General Groundwater Concepts

Hydrologic Cycle

All water on the surface of the earth and underground are part of the hydrologic cycle (Figure 1), driven by natural processes that constantly transform water from liquid to solid or vapor and back to liquid while moving it from place to place.

Water evaporates from ponds, lakes, oceans, reservoirs, and soils. Plants take water from the ground and emit water vapor into the air called evapotranspiration. The water vapor forms clouds that eventually condense and return to the earth's surface as precipitation such as fog, rain, sleet, or snow.

During storms, water runs off the surface into streams or water bodies or seeps into the ground. Water that sinks into soils or surface rock recharges groundwater reservoirs or aquifers. Groundwater can discharge at seeps or springs, or into rivers, streams, lakes and oceans, or wells. In arid areas and during the summer, precipitation may first infiltrate into the ground, but much of it quickly returns to the cycle through evapotranspiration.

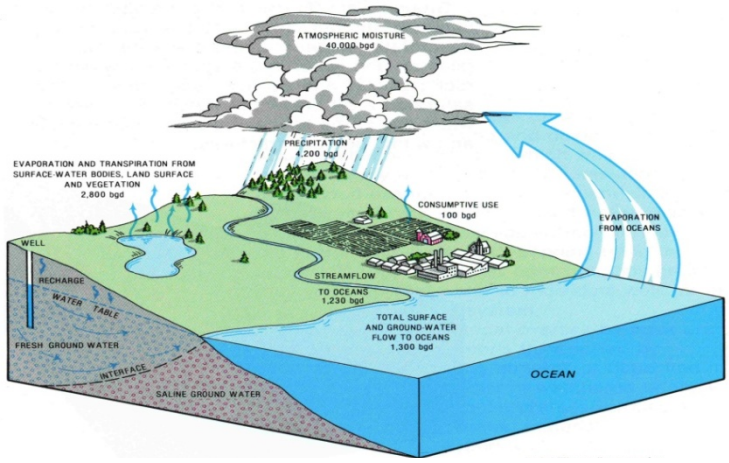

Figure 1: The Hydrologic Cycle – The Earth contains a finite amount of water as is illustrated here, showing how the water moves, from the oceans by evaporation, falling as precipitation back to the land and moving through streams, into lakes and into the subsurface as groundwater.

How to Stay Involved

Visit Website: sonomacountygroundwater.org

Join Email List to Receive Periodic Updates: sonomacountygroundwater.org/email/

What Is Groundwater?

Water infiltrates and collects underground, and is held in an upper unsaturated zone and a lower saturated ("groundwater") zone (Figure 2).

The **unsaturated zone** is located immediately beneath the land surface and above the water table, and the zone's pore spaces contain both air and water. Forces exerted by soil and rock surfaces bind water drops or films in the pore spaces. A well drilled into the unsaturated zone will not produce water because the water drops or films attach too tightly to the surfaces to be pumped.

In the **saturated zone** all the open spaces are filled with groundwater. The top of the saturated zone is called the water table. **The saturated zone supplies water to wells.** Like surface water, groundwater flows from higher to lower levels, under the influence of gravity (Figure 3). The pressure or elevation difference between higher and lower levels is called the hydraulic head.

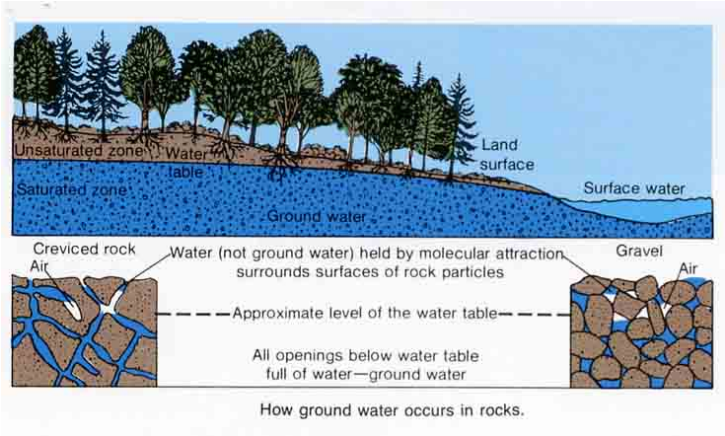

Figure 2: Schematic showing the unsaturated and saturated zones, and the occurrence of groundwater in porous media (right bottom - alluvial sands and gravels), and fractured hard rock (left bottom). Fractures in hard rock typically range from a few millimeters to more than a centimeter.

"The saturated zone supplies water to wells."

Finding Groundwater

Sediment and rock characteristics determine where groundwater may be tapped for human use. Wells produce water from two general types of geologic materials:

1. **Sediments**: Sediments are made up of gravel, sand, silt and clay. Coarse gravel and sand sediment in and near stream channels tend to have abundant, large interconnected pore spaces between grains that allow groundwater to readily flow. Fine silt- and clay sediments tend to have small pore spaces that are not well interconnected, with small grain sizes that have large surface areas causing increased friction that impedes water flow.

2. **Bedrock**: Bedrock is a general term for solid rock, such as granite or sandstone that lies beneath soil and sediments. In bedrock, most of the water is held and flows through fractures in the rock.

The amount of available groundwater depends on porosity and permeability. Groundwater moves through the open pore spaces between sediment grains. The porosity of the sediment or sedimentary rock is the volume of pore spaces divided by the total volume of rock, usually expressed as percent porosity.

The permeability, also called hydraulic conductivity, of the porous sediment or rock measures the ability of water to move through the material. Permeability depends on many factors, including porosity, grain size and distribution, and grain shape and arrangement. Although clay is considered to have a high porosity and water holding capacity, its permeability is very low due to the lack of connection between pore spaces. In contrast, gravels have both a high porosity and permeability, as it typically contains open and connected pore spaces.

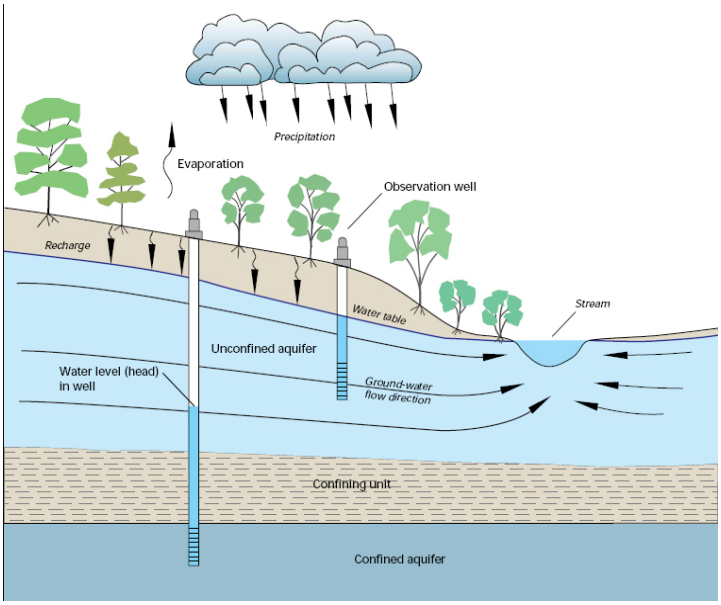

Figure 3: Recharge of groundwater, groundwater flow and interconnection of surface water, showing wells completed in unconfined and confined aquifers.

There are many different types of rock, and porosity can form in a variety of ways. Bedrock, such as granite, has porosity in the fractures that form over time. Volcanic rocks can have porosity from holes in the rock and also fractures. Fractures occur from the varying stresses within the earth or from weathering processes at the earth's surface.

Fractures are generally quite small, on the order of a few millimeters to more than a centimeter wide, but vary significantly at local and regional scales, and even on the scale of a well site. While exceptions exist, the yield from wells in fractured bedrock is generally much lower than yields from wells in sediments.

Aquifers

An aquifer is a saturated zone of sediment or rock with high enough permeability to transmit groundwater, yielding economically significant quantities of water to wells and springs. Groundwater stored in aquifers can be pumped to the surface through wells to supply water for agriculture, homes and cities.

Saturated sediments and rocks are called aquifers when they are permeable enough to transmit water sufficient to supply a residence, farm, town, or city. Aquifers are complex environments that can be highly variable in composition and how they influence the direction of groundwater flow and affect the water quality.

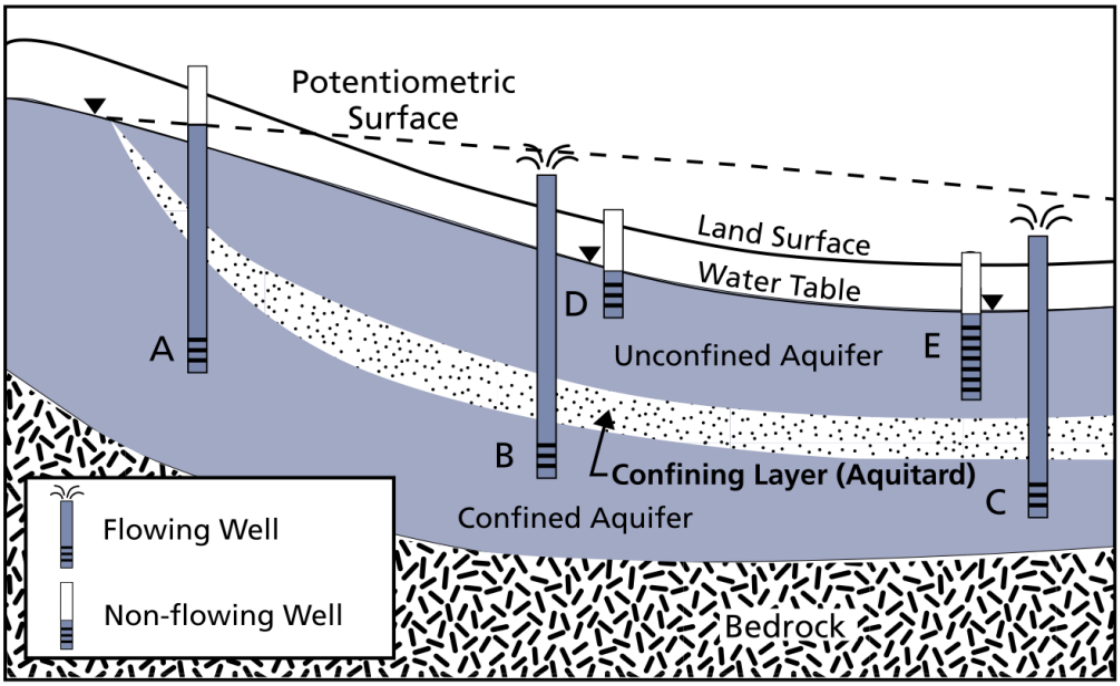

Figure 4: Types of aquifers showing groundwater levels in wells in unconfined (or water table), and confined.

While aquifers may be thought of as underground reservoirs, storing water underground is more complex than in a surface reservoir. An aquifer is something like a sponge, but made of various rock materials with variously-sized open spaces. The water surface and flow patterns within aquifer material are not visible from the surface, and groundwater reservoirs take much longer to fill and extract water from than a surface water reservoir.

Aquifers can be either unconfined or confined (under pressure). Figure 4 illustrates the difference between an unconfined aquifer and a confined aquifer both of which occur below the unsaturated zone in the saturated zone. Unconfined aquifers are open to the atmosphere and are bounded at the top by the water table, which forms the transition between the unsaturated and saturated zones. Confined aquifers are typically found beneath unconfined aquifers and are separated by low permeability silt or clay confining layers (or aquitards).

Groundwater pressure varies depending on the aquifer. The groundwater level in a well completed in an unconfined aquifer will be the same as the water table (wells D and E) and, like surface water, will be at atmospheric pressure.

The groundwater in a confined aquifer is under a pressure greater than atmospheric pressure. When a well penetrates the layer that confines the aquifer, the water will rise in the well to the potentiometric surface level of the confined aquifer (wells A, B and C). The potentiometric surface is determined by the confined aquifer's highest elevation.

Where there is substantial rainfall, the water table generally mimics a slightly flattened outline of the land surface. In arid zones the water table is much flatter and frequently much deeper than in more temperate zones.

Surface Water and Groundwater Interaction

Surface water is commonly connected to groundwater, but the relationship is difficult to observe and measure. The relationship between surface water and groundwater depends on the amount of water available in the stream and in local aquifers, as well as the subsurface geology. Under natural hydrologic conditions, some streams gain flow from groundwater (Figure 5-A, right) and other streams lose flow to groundwater (Figures 5-B and C, right). Thus, in some areas (gaining streams) groundwater aquifers can help support streamflow during dry weather conditions and in other areas (losing streams) surface water bodies are important sources of recharge to groundwater aquifers. Streams can also shift between gaining and losing flow along their courses and over time when the hydrology, underlying geology, local climate, or streamflow conditions change.

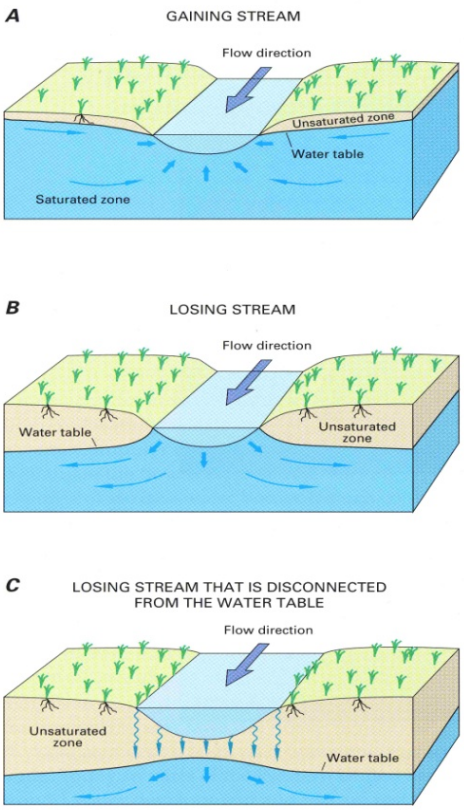

Figure 5: (A) Gaining streams receive water from the groundwater system. (B) Losing streams lose or add water to the groundwater system. (C) Disconnected streams are separated from the groundwater system by an unsaturated zone.

Groundwater Movement

Groundwater is generally hidden from view and therefore its presence and movement through the aquifers cannot be tracked visually. Collecting and evaluating well and stream-flow data can provide good information about groundwater flow and quality. Information from multiple wells is used to determine where groundwater is present and which way it is flowing.

Aquifers recharge whenever precipitation or surface water supplies exceed evapotranspiration. Gravity moves groundwater away from recharge areas toward natural discharge areas. In an unconfined aquifer, an increase in water level is caused by adding water to the aquifer. In a confined aquifer, an increase in pressure is the result of an increase in the height of water in the recharge areas. As the aquifer's pressure decreases, the level of discharge also will decrease.

Time provides another complexity. The rate of movement depends on a variety of factors:

- Hydraulic conductivity, also known as permeability—a measure of how much water the rock can transmit
- Fluid viscosity or the thickness of the fluid
- The gradient or slope of the water table

Water that recharges an aquifer does not immediately supply a pumping well, but may take days to centuries or more to reach a well site.

Groundwater Recharge

Natural recharge generally occurs in permeable soils, sediments and fractured bedrock during periods when precipitation exceeds evapotranspiration or when streams are flowing. When rain falls faster than it can soak into the ground, runoff occurs and limits the amount of water that is recharged. Other factors that can limit recharge include the presence of hard surfaces, such as roads and driveways, the presence of shallow clay layers, and areas with a shallow water table. In many areas of California, stream channels typically provide a significant source of recharge to groundwater basins. The identification and protection of groundwater recharge areas is an important step in sustaining groundwater basins.

Seepage from canals, surface reservoirs, septic and leaking water supply systems, urban watering and storm runoff also contribute to recharge. Recharge can also result from irrigating crops. When applying more irrigation water than a crop can absorb or water can evaporate, the excess sinks through the root zone and gradually recharges groundwater.

Recharge can be enhanced by placing water in spreading basins to percolate into the ground, modifying stream channels and surface topography to slow the rate of runoff and increase infiltration of stormwater, and inserting water into recharge wells.

Groundwater Discharge

The speed and manner of groundwater movement from recharge areas to discharge areas where it exits the aquifer (Figure 6), depend on the permeability of the various materials (sediments, soils, rocks) that the water must flow through, the hydraulic gradient of the water moving underground, hydraulic conductivity of the geologic formation, and the cross-sectional area of the aquifer (if the aquifer is a hallway, a door frame in the hallway is the cross-sectional area).

Most natural discharge occurs at springs, seepage into stream channels, wetlands and seasonal lakes in desert areas. In some basins, subsurface flow into another basin or into the ocean discharges significant amounts of groundwater. Humans can also significantly contribute to discharge by pumping groundwater from water wells.

Wetlands or lakes can form when the water table lies close to or at the ground surface. The wetland may disappear if groundwater levels are lowered. Water evaporates from damp soil marginal to the wetland and is removed by the roots of plants.

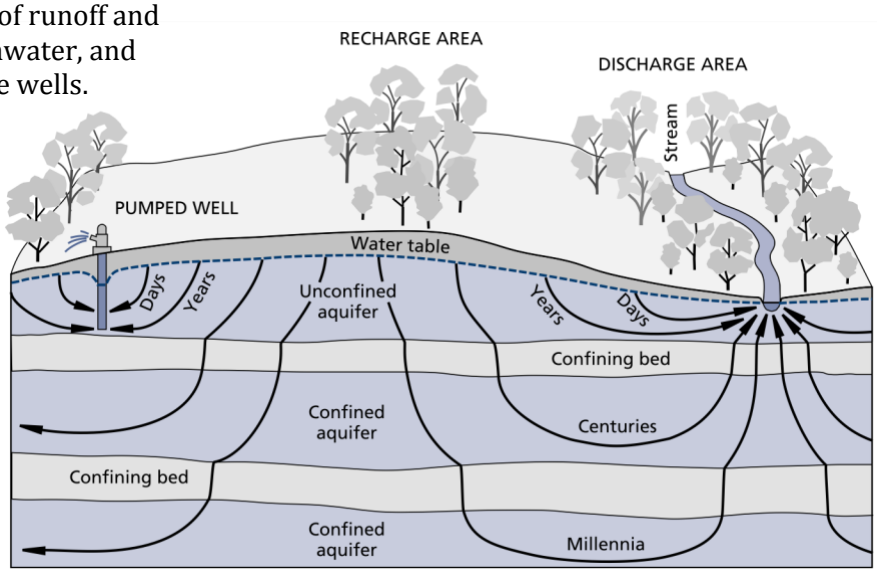

Figure 6: The figure illustrates groundwater system recharge and discharge areas and estimates time for a water molecule to flow along various paths from recharge to discharge areas.

Basin Yield

Basin yield is the average amount of water that can be extracted annually from an aquifer or groundwater basin, without causing undesirable results, such as permanently lowered groundwater levels, land surface subsidence, groundwater quality degradation, or decreased stream flow. Well pumping may vary above or below the long-term yield during drought or wet years, or as part of basin management plans. If water conditions (precipitation, recharge, natural discharge, pumping, etc.) in a basin change, the basin yield may change.

Basin yield does not equal groundwater storage. Groundwater storage in a basin is the amount of usable water that can be technically and economically extracted from a basin and is likely to be a very large number compared to the yield. For example, many arid groundwater basins may contain a large amount of usable groundwater that accumulated from low amounts of annual recharge over a significant time period (thousands of years or more).

The low annual recharge provides low basin yield. If annual extractions consistently exceed this yield, the withdrawals will remove more groundwater than can be replaced by natural recharge ("mining the groundwater" or "aquifer depletion").

The term "safe yield" is often used in judicial proceedings. It is determined by technical professionals and subsequently interpreted by courts to define the legal rights to extract groundwater in a basin.

Groundwater Level Data and Overdraft

Determining how groundwater levels change in an aquifer over time requires measurements of the depths to groundwater in that aquifer's wells (Figure 7). The water depth measurements are recorded on charts called hydrographs. These measurements are the main source of information for tracking how the aquifer behaves over time during pumping and recharge.

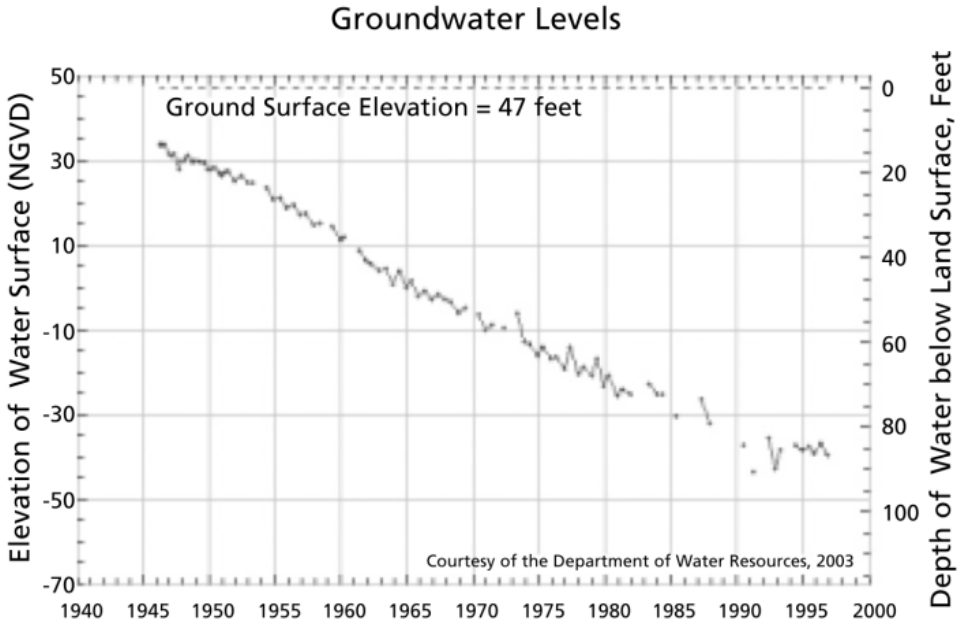

Figure 7: A water well hydrograph showing the long-term change in the groundwater level in the well over time. This well shows an overall downward change of more than 70 feet in 50 years, with seasonal changes of a few feet.

Just a few measurements are not adequate for understanding how the aquifer responds to water use and recharge and to make long-term projections of groundwater levels in response to pumping. Instead, groundwater level measurements should be collected consistently over a long period (decades) so that changes in groundwater levels can be assessed and management strategies can be developed.

Overdraft of a groundwater basin or aquifer occurs if the amount of water extracted exceeds the amount of recharge to the basin over a period of many years (during which hydrologic conditions do not significantly change). A groundwater basin is in a condition of overdraft when the water level measurements show a downward trend in water levels over a period of years, including wet years. The hydrograph plots water depth measurements for a single well that shows long-term decline of that well's groundwater level (Figure 7). If other wells within the basin exhibited the same decline, the basin would likely be in overdraft.

Overdrafting groundwater basins may have significant negative consequences, such as water quality degradation, saline intrusion, surface subsidence, and increased costs to pump groundwater and replace wells.

Limited droughts, or isolated periods of abnormally low rainfall, do not cause overdraft. Droughts temporarily reduce the amount of water available to recharge the basin, and if pumping rates remain the same, groundwater levels often exhibit declines during drought periods. This reduction in groundwater storage is similar to the lower water level in a surface-water reservoir during a drought. When the drought is over, groundwater levels often exhibit increasing or rising trends (again assuming pumping rates remain the same), just like a surface water reservoir.

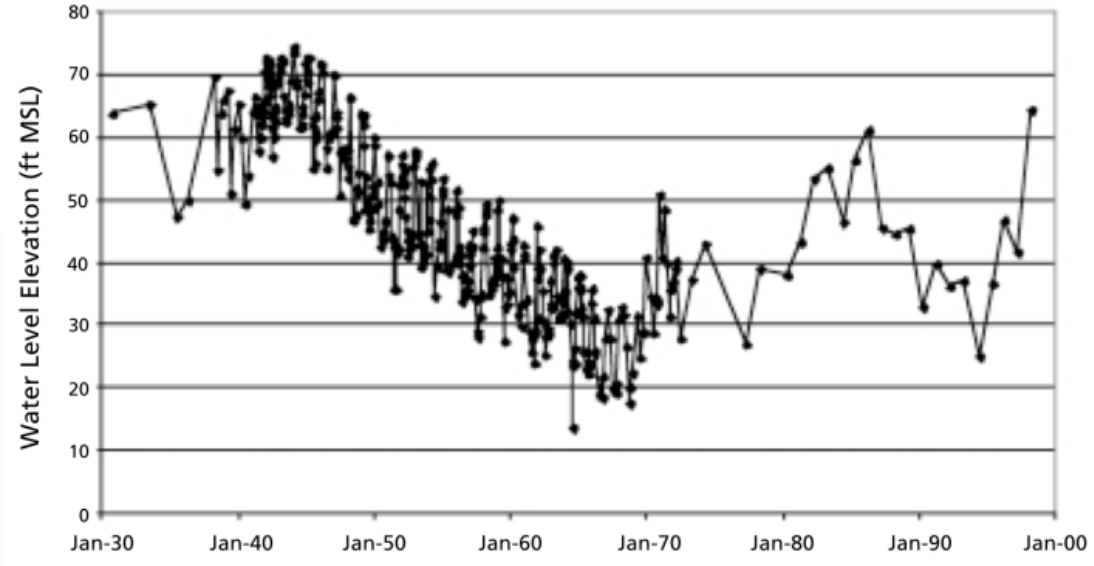

Figure 8: A water well hydrograph clearly showing the seasonal changes of 10 to 20 feet in the groundwater level in the well each year.

Water Wells

Water wells can be thought of as windows to the aquifer and provide the only opportunity to collect direct information on the groundwater system. Water wells are typically quite expensive to install. Therefore, collecting high quality information during water well drilling, constructing and testing is important.

Wells and How They Work

A well is a hole drilled below the ground surface into the saturated zone (Figure 9). Wells typically have screens at intervals to allow groundwater to flow into the well from the most productive aquifer(s). All water wells are required to prevent foreign substances from entering the well and the aquifer. This is called surface completion and consists of installing casing and sanitary seals. The casing also keeps the material of the aquifer from falling into the well and provides space for a pump and a filter pack. Well casing typically consists of steel pipe, but can also consist of plastic pipe (e.g., PVC) for some applications. The most common pumps used in wells today are line-shaft turbines and submersible turbine pumps. A well also could be an "open hole" completion below the sanitary seal and casing as in many bedrock wells. A well that is built correctly and is properly developed will not impede the flow of groundwater from the aquifer into the well or allow sediment from the aquifer to enter the well.

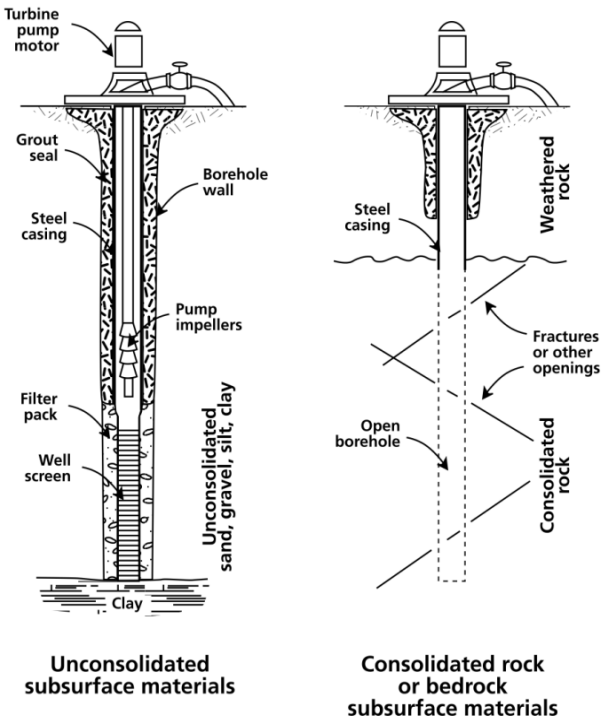

Figure 9: Water well construction diagram for sand or gravel, known as unconsolidated material and bedrock completion.

Until the well pump is turned on, the groundwater level in the well will be that of the local water table for an unconfined aquifer or the potentiometric surface in a confined aquifer. When the pump is turned on, the groundwater inside the casing is pumped to the surface, and the water level within the casing is lowered. The difference in pressure between the water level in the casing and the water level in the aquifer creates a hydraulic gradient between the aquifer and the casing. As a result, groundwater flows from the aquifer into the casing to replace the water that is being removed.

The rate at which groundwater flows from the geologic formation into the well is determined by the permeability and storage capacity of the aquifer material and efficiency of the well during pumping (effected by well design and construction).