness due to a one-time or short-time exposure to a chemical contaminant or waterborne pathogen; for example, gastrointestinal illness due to exposure to bacteria or water-borne toxin.
Alkalinity	The ability of water to neutralize acids and resist changes in pH, thus acting as a buffer maintaining a stable chemical environment. It represents the sum of all titratable bases, generally: carbonates, bicarbonates, and hydroxides. Alkalinity is usually reported as an equivalent amount of bicarbonate ($CaCO_3$) in mg/l or parts per million (ppm).
Alluvial and Alluvium	A general term that that refers to sediments deposited by streams in riverbeds, flood plains, and alluvial fans.
Anion/Cation Exchange	The replacement of one charged ion for another. Typical ion exchangers are resins (porous gel polymers), used in water treatment systems. Cation systems (water softeners) exchange sodium or potassium, for positively charged ions (cations) like calcium, magnesium, iron, manganese, and radium. Anion systems exchange chloride for negatively charged ions (anions) like nitrate, sulfate, and uranium. Section 7 discusses water softeners.
Annulus	The space between the well casing and/or screen and borehole. Only a few inches in width, this area is typically filled with sand, gravel, or concrete to keep the borehole open.
Aquitard	Term applied to a sedimentary deposit, such as clay, where groundwater is slowed, or retarded, because of the nature of the geology.
Artesian	Term applied to a confined aquifer with groundwater under sufficient hydrostatic pressure to rise above the confined aquifer in a well open to the aquifer. If the pressure in an artesian well is sufficient to bring the water to land surface, the well is termed a *flowing well*.
Caliche	A hardened natural cement of calcium carbonate and other minerals that binds other materials—such as gravel, sand, clay, and silt. Caliche is found around sand in arid soils.
Confined	An aquifer bounded above and below by impermeable sediments or rock, or by geologic material of distinctly lower permeability, such as clay, than that of the aquifer itself.

Disinfection By-Products (DBPs)	Result from reactions between organic matter and some ions, such as chlorine, in water treated by disinfection. Typically, gaseous chlorine (Cl_2) or liquid sodium hypochlorite (bleach, $NaOCl$) is added to, and reacts with, water to form strong oxidizing agents, which disinfect the water. The reaction forms potentially harmful compounds including trihalomethanes (THMs) or haloacetic acids (HAAs).
Drawdown Cone or Cone of Depression	The lowering of the water level in a well because of pumping. The water level is drawn-down, or depressed, typically in the approximate shape of an inverted cone.
Endocrine Disruptors	Naturally occurring or man-made substances that may mimic or interfere with the function of hormones in the body. Endocrine disruptors may turn on, shut off, or modify signals that hormones carry and thus affect the normal functions of tissues and organs. The detection of numerous pharmaceutical agents and chemicals with endocrine disrupting potential in surface and groundwaters has raised concern about drinking water as a significant route of exposure.
Fracking	The process of injecting water or other liquids and sand at high pressure into subsurface consolidated formations through boreholes to force open existing fissures and increase the flow of water, oil, or natural gas.
Hydrograph	A graph of water level (elevation) or stream flow at a particular location as a function of time.
Half-life	With radioactive materials, the time in which half of the element has decayed to the daughter product. For example, half of Carbon-14 decays to nitrogen gas in 5,730 years.
Microbial Indicators	Types of microbes, such as coliform bacteria, that are easy to test and that indicate the likely presence or absence of pathogens that are difficult to test individually, in water. Public agencies therefore use the presence of these more abundant and more easily detected microbial indicators to assess the presence of fecal and other pathogenic contamination.
Natural Organic Matter, NOM	Found in all surface, ground, and soil waters, NOM is the result of organic material dissolving in water, similarly to how tea leaves are extracted to make tea.

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Nitrate-N	Amount of nitrate in water expressed as the mass of the element nitrogen (N), excluding the mass of the three oxygens in nitrate, NO_3. The drinking water standard is 10 mg/L as $NO_3\text{–}N$, but the standard is 44 mg/L if expressed as the complete molecule NO_3. Most analytical laboratories measure nitrate in water as Nitrate-N.
Overdraft	In hydrology, an overdraft is the extraction of more groundwater than the aquifer can sustain, similar to a deficit in a bank account caused by withdrawing more money than the account holds.
pCi/L.	Picocuries per liter (pCi/L) is a unit for measuring radioactivity concentrations. The curie (Ci) unit is the activity of 1 gram of pure radium-226. A picocurie is one-trillionth of a curie. A curie is equivalent to 37 billion radioactive disintegrations per second. One picocurie equals 2.2 radioactive disintegrations per minute (dpm) in a liter of air.
Permeable	A measure of the ease with which liquids or gases pass through a porous material.
POE, POU	Point of entry and point of use. POE refers to the point where water from a treatment system enters into the home, such that all water in the home is treated. POU refers to a treatment system is installed at the point of use, such as under a sink to treat only water delivered to a faucet.
Porosity	Porosity is a measure of the total pore space in a material. This is measured as a volume or percent of space between the material particles. The porosity of an aquifer depends on the particle size of minerals, their distribution, and the amount of sorting that occurs within the aquifer structure.
Precipitate	A precipitate is a solid that emerges from a liquid solution. The emergence of the solid from solution is called precipitation, which often forms scale in plumbing fixtures.
Salinity (TDS)	The saltiness or dissolved salt content in water, reported as Total Dissolved Solids (TDS), measured in mg/L. The salt in the ocean is mostly made up of the elements sodium (Na) and chlorine (Cl), accounting for ~85.7 percent of dissolved salt, and is measured at around 34,000 to 35,000 mg/L of TDS. Groundwater is considered 'fresh' when the TDS is below 3,000 mg/L, although a TDS <500 mg/L is recommended for drinking water. Groundwater is considered brackish between 3,000 to 10,000 mg/L; saline between 10,000 to 35,000 mg/L; and brine above 35,000 mg/L TDS.

Soil	The dynamic natural upper part of the earth's surface, composed of unconsolidated minerals, organic residues, air, and water that together support microbe, plant, and animal terrestrial life.
Solubility	The property governing how a solid, liquid, or gaseous chemical substance interacts and mixes with a solvent (another solid, liquid, or gas). By far the most common solvent is water, also called the *universal solvent*, as it reacts with and dissolves most inorganic and organic substances.
Suspended Matter or Suspended Solids	Refers to small solid particles that remain in suspension in water. In groundwater, most suspended solids are made up of inorganic materials such as clays, though bacteria and algae can also contribute to the total solids concentration. Suspended solids reduce water clarity by creating an opaque, hazy or muddy appearance. Turbidity is often used as an indicator of water quality and is based on the amount of light scattered by particles in the water column. The more suspended particles that are present, the more light will be scattered.
Turbidity	A measure of suspended solids in water in Nephelometric Turbidity Units (NTU).
Vadose	The vadose zone, also termed the unsaturated zone, is the part of the aquifer between the land surface and the top of the water table. As precipitation (rain and melting snow) filters through to recharge the aquifer, some moisture and many contaminants are retained within the vadose zone.
Water Table	The top surface of the saturation zone of the aquifer.
Water Well Logging	The practice of making a detailed record (a well log) of the geologic formations penetrated by a borehole. Also known as borehole logging. Many logs will include the as-built diagram of the well depth, screen length, and pump placement.
Yield	The rate a well is capable of extracting when pumped, typically measured in GPM.

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12 Boxes

Box 1 - USEPA Drinking Water Standards

LEGEND

Light Green – D = Disinfectant

Deep Purple – IOC = Inorganic Chemical

Dark green – OC = Organic Chemical

Deep Blue – DBP = Disinfection Byproduct

Orange – M = Microorganism

Red – R = Radionuclide

Notes, including definitions of items in the table, rules, and guidance for well owners are provided at the end of the table.

	CONTAMINANT	MCL OR TT[1]	POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE	COMMON SOURCES OF CONTAMINANT IN DRINKING WATER	PUBLIC HEALTH GOAL
OC	Acrylamide	TT[7]	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment	Zero
OC	Alachlor	0.002	Eye, liver, kidney, or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops	Zero
R	Alpha particles	15 picocuries per Liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit alpha radiation	Zero
IOC	Antimony	0.006	Increase in blood cholesterol; decrease in blood sugar	Erosion of natural deposits. Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder	0.006
IOC	Arsenic	0.010 (as of 1/23/06)	Skin damage or problems with circulatory systems; increased risk of cancer	Erosion of natural deposits; runoff from orchards; runoff from glass & electronics production wastes	0
IOC	Asbestos (fibers>10 micro meters)	7 million fibers per Liter (MFL)	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits	7 MFL

CONTAMINANT		MCL OR TT[1]	POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE	COMMON SOURCES OF CONTAMINANT IN DRINKING WATER	PUBLIC HEALTH GOAL
OC	Atrazine	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops	0.003
IOC	Barium	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits	2
OC	Benzene	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gasoline storage tanks and landfills	Zero
OC	Benzo(a)pyrene (PAHs)	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines	Zero
IOC	Beryllium	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries	0.004
R	Beta particles and photon emitters	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation	Zero
DBP	Bromate	0.010	Increased risk of cancer	Byproduct of drinking water disinfection	Zero
IOC	Cadmium	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints	0.005
OC	Carbofuran	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa	0.04
OC	Carbon tetrachloride	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities	Zero

	CONTAMINANT	MCL OR TT[1]	POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE	COMMON SOURCES OF CONTAMINANT IN DRINKING WATER	PUBLIC HEALTH GOAL
D	Chloramines (as Cl_2)	MRDL[1]=4.0	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes	MRDLG[1]=4.0
OC	Chlordane	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide	Zero
D	Chlorine (as Cl_2)	MRDL[1]=4.0	Eye/nose irritation; stomach discomfort	Water additive used to control microbes	MRDLG[1]=4.0
D	Chlorine dioxide (as ClO_2)	MRDL[1]=0.8	Anemia; infants & young children: nervous system effects	Water additive used to control microbes	MRDLG[1]=0.8
DBP	Chlorite	1	Anemia; infants & young children: nervous system effects	Byproduct of drinking water disinfection	0.8
OC	Chlorobenzene	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories	0.1
IOC	Chromium (total)	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits	0.1
IOC	Copper	TT[6]; Action Level=1.3	Short term exposure: Gastrointestinal distress. Long term exposure: Liver or kidney damage. People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits	1.3
M	*Cryptosporidium*	TT[2]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	Zero

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	CONTAMINANT	MCL OR TT[1]	POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE	COMMON SOURCES OF CONTAMINANT IN DRINKING WATER	PUBLIC HEALTH GOAL
IOC	Cyanide (as free cyanide)	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories	0.2
OC	2,4-D	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops	0.07
OC	Dalapon	0.2	Minor kidney changes	Runoff from herbicide used on rights of way	0.2
OC	1,2-Dibromo-3-chloropropane (DBCP)	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards	Zero
OC	o-Dichlorobenzene	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories	0.6
OC	p-Dichlorobenzene	0.075	Anemia; liver, kidney, or spleen damage; changes in blood	Discharge from industrial chemical factories	0.075
OC	1,2-Dichloroethane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	Zero
OC	1,1-Dichloroethylene	0.007	Liver problems	Discharge from industrial chemical factories	0.007
OC	cis-1,2-Dichloroethylene	0.07	Liver problems	Discharge from industrial chemical factories	0.07
OC	trans-1,2-Dichloroethylene	0.1	Liver problems	Discharge from industrial chemical factories	0.1
OC	Dichloromethane	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories	Zero
OC	1,2-Dichloropropane	0.005	Increased risk of cancer	Discharge from industrial chemical factories	Zero
OC	Di(2-ethylhexyl) adipate	0.4	Weight loss, liver problems, or possible reproductive difficulties	Discharge from chemical factories	0.4
OC	Di(2-ethylhexyl) phthalate	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories	Zero

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CONTAMINANT		**MCL OR TT**[1]	**POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE**	**COMMON SOURCES OF CONTAMINANT IN DRINKING WATER**	**PUBLIC HEALTH GOAL**
OC	Dinoseb	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables	0.007
OC	Dioxin (2,3,7,8-TCDD)	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories	Zero
OC	Diquat	0.02	Cataracts	Runoff from herbicide use	0.02
OC	Endothall	0.1	Stomach and intestinal problems	Runoff from herbicide use	0.1
OC	Endrin	0.002	Liver problems	Residue of banned insecticide	0.002
OC	Epichlorohydrin	TT[7]	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals	Zero
OC	Ethylbenzene	0.7	Liver or kidney problems	Discharge from petroleum refineries	0.7
OC	Ethylene dibromide	0.00005	Problems with liver, stomach, reproductive systems, or kidneys; increased risk of cancer	Discharge from petroleum refineries	Zero
IOC	Fluoride	4	Bone disease (pain and tenderness of the bones); children may get mottled teeth	Erosion of natural deposits; water additive to prevent tooth decay	4
M	*Giardia lamblia*	TT[2]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	Zero
OC	Glyphosate	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use	0.7
DBP	Haloacetic acids (HAAs)	0.060[5]	Increased risk of cancer	Byproduct of drinking water disinfection	n/a
OC	Heptachlor	0.0004	Liver or kidney problems; increased risk of cancer	Residue of banned termiticide	Zero

	CONTAMINANT	**MCL OR TT**[1]	**POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE**	**COMMON SOURCES OF CONTAMINANT IN DRINKING WATER**	**PUBLIC HEALTH GOAL**
OC	Heptachlor epoxide	0.0002	Liver or kidney problems; increased risk of cancer	Breakdown of heptachlor	Zero
M	Heterotrophic plate count (HPC)	TT[2]	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is	HPC measures a range of bacteria that are naturally present in the environment	n/a
OC	Hexachlorobenzene	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories	Zero
OC	Hexachlorocyclopentadiene	0.05	Kidney or stomach problems	Discharge from chemical factories	0.05
IOC	Lead	TT[6]; Action Level = 0.015	In infants and children: delays in physical or mental development; children could show slight deficits in attention span and learning abilities. In adults: kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits	Zero
M	*Legionella*	TT[2]	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems	Zero
OC	Lindane	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens	0.0002

	CONTAMINANT	**MCL OR TT**[1]	**POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE**	**COMMON SOURCES OF CONTAMINANT IN DRINKING WATER**	**PUBLIC HEALTH GOAL**
IOC	Mercury (inorganic)	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands	0.002
OC	Methoxychlor	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock	0.04
IOC	Nitrate (measured as Nitrogen)	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	10
IOC	Nitrite (measured as Nitrogen)	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits	1
OC	Oxamyl (Vydate)	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes	0.2
OC	Pentachlorophenol	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories	Zero
OC	Picloram	0.5	Liver problems	Herbicide runoff	0.5

CONTAMINANT		MCL OR TT[1]	POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE	COMMON SOURCES OF CONTAMINANT IN DRINKING WATER	PUBLIC HEALTH GOAL
OC	PFAS: PFOA PFOS PFNA PFHxS HFPO-DA Mixture of two or more PFNA, PFHxS, HFPO-DA, and PFBS	4 ppt 4 ppt 10 ppt 10 ppt 10 ppt 1 (Hazard Index)	Increased risk of cancer, liver disease, circulatory problems, reproductive and development effects	Fire-fighting foam, runoff/leaching from landfills and from chrome plating and electronics facilities	0 0 10 ppt 10 ppt 10 ppt 1 (Hazard Index)
OC	Polychlorinated biphenyls (PCBs)	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals	Zero
R	Radium 226 and Radium 228 (combined)	5 pCi/L	Increased risk of cancer	Erosion of natural deposits	Zero
IOC	Selenium	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines	0.05
OC	Simazine	0.004	Problems with blood	Herbicide runoff	0.004
OC	Styrene	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills	0.1
OC	Tetrachloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners	Zero
IOC	Thallium	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories	0.0005
OC	Toluene	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories	1

	CONTAMINANT	**MCL OR TT[1]**	**POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE**	**COMMON SOURCES OF CONTAMINANT IN DRINKING WATER**	**PUBLIC HEALTH GOAL**
M	Total Coliforms (including fecal coliform and *E. coli*)	5.0%[3,4]	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present	Coliforms are naturally present in the environment as well as feces; fecal coliforms and *E. coli* come from human and animal fecal waste	Zero
DBP	Total Trihalomethanes (TTHMs)	0.080[5] (after 12/31/03)	Liver, kidney, or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection	n/a
OC	Toxaphene	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle	Zero
OC	2,4,5-TP (Silvex)	0.05	Liver problems	Residue of banned herbicide	0.05
OC	1,2,4-Trichlorobenzene	0.07	Allergic dermatitis; changes in adrenal glands	Discharge from textile finishing factories	0.07
OC	1,1,1-Trichloroethane	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories	0.20
OC	1,1,2-Trichloroethane	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories	0.003
OC	Trichloroethylene	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories	Zero

CONTAMINANT		**MCL OR TT**[1]	**POTENTIAL HEALTH EFFECTS FROM EXCESSIVE EXPOSURE**	**COMMON SOURCES OF CONTAMINANT IN DRINKING WATER**	**PUBLIC HEALTH GOAL**
M	Turbidity	TT[2]	High turbidity levels are often associated with high levels of disease-causing micro-organisms such as viruses, parasites, and some bacteria, which can cause symptoms such as nausea, cramps, diarrhea, and headaches.	Soil runoff	n/a
R	Uranium	30 µg/L (as of 12/08/03)	Increased risk of cancer, kidney toxicity	Erosion of natural deposits	Zero
OC	Vinyl chloride	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories	Zero
M	Viruses (enteric)	TT[2]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste	Zero
OC	Xylenes (total)	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories	10

NOTES

1. Definitions:
    - Maximum Contaminant Level (MCL)—The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to Maximum Contaminanat Level Goals (MCLGs) as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. Units for MCLs in the table are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (ppm).
    - Maximum Residual Disinfectant Level (MRDL)—The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants
    - Maximum Residual Disinfectant Level Goal (MRDLG)—The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.
    - Treatment Technique (TT)—A required process intended to reduce the level of a contaminant in drinking water.
2. EPA's surface water treatment rules require systems using surface water or groundwater under the direct influence of surface water (GWUDI) to (a) disinfect their water, and (b) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled in the following manner:

- *Cryptosporidium*: Unfiltered systems are required to include Cryptosporidium in their existing watershed control provisions
- *Giardia lamblia*: 99.9% removal/inactivation
- Viruses: 99.99% removal/inactivation
- Legionella: No limit, but USEPA has found that if Giardia and viruses are removed/inactivated, Legionella will also be controlled.
- Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) exceed 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, most of which specify that turbidity can at no time exceed 5 NTUs.
- HPC: No more than 500 bacterial colonies per milliliter

3. No more than 5.0% of samples can test positive for total coliform (TC) in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be TC-positive per month.) Every sample that has TC must be analyzed for either fecal coliforms or *E. coli*. If there are two consecutive TC-positive samples and one is also positive for *E. coli* fecal coliforms, then the water system has an acute MCL violation.
4. Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.
5. Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:
   - Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L): chloroform (0.07 mg/L).
   - Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.02 mg/L); monochloroacetic acid (0.07 mgL). Bromoacetic acid and dibromoacetic acid are regulated with this group but have no MCLGs.
6. Lead and copper are regulated by a Treatment Technique that requires water system operators to control corrosiveness. If more than 10% of tap water samples exceed the action level, water systems must take additional steps.
7. Each public water system must certify, in writing, to the state (using third-party or manufacturers' certification) that when it uses acrylamide and/or epichlorohydrin to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:
   - Acrylamide=0.05% dosed at 1 mg/L (or equivalent);
   - Epichlorohydrin=0.01% dosed at 20 mg/L (or equivalent).

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Box 2 - Water Problems: Symptoms, Possible Causes, and Treatment Devices

Category	*Symptom*	*Cause*	*Treatment Devices*
VISUAL (water appear-ance)	Cloudiness of water with a yellow, brown, or black cast that clears after standing 24 hours	Turbidity	Flocculation and sedimentation or particle and microfiltration (POE)
	Transparent yellow-brown tint to water that does not clear after standing 24 hours	High levels of natural organic matter (NOM), usually in surface water	Activated carbon filtration or chlorination followed by activated carbon filtration. Water utilities use flocculation to remove NOM.
	Brown-orange stains or reddish slime or tint to water	Presence of dissolved iron and iron bacteria	Low amounts: reduce with particle filter or during reverse osmosis or distillation treatments (POE or POU). High amounts: remove by potassium permanganate-regenerated oxidizing filter and particle filter (POE). Very high amounts: remove by chlorination followed by particle filter (POE). Consider well and distribution/storage shock chlorination to kill iron bacteria.
VISUAL (staining and deposits)	Brownish color or rusty sediment	Suspended iron and manganese particles	Particle filter (POE)
	Blackened or tarnished metal utensils and pipes	High chloride and sulfate levels	Reverse osmosis unit (POE) or distillation unit (POU)
	Blackened or tarnished metal utensils and pipes	High water acidity and high hydrogen sulfide	Acid-neutralizing filters (calcite or calcite/magnesium oxide) (POE) or addition of alkaline chemicals such as lime
	Stains in showers, toilet bowls, and faucet ends	Hardness	Water softener (POE or POU)
	Excessive staining in showers and aluminum cookware	Salinity	Reverse osmosis unit or distillation unit (POU)
	Green water stains	Acidity	Acid neutralizing filters (POE) or addition of alkaline chemicals such as lime
	Soap deposits or excessive scaly deposits in plumbing and appliances	Hardness	Water softener or reverse osmosis or distillation (POE or POU)
	Excessive salt deposits	Alkalinity (high pH and sodium)	Reverse osmosis or distillation systems (POE)

Category	***Symptom***	***Cause***	***Treatment Devices***
OTHER VISUAL	Houseplants stunted or with burned leaf tips	Salinity	Reverse osmosis unit or distillation unit (POU)
TASTE	Taste of chlorine, gasoline, or oil	VOCs, including residual chlorine, disinfection byproducts, pesticides, or fuel (gasoline, diesel, oil products)	Activated charcoal filter or aeration (POE)
	Metallic taste	Acidity	Acid neutralizing filters (POE) or addition of alkaline chemicals such as lime
	Salty or bitter taste	High total dissolved solids, sodium, sulfates, or nitrates (salinity)	Reverse osmosis or distillation (POU)
SMELL	Chlorine-like smell	VOCs, including residual chlorine, disinfection byproducts, pesticides, gasoline products	Activated charcoal filter or aeration (POU)
	Gasoline-like smell	Gasoline, diesel, oil products	Activated charcoal filter or aeration (POU)
	Earthy, musty, or chemical smell	Algae products (geosmin and MIB)	Activated charcoal filter (POU)
	Rotten egg odor	Excessive acidity, lack of oxygen in water source, or contamination by hydrogen sulfide gas (occurs naturally in aquifers and sediments)	Oxidation of water during aeration (POE) or chlorination and a particle filter (POE) or oxidizing filter (POE) followed by an activated carbon filter. Acidity control may also be needed.
ILLNESS	Gastro-intestinal problems such as diarrhea and vomiting	Pathogens	Remove source of contamination. Reduce pathogens through chlorination, UV radiation, or ozonation (POE). Chloramine chemicals may be used after chlorination is completed to maintain acceptable chlorine residual levels.

NOM–Natural Organic Matter
VOC–Volatile Organic Chemical
POE–Point of Entry
POU–Point of Use

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13 Exercise Solutions

Solution Exercise 1

If you do not have your well report, you may be able to obtain a copy by going to the state or provincial agency that maintains the database of all wells, including municipal, industrial, and domestic wells. Many agencies have a searchable map-based system where you can find your well and other wells in your area. Some databases include extended water chemistry reports. You should always have your well report on file, as well as a record of any work done on the well or pump replacement

Return to Exercise 1↥

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Solution Exercise 2

If you have grit or sand in your toilet tank, your pump may be failing. Possible causes are a decline of the water level in your well due to excessive pumping or drought; or the screen was not properly selected for your well conditions. Excessive grit in the water can damage the pump and result in pressure tank failure. In you see sediment in the toilet tank, have a licensed pump installer check your pump. A high-quality, well-maintained submersible pump can last for 20 to 30 years.

Return to Exercise 2↥

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Solution Exercise 3

Your pressure tank may have failed—have a plumber check your system.

Return to Exercise 3↥

Return to where text linked to Exercise 3↥

Solution Exercise 4

If you do not have any information about your water chemistry, you should sample and analyze your water now to establish a baseline. You may wish to talk to your local health department, and they can suggest what constituents to sample. They can also recommend certified laboratories in the area. At a minimum, on a yearly basis, analyze for nitrate and bacteria—these constituents are more likely than others to change in concentration over a short time and are more serious for your health. You should always maintain all your analytical reports.

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Solution Exercise 5

One cause of cloudy water is cold water, which will hold air bubbles, but should clear after standing for several minutes. Cloudy water that does not clear on standing indicates well screen failure. Bacteria cling to clay and so clay particles can introduce bacteria to your water supply. A bad odor suggests pollution—call your certified laboratory and describe the odor and they will recommend what tests to do. A chemical or gasoline odor is of serious concern, whereas a rotten egg smell can be naturally occurring, as discussed in Section 5.4.1. Some labs will allow you to contract one of their staff to come to your home to collect a sample.

It is strongly recommended that you print out the contact information for driller, pump installer, and analytical laboratory and post that information on your interior water system, such as your water heater, for quick access during an emergency.

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Solution Exercise 6

Flooding will introduce contaminants that could enter your well, so you should analyze your well water quality following a flood event. Flooding may introduce oil and grease from roadways, as well as road salts. Ask your lab to recommend a list of constituents for analysis.

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Solution Exercise 7

If your well water feels warmer than it should, your pump may be overheating. Have a licensed pump installer check your pump.

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Solution Exercise 8

Your well may need to be scrubbed and shock chlorinated. Only a licensed well installer will have the tools and can assure they will not use excess chlorine that could enter the aquifer geology and mobilize arsenic or another toxic element that is dangerous to your health.

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14 Acronyms and Abbreviations

BDL = Below Detection Limit

USCDC = Centers for Disease Control, USA

gpm = Gallons per minute

MCL = Maximum Contaminant Level

MCLG = Maximum Contaminant Level Goal

MFL = Million fibers per liter, used for asbestos

mg/L (ppm) = milligrams per liter (parts per million)

micrograms/L or µg/L (ppb) = micrograms per liter (parts per billion)

ND = Not Detected

NOM = Natural Organic Matter

NTU = Nephelometric Turbidity Unit

pCi/L = picoCuries per liter

PVC = Polyvinyl chloride (a type of plastic)

pH = concentration of hydrogen ions that reflects the acidic or basic state of a fluid

TDS = Total Dissolved Solids

USEPA = United States Environmental Protection Agency

WHO = World Health Organization

15 About the Author

After retirement from the University of Arizona in June of 2015, **Ms. Uhlman** continues working on hydrogeologic projects addressing water resource management and protection. She provides expert witness testimony on contaminant transport in the subsurface. She has over 45 years of experience in the management of multi-disciplinary, environmental projects involving site characterization; geologic data acquisition and analysis; GIS applications; mine site restoration; and aquifer vulnerability assessment. With an academic background in classical well hydraulics and hydrology, her aquifer characterization experience includes subsurface exploration in many geologic settings, including the arid regions of the Middle East and the Southwestern United States, glacial outwash aquifers, fractured bedrock, karst, and coastal areas susceptible to salt-water intrusion.

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