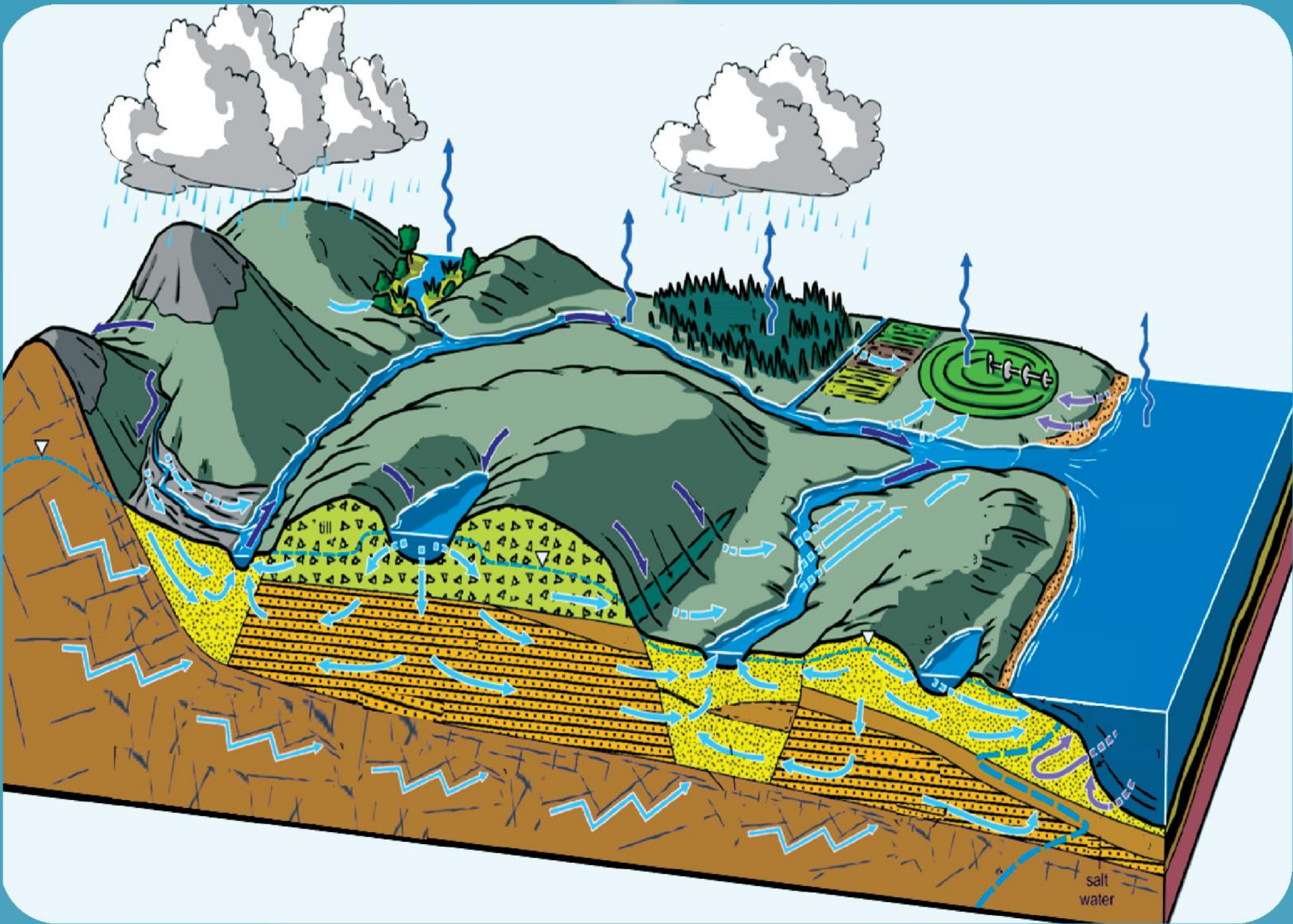

Groundwater in Our Water Cycle

Getting to Know Earth's Most Important Fresh Water Source

Eileen Poeter, Ying Fan, John Cherry
Warren Wood and Douglas Mackay

THE GROUNDWATER PROJECT

Groundwater in Our Water Cycle

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The Groundwater Project

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The Groundwater Project
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THE GROUNDWATER PROJECT

Cover Image: Adapted from Hinton (2014)

Dedication

We dedicate this book to the scholars, practitioners, and educators who came before us and taught us what we know about groundwater, and to all future scholars, practitioners and educators who aspire to create a sustainable path for our beautiful, and one and only, planet Earth.

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The Groundwater Project Foreword

The United Nations Water Members and Partners establish their annual theme a few years in advance. The theme for World Water Day of March 22, 2022, is "Groundwater: making the invisible visible". This is most appropriate for the debut of the first Groundwater Project (GW-Project) books in 2020, which have the goal of making groundwater visible.

The GW-Project, a non-profit organization registered in Canada in 2019, is committed to contribute to advancement in education and brings a new approach to the creation and dissemination of knowledge for understanding and problem solving. The GW-Project operates the website https://gw-project.org/↗ as a global platform for the democratization of groundwater knowledge and is founded on the principle that:

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

The mission of the GW-Project is to provide accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater and understand how groundwater relates to and sustains ecological systems and humanity. This is a new type of global educational endeavor in that it is based on volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 hundred organizations from over 14 countries and six continents, with growing participation.

The GW-Project is an on-going endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

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

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

The GW-Project Steering Committee

August 2020

Foreword

This book is about the role and importance of groundwater in our Planet's water cycle and is the flagship product of the GW-Project. Many books have been published in the past decade drawing attention to the looming global water crisis. Although many are focused on the immense importance of freshwater for humanity and the multitude of water problems we are facing, none were written by water science experts to cover the groundwater part of our water cycle for a broad readership as comprehensively as this book. This book, titled "Groundwater in Our Water Cycle: Getting to Know Earth's Most Important Fresh Water Source" makes "hidden" groundwater come to life for the reader.

This book was initiated by Eileen Poeter, who reached out to each of the co-authors, progressively, as more and more expertise was needed to cover the expanding scope. The end result is a book prepared by senior, globally recognized, experts with specialties including field investigation, analysis and modeling of groundwater flow, geochemistry and pollution. The result is a collaborative effort of the type that the GW-Project strives to encourage in the quest to synthesize knowledge and achieve simplicity on the other side of complexity.

The authors are all on the Steering Committee of the GW-Project. While preparing the book, they received advice from experts on groundwater governance among other topics. The book was subjected to comprehensive peer review. Consequently, the material in this book represents the type of interdisciplinary collaborations that the world urgently needs to transfer groundwater knowledge and raise groundwater consciousness in support of better groundwater management and protection.

John Cherry, The GW-Project Leader

Guelph, Ontario, Canada, August 2020

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Eileen Poeter
Ying Fan
John Cherry
Warren Wood
Douglas Mackay

Groundwater in Our Water Cycle

Getting to Know Earth's Most Important Fresh Water Source

The Groundwater Project

1 Preamble

The presence of water on this planet is the essential feature that allowed life as we know it to come into existence. The circulation of water on the planet continues to control the life patterns of all organisms and is the foundation for individual and societal human health, as well as ecological health. Knowing how and where water circulates through the water cycle is the foundation on which wise water management is built.

The effects of human activity on geological processes of planet Earth are now so significant that a new subdivision of geologic time, the Anthropocene Epoch, has been proposed for formal adoption. Knowledge of natural processes has always been of great importance to human survival in prosperous and resilient cultures. Now human activity is altering these processes in unexpected ways, thus understanding these natural processes and human-originated effects on them is of crucial importance to developing knowledge for their sustainable management.

The United Nations World Water Development Report of 2016 (UNWWAP, 2016) projects that the world could face a 40% global water deficit by 2030. This staggering figure is projected to worsen with increasing global temperatures due to climate change, expanding urbanization and population growth. By 2025, two-thirds of the global population will live under water-stressed conditions. The Global Water Crisis is urgent and requires innovation to identify, prioritize and accelerate global solutions.

Groundwater must be included in the solution to the global water crisis because it makes up 99% of Earth's liquid fresh water (Shiklomanov, 1993) 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 reader is invited to think about Earth’s fresh water in a new way, to envision that all the surface water we see in rivers, lakes and wetlands is just the tip of the Earth’s vast fresh water reservoir; that is, just the “tip of the iceberg” with the hidden portion of the “iceberg” being liquid groundwater rather than ice.

2 Purpose

This book introduces groundwater science in the larger context of our water cycle, also called the hydrologic cycle. The hydrologic cycle is the continuous movement of water on, above, and below the surface of the Earth as portrayed in Figure 1.

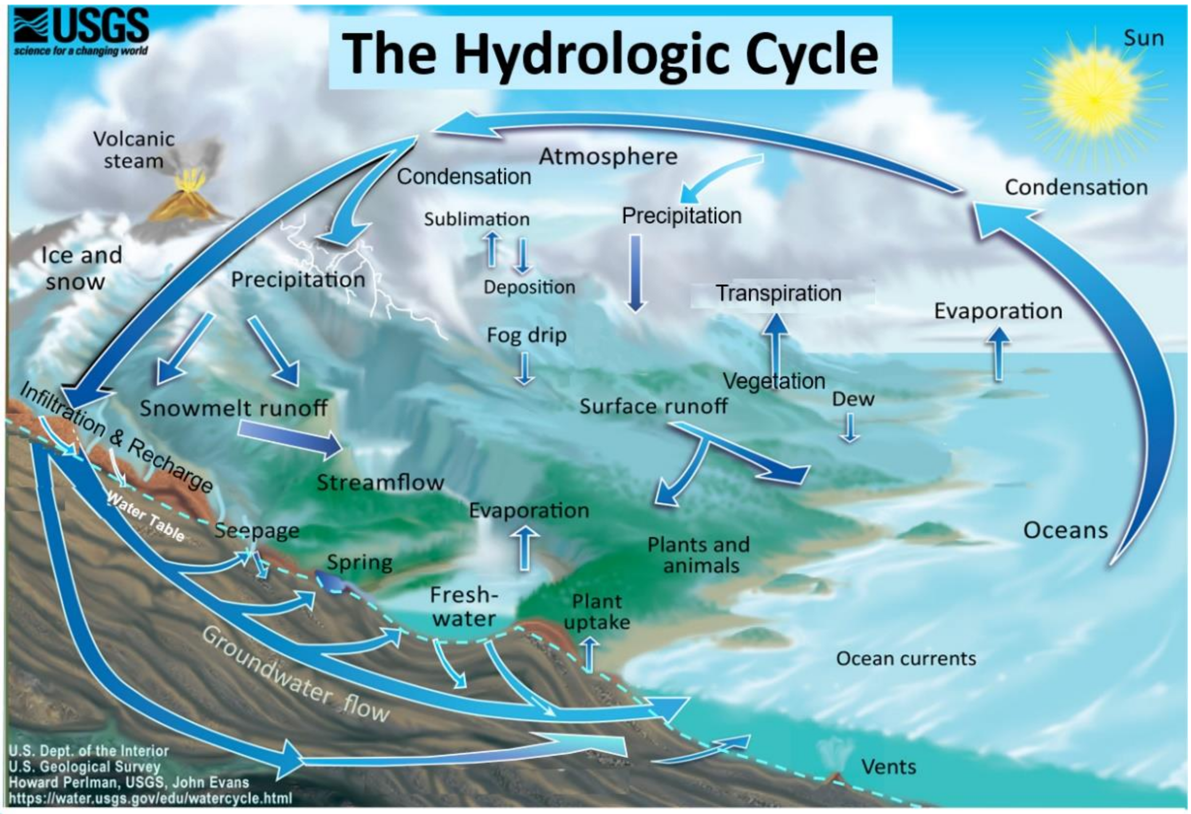

Figure 1 - The hydrologic cycle is the continuous movement of water on, above and below the surface of the Earth (adapted from the USGS, 2020).

This book explains that, although groundwater accounts for 99% of our liquid fresh water, only a fraction of groundwater is accessible without over-pumping aquifers. Consequently, only a small portion of the huge groundwater reservoir can be used annually without depleting this vital resource. Yet, global groundwater extraction has increased more than fourfold in the last 50 years and has caused approximately 25% of the current 3.1 mm/year rise of the oceans (Wood and Hyndman, 2018).

Groundwater shapes the Earth through weathering and geomorphologic processes. Rivers, lakes and wetlands are surface manifestations of groundwater, exchanging flow with the groundwater reservoir that feeds them when they need water and takes some of their flow when surface water is present in excess. This book draws attention to the ways in which the surface water that we can see is connected to and supported by the hidden groundwater reservoir that is continually flowing and replenishing the hydrologic cycle. This continual flow of groundwater is a conveyor belt for natural, as well as anthropogenic (human-made), chemicals. The distribution of such chemicals governs where groundwater is suitable to drink and the capability for soil to grow crops is largely dependent on how subsurface water interacts with the soil.

This book takes the broad view of the subject "groundwater in our water cycle" to include the natural and anthropogenic chemicals transported by groundwater flow and introduce many topics that are explained comprehensively in other Groundwater Project books↗. Groundwater provides multiple services by: regulating surface water flow, supporting ecosystems, and providing water for all life on Earth. In short, groundwater is the Earth's life support system.

3 The Earth's Plumbing System

In most cases, groundwater originates as precipitation that infiltrates at the ground surface and percolates down to the water table, which is a conceptual surface existing everywhere at some depth below the land surface (Figure 2). The depth of the water table varies from location to location. Its depth can be measured by drilling (or if the water is close to the surface, digging) a borehole to below the level where water begins to flow into the hole, and measuring depth from the ground surface to water surface. The water surface in a lake or river becomes the water table where the land surface meets the edge of the lake or river (Figure 2). That is, the water surface along a shoreline extends beneath the land surface. Along the shoreline, water is generally flowing (discharging) from the land into the lake or river but, in some instances, the direction of flow is from the water body into the earth.

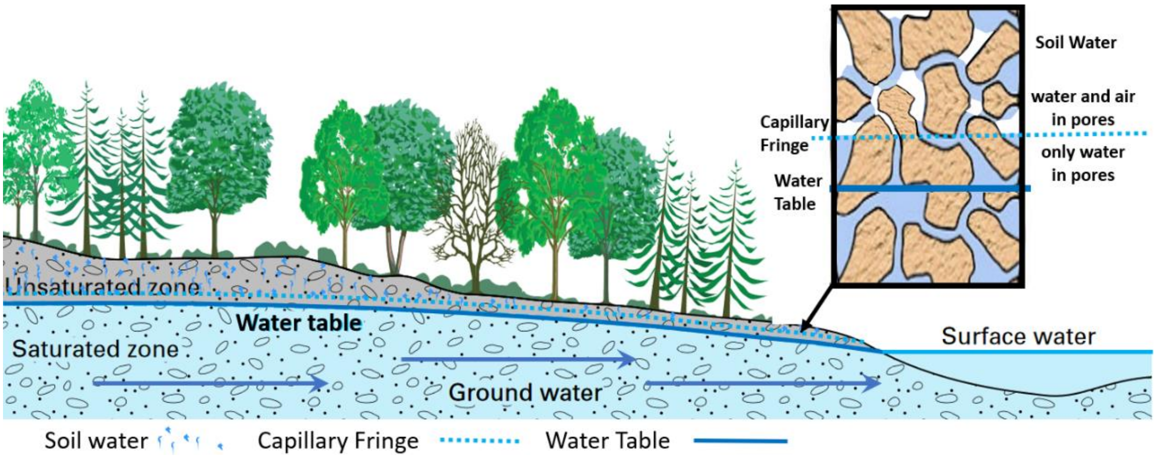

Figure 2 - The water table extends beneath the ground where the surface of a water body such as a lake or stream meets the shoreline (adapted from USGS, 2019a).

Water rises a small distance into soil pores above the water table due to capillary forces that result from the adhesion of water molecules to subsurface solids and the cohesion of water molecules to one another. These capillary forces pull soil water upward, opposing the force of gravity that pulls the water downward. This is similar to a dry sponge that pulls water upward from a kitchen countertop to fill the pore spaces within the sponge. This zone is called the capillary fringe. Above the capillary zone and extending up to the surface is the "unsaturated" or "vadose" zone in which some of the spaces are filled with air and some with water. Below the water table, water occupies all the space between particles of sediment (pores), within cracks (fractures) and in channels (caves) of rocks as shown in Figure 3. All sediments and rock within the upper few thousand meters of the land surface have connected open spaces between the particles, fractures, or caverns and those space are called porosity. Porosity is the fraction of the geologic material that is open space and can hold fluid. Interconnected pore spaces render the geologic material permeable, that is, allow groundwater to flow through the material. Permeability is a measure of the ease by which water passes through the cracks and pores of geologic material.

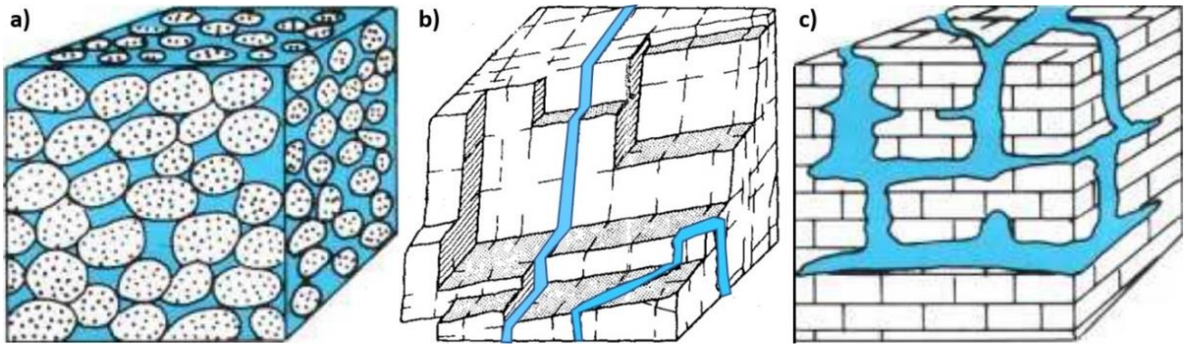

Figure 3 - Below the water table, water fills subsurface materials including within: a) the pores between particles of sediments; b) fractures of rocks; and c) caverns of carbonate rocks known as karst. (a and c from Heath, 1983; b adapted from Gale, 1982).

Aquifers are defined as geologic layers that store and transmit useful volumes of water. Aquifers are more porous and permeable than the geologic layers surrounding them. A clean bed of coarse sand below the water table is a good example of an aquifer. Confining units are impediments to groundwater flow to and from aquifers. A layer of low permeability clay between layers of coarse sand or a layer of unfractured basalt rock between layers of fractured basalt are examples of confining units.

Hand-dug wells are common in many regions around the globe where the water table is shallow enough to be reached using shovels and picks or small excavators. We can see the water table by looking down into a well that was dug long ago by nomads in the Gobi Desert (Figure 4). In most cases, water wells are deeper and are drilled with heavy-duty, truck-mounted drill rigs rather than being dug by hand. Drilled wells typically have a small diameter and it can be difficult or impossible to see the water surface in the well, so a hand dug well is useful for the image of Figure 4.

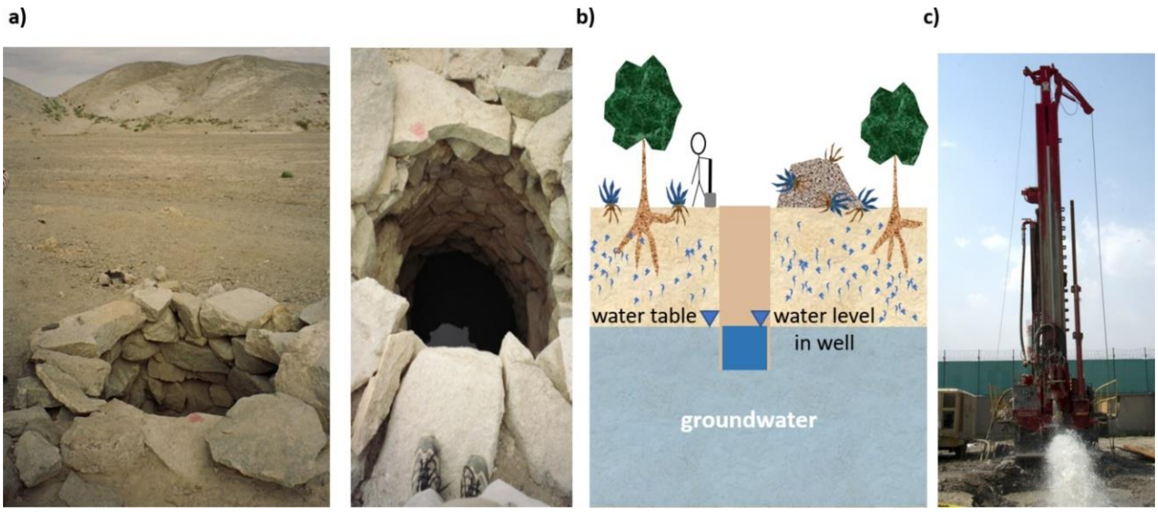

Figure 4 - Wells are created to access the water table. a) A hand dug well in the Gobi Desert with the sky reflected by the water (photo by Cherry, 2019). b) A schematic illustrating a hand-dug well intercepting the water table (Poeter et al., 2020, gw-project.org). c) A photo of a motorized water-well drilling rig (photo by Mellin, 2013).

Groundwater is an integral part of the hydrologic cycle. Figure 5 provides a link to a video that illustrates the hydrologic cycle in action.

Figure 5 - Click to view an animation of the hydrologic cycle (NASA, 2020).

Water enters the atmospheric portion of the hydrologic cycle by evaporation and leaves by precipitation. Movement of water in the atmosphere is powered by the sun and controlled by the continuous exchange of water molecules between liquid surface-water bodies (e.g., lakes, streams, oceans) and water vapor in the air.

The sun's energy heats surface water bodies causing individual water molecules to break their bonds with neighboring molecules and escape into the atmosphere. At the same time, individual gaseous water molecules make contact with the liquid water and are absorbed. Depending on the temperature of the air and surface water, as well as the amount of water vapor in the air, this exchange results in either evaporation (a net movement of water from the surface into the air), or condensation (a net movement of water from the air to the surface). Air has limited ability to hold water vapor, so if the amount of water vapor in the air exceeds the maximum amount it can hold at the prevailing temperature (saturation), excess water vapor condenses as liquid water; forming dew or fog.

Evaporation creates humid air. As air near Earth's surface is heated by the sun, it expands and rises. The Earth's atmosphere is warmer near the surface and cooler aloft, thus rising humid air reaches a height where it has cooled to the point that the water-vapor content exceeds saturation. The excess water vapor then condenses as small droplets that are clouds (or fog, if near the ground). The small droplets grow by collision with one another and by condensation of water vapor on their surfaces. If they become large enough, they are too heavy to be held by the buoyancy of the air and they fall from the clouds as precipitation in the form of rain drops, snow, sleet or hail.

When precipitation falls on the ground surface it may:

1) evaporate back into the atmosphere;
2) flow over the ground (overland runoff) or through temporarily saturated shallow layers of soil above the water table (interflow) to surface water bodies such as streams and become storm flow in the stream; or,
3) infiltrate into the soil.

Infiltrated water enters the vadose zone and some of it is used by vegetation. When there is surplus water in the vadose zone it percolates down to the water table becoming recharge to the groundwater system. When recharge occurs, the water table rises, water is stored in the groundwater system and flows slowly toward rivers, lakes, marshes and oceans where it discharges to the surface. This slow-moving water is stored in the subsurface as it moves toward discharge areas, and acts as a regulator (or buffer) that provides water to surface water bodies even during droughts. Stream flow that persists in dry seasons is called baseflow. In most watersheds, groundwater discharge is the principal, and often the only, source of baseflow.

Water moves between the surface, subsurface, and the atmosphere as it makes its way across the continents to the oceans. Most groundwater reaches the ocean as the baseflow component of stream flow, but some groundwater discharges directly to the ocean as seepage near coastlines and some rejoins the atmospheric portion of the hydrologic cycle by evaporation. Much of groundwater that enters the atmosphere without reaching the ocean occurs in closed depressions. The Aral Sea (between Kazakhstan and Uzbekistan), Caspian Sea (between Europe and Asia), and Dead Sea (in the Jordan Rift Valley), as well as the saline ponds and marshes of Death Valley (in the southwestern United States) are examples of such closed drainage systems.

Evaporation occurs from both the land and the ocean, but the ocean covers 71% of our planet and, unlike the land surface, the ocean surface does not dry out so there is an endless supply of water available for evaporation from the ocean, thus we often simplify the hydrologic cycle by saying it starts from the ocean. However, evapotranspiration from the land surface, which includes transpiration from vegetation, can move a large quantity of water from the shallow subsurface into the atmosphere. Plant roots draw water from the soil and the water table and transport it up through the plant (Figure 6). It is not uncommon for a single tree to move 500 liters of water a day from the soil into the atmosphere. Globally between 70 and 75% of water falling on the land is transpired or evaporated back to the atmosphere (Dai and Trenberth, 2002). That is, only 25 to 30% of rainfall flows through the ground and rivers back to the oceans. On a yearly average, approximately half of the river water reaching the ocean is groundwater (Reitz, et al., 2017) and about half flow over the surface or through the shallow subsurface as "quick flow".

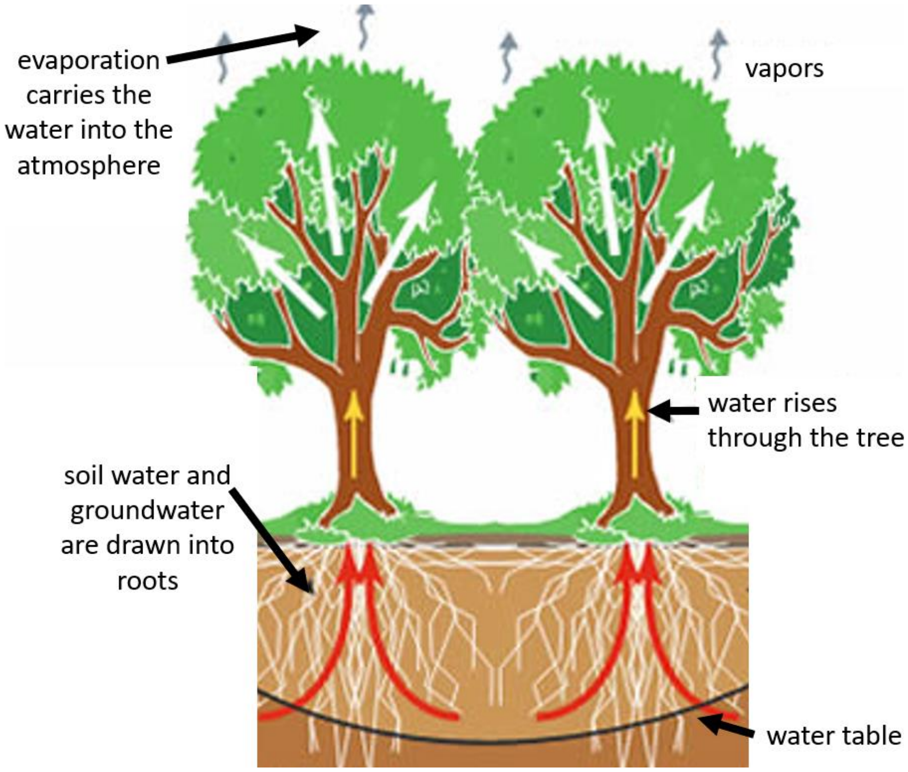

Figure 6 - Trees draw water from the soil and/or the water table to the atmosphere. It is not uncommon for a single tree to move 500 liters of water a day from the subsurface into the atmosphere, causing a depression in the water table as illustrated here beneath a grove of trees (adapted from USEPA, 2012).

The combination of evaporation from small water bodies such as lakes, ponds, streams, as well as from the ground surface, and transpiration of water through the pores of plants, are collectively called evapotranspiration which comprises the movement of water from the Earth to its atmosphere.

Climate aridity is defined based on the ratio of the annual precipitation (P) and the potential evapotranspiration (PET) of a locale. PET is the amount of water that could be evapotranspired if there was an unlimited supply of water in the soil. PET is higher in areas with higher temperatures, lower humidity, and higher wind speeds. The level of aridity is defined by the Aridity Index (AI) which is the amount of precipitation divided by the potential evapotranspiration.

Humid areas are defined as areas with an AI greater than 0.65 and typically receive more than 500 millimeters per year (mm/yr) of precipitation. Although it varies widely from place to place, in humid areas:

- groundwater recharge typically occurs several times a year.

Dry sub humid areas have an AI between 0.5 and 0.65.

Semi-arid areas are defined as areas with an AI between 0.2 and 0.5. They typically receive on the order of 250 to 500 mm/yr. Arid areas have an AI between 0.05 and 0.2. Arid and semi-arid regions:

- lose a large fraction of precipitation to evapotranspiration with only a small amount reaching the water table (from near 0up to about 4% of precipitation); and,
- groundwater recharge occurs in frequently.

Hyper-arid areas have an AI of less than 0.05, and:

- groundwater recharge only occurs in depressions that collect sufficient runoff following a storm event to infiltrate enough water through the soil such that excess water reaches the water table; and,
- groundwater is often the only source of water because surface waters tend to be saline given that evaporation removes water molecules and leaves the dissolved salts behind in the surface water body.

The distribution of semi-arid and arid regions is shown in Figure 7. Arid regions are home to approximately 2.5 billion people, grow roughly 44% of the world's food and raise about 50% of the world's livestock.

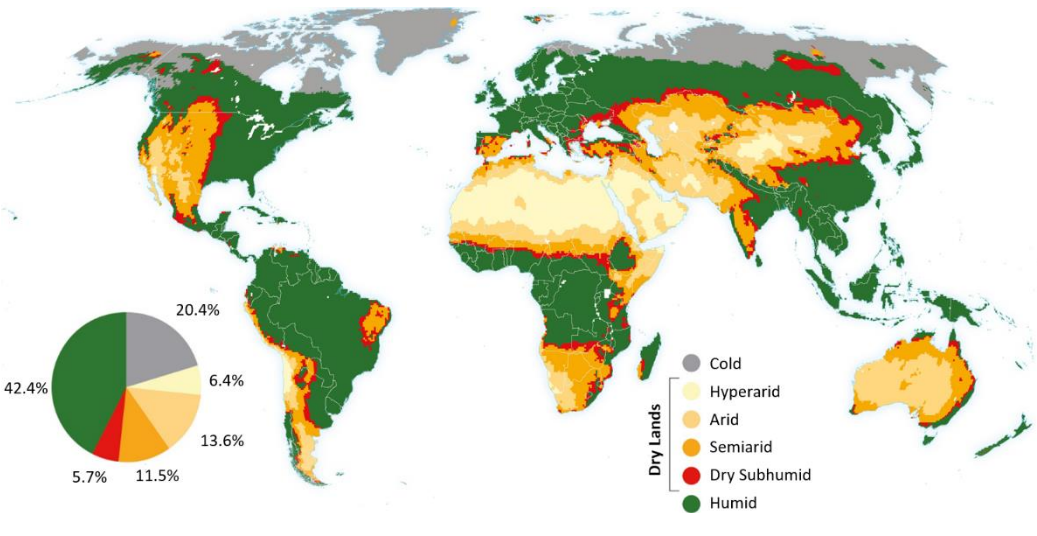

Figure 7 - Distribution of aridity on Earth (adapted from European Commission Joint Research Center, 2020).

The distribution of evapotranspiration on Earth is illustrated by the video of Figure 8. The video was created using a United States National Center for Atmospheric Research (USNCAR) Community Climate System Model simulation of water vapor and precipitation. In the video, clouds (white wisps) rise from both the oceans and continents, especially from tropical rainforests, such as the Amazon rainforest. Bursts of orange in the video indicate initiation of precipitation when the clouds become heavy with water and precipitation begins. These precipitation events are "fed" by evaporation from both the ocean and continents. As shown in the video, the rising water vapor from a location on land can join the moving air mass above, contributing to its vapor content, and then be carried downwind, and "rained out" at another location on the continent. This process is called precipitation recycling because this precipitation began as rain that fell on land then evaporated and became precipitation again.

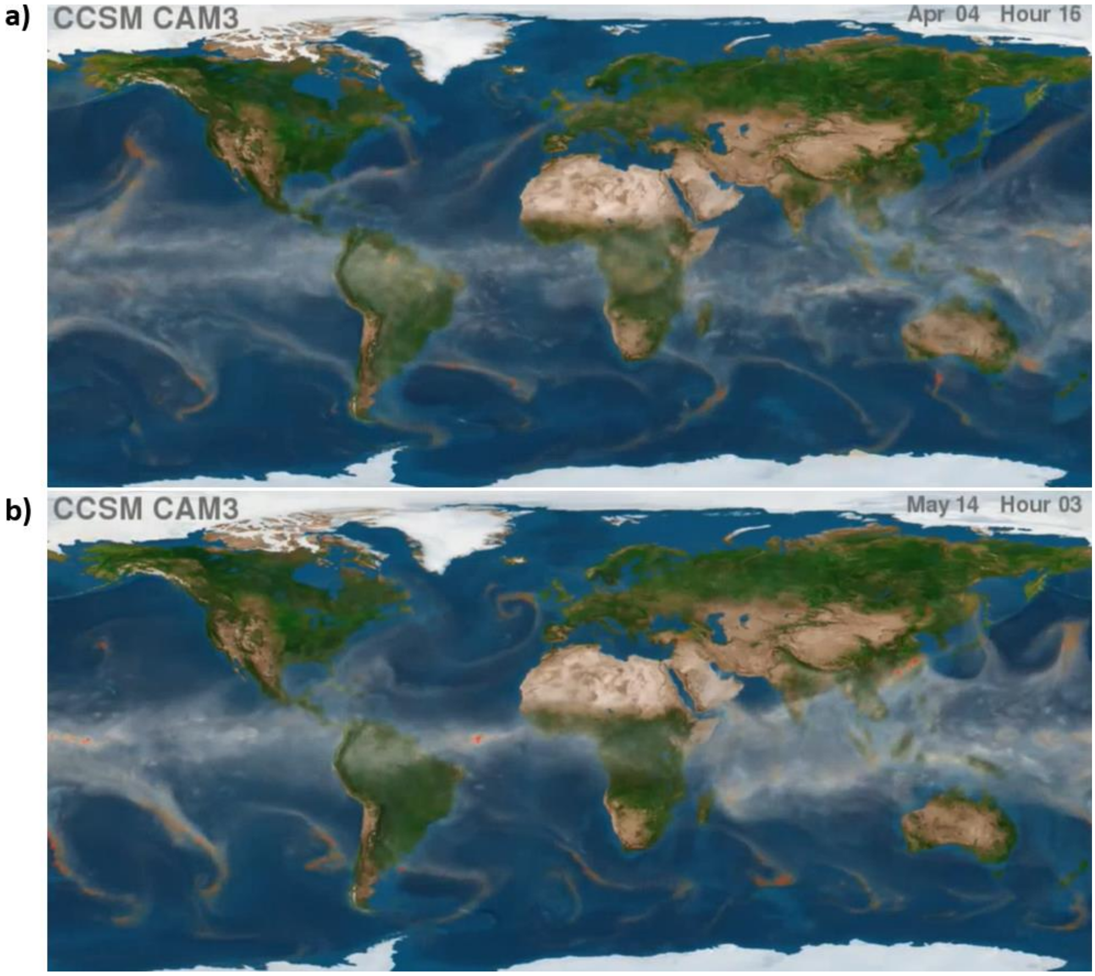

Figure 8 - Click to view ▶ an animation of evaporation and evapotranspiration (white) and precipitation (orange) created by a climate simulation model for a period of time during 2010. The orange spots indicate initiation of a storm a) on the north end of the Amazon rain forest in South America and b) in the Atlantic Ocean to the northeast of South America as well as in southeastern China. Initiation of storms shows up more clearly as bursts of orange in the video (USNCAR, 2020).

Recycled precipitation can be a large portion of the total precipitation received in regions far from the ocean (Figure 9a). For example, more than half of the precipitation over the southern part of South America originates from water that is transpired in the Amazon forest (van der Ent et al, 2010). The video link of Figure 8 shows that water vapor rises from the Amazon Basin and moves to the south, along the eastern flank of, and bent by, the Andes mountain range, and eventually precipitates on the La Plata River Basin far to the south. A basin is the area drained by a river system as defined by a line connecting the topographic divide between river systems where a drop of water on one side flow to one river and on the other side flows to the other river. Groundwater basins may coincide with river basins, but can differ and are delineated by the line connecting the highest water levels between adjacent groundwater basins. The arrows of Figure 9b correspond with the direction of vapor transport in the atmosphere simulated in the video of Figure 8. The farther away a region is from the location where moist marine air reaches the continent, the more its precipitation depends on the evapotranspiration from the land upwind of its location. Because the La Plata Basin in the south depends on transpiration from the Amazon, the Amazon has been called a "green ocean".

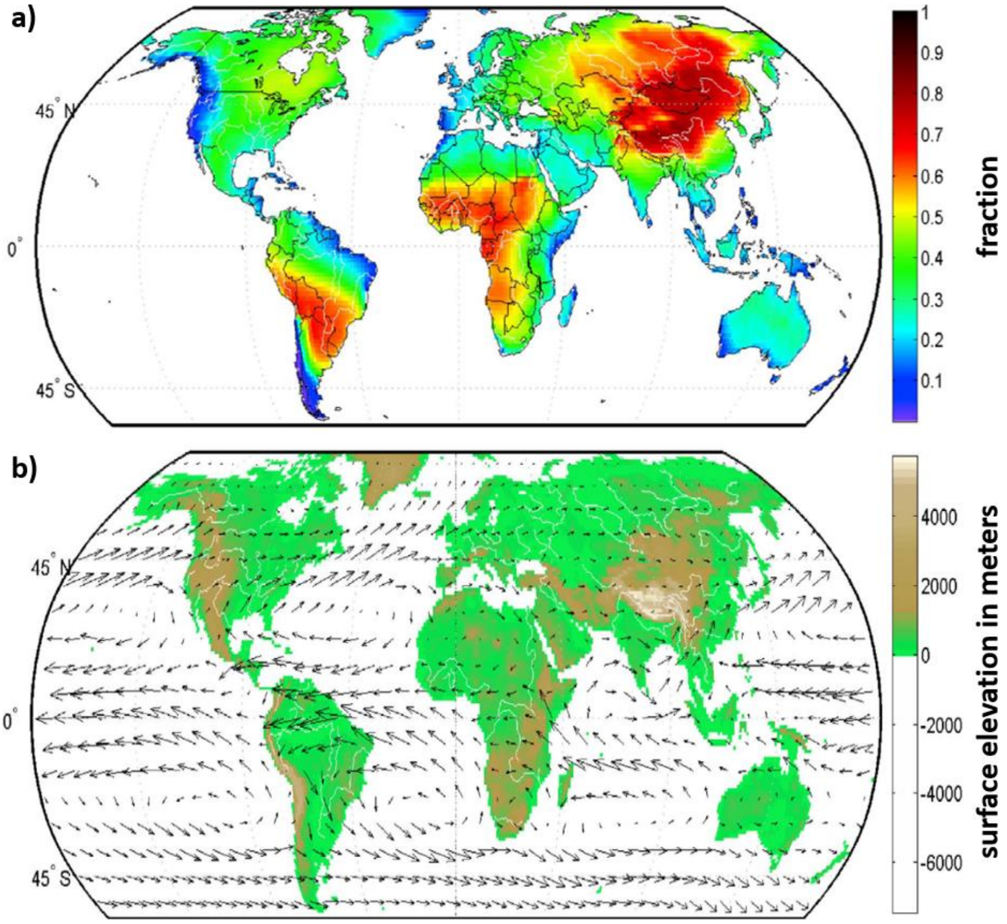

Figure 9 - Recycled precipitation: a) colors indicate the estimated fraction of precipitation originating from evaporation on land; and, b) size and direction of arrows indicate the magnitude and direction of atmospheric vapor transport, overlaid on a topographic map with elevation in meters (van der Ent et al., 2010).

4 The Below-Ground Portion of Our Water Cycle

To examine groundwater's role in the hydrologic cycle, consider the opaque, elusive, below-ground portion of the hydrologic cycle to which most of the Groundwater Project (GWP) books are devoted.

4.1 The Shallow View

When precipitation moves below the ground surface it is called infiltration (dark blue downward dashed arrows in Figure 10. Figure 10 shows a fractured medium environment on the left and a porous medium environment on the right. In fractured rock, water moves through cracks, while in porous media water moves through spaces between granular particles. Flow processes are the same in both systems, but the character of the geologic material differs.

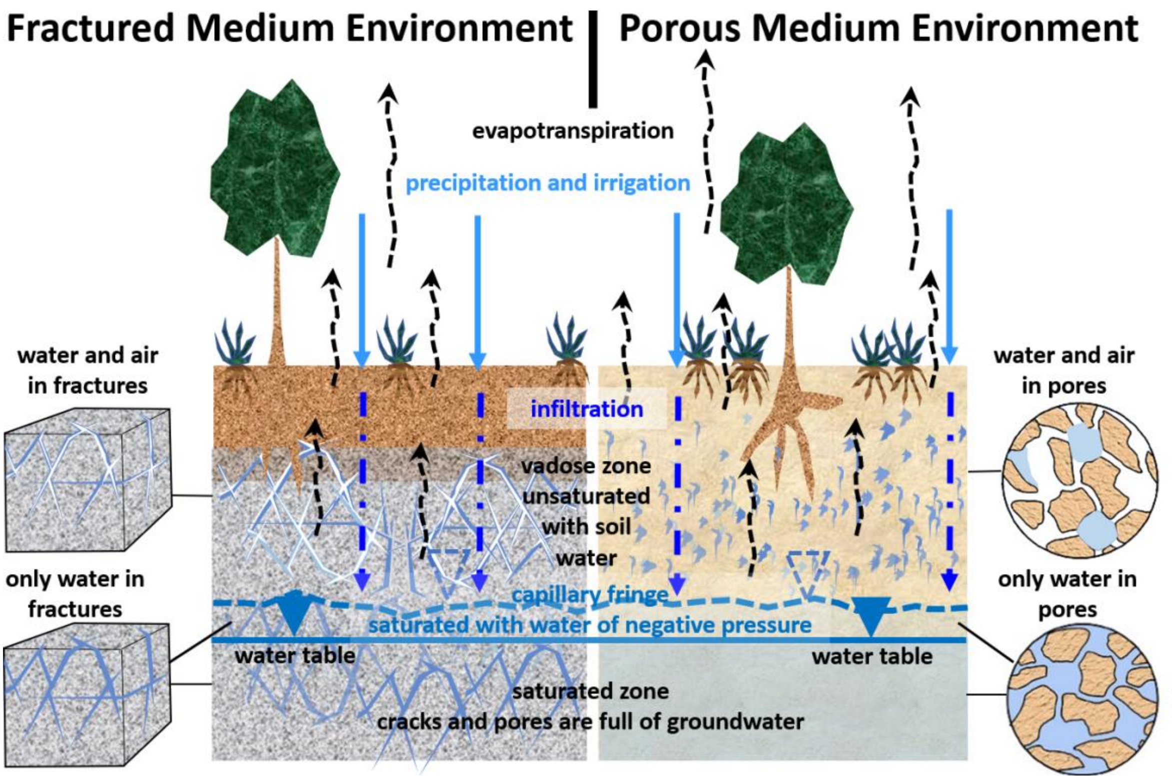

Figure 10 - Schematic showing infiltration through the unsaturated zone to the capillary fringe and the water table, where it recharges the groundwater. Water in the unsaturated zone generally moves downward as infiltration (blue arrows) or upward as evapotranspiration (black arrows) thus flow is often envisioned as one-dimensional even though there are localized areas of lateral water movement (Poeter et al., 2020, gw-project.org).

Water from a short rain event only infiltrates to a shallow depth, but long, gentle rains infiltrate deeper, sometimes reaching the water table (solid horizontal line marked with a filled triangle in Figure 10) where it becomes groundwater recharge. Although there are localized areas of lateral water movement, flow is primarily one-dimensional in the zone above the water table.

Below the water table, the fractures and pores are filled with water and the water pressure is greater than the atmospheric pressure (positive gauge pressure). In contrast above the water table, the pores and fractures are filled with a mixture of water and air and the water pressure is less than the atmospheric pressure (negative gauge pressure).

The zone above the capillary fringe is called the unsaturated zone because soil pores are only partially filled with water; it is also called the vadose zone (Figure 10). Even though the subsurface material may be rock or sand (that is, may be different from surficial soil) the water in the vadose zone is often called soil water in order to differentiate it from groundwater in the saturated zone below the water table. Soil water is indicated as blue shapes throughout the vadose zone in Figure 10. The negative gauge pressure of water in the vadose zone are due to capillary forces.

Near the water table, capillary forces create a capillary fringe (Figure 10) in which the pores and fractures are completely full of water but the water pressure is negative. The capillary fringe extends a few tens of millimeters above the water table in large pores such as in sand deposits, and several meters above the water table in small pores such as in clay deposits or small hair-line fractures in rocks. Although the capillary fringe is saturated with water like the groundwater zone, it is considered part of the unsaturated zone because the water has negative pressure. This is why the term vadose zone includes the capillary fringe.

When the soil water reservoir is filled to the point that no more water can be held by capillary forces, gravity pulls the extra water downward to reach the water table. This process is referred to as groundwater recharge because infiltrated precipitation is replenishing the groundwater reservoir. The groundwater is recharged only where and when there is a soil water surplus. The recharged water is stored in the groundwater system as it slowly flows toward discharge locations.

Capillary forces have less influence when the subsurface is wetter, so water is more likely to migrate down to the water table when the shallow subsurface contains more moisture. Consequently, in the wet and cool seasons, or during periods of steady rain or snowmelt, infiltrating water can reach the water table and add water to the groundwater reservoir. Cleary, not all rain events recharge the groundwater reservoir; most events only wet the vadose zone, replenishing the soil water reservoir and being consumed by transpiration of the vegetation. The timing and magnitude of recharge reaching the water table depends on the soil properties and depth of the water table as well as the duration and intensity of precipitation as illustrated by the rise of the water table following precipitation (Figure 11).

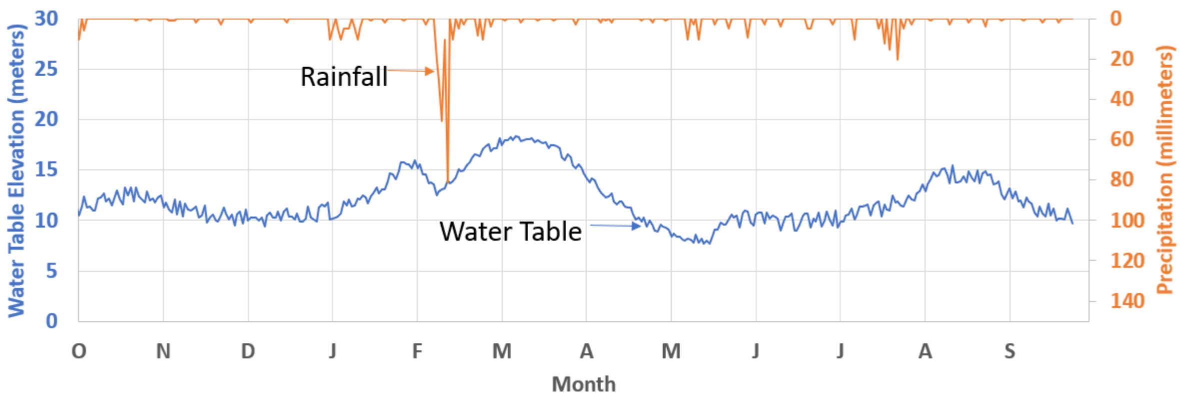

Figure 11 - Example of timing of precipitation and water table rise and fall. Precipitation amount is shown on a reverse axis such that larger precipitation events have a larger downward spike. Water table rise is typically delayed (notice, in this case, the water table peaks about a month after the precipitation occurs) and the elevated water levels are longer lived than the precipitation event. Other factors such as local pumping influence water table elevation, so correlation between major precipitation events and water table elevation is not one to one (Poeter et al., 2020, gw-project.org).

Vegetation on land (terrestrial vegetation) uses the vadose zone reservoir for water supply. Plant roots occupy this zone because it contains air, and oxygen is essential to root respiration (much like our breathing). Plants draw soil water into their roots by lowering the effective water pressure in their roots to enhance the movement of soil water into the plant.

In arid areas, the shallow groundwater may contain too much salt for most types of vegetation to grow, so the vegetation will consist of only salt tolerant plant species. Also, in arid areas, some plants, called phreatophytes, grow their roots deep enough below the surface to tap groundwater. Examples of phreatophytes include cottonwood, willow, eucalyptus and Russian olive trees; brush such as salt cedar; and crops such as alfalfa. Phreatophyte roots commonly extend to depths up to 15 meters, however, some salt cedar roots have been found to extend to 30 meters depth along the Suez Canal.

There is a significant awareness that the introduction of some animal species from one continent to another (e.g., rabbits brought from England to Australia) can result in an extreme ecological imbalance. However, there is far less awareness of the effect that the introduction of non-native, groundwater-consuming vegetation (e.g., eucalyptus trees from Australia; salt cedar from Eurasia and Africa) has on dry regions of other continents. Such plants can become unwanted groundwater consumers, affecting native plants and agriculture.

4.2 The Deeper View

Once the infiltrated precipitation reaches the water table, the water table rises. Gravity causes groundwater to flow laterally from locations where the water table elevation is higher to locations where the water table is lower as shown on the cross-sectional face of Figure 12. The brown frame on the vertical face of Figure 12 places the earlier view of one-dimensional flow through the vadose zone (Figure 10) into a larger, two-dimensional spatial flow pattern. Groundwater flow occurs in three-dimensional patterns, but first we consider flow a two-dimensional cross section to simplify visualization and discussion.

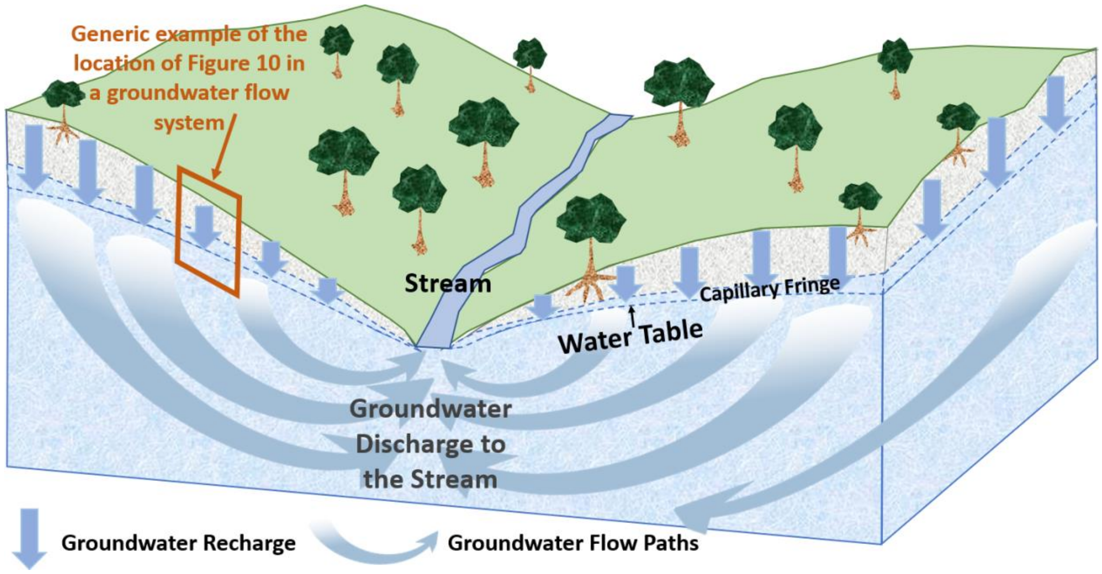

Figure 12 - After water recharges the groundwater system, the sloping water table moves water laterally from hills to valleys where it seeps out into streams. The inset window places the one-dimensional flow of Figure 10 with in a broader spatial context (Poeter et al., 2020, gw-project.org).

The water table is higher beneath upland areas because the precipitation entered the land at a higher elevation, and the groundwater flows downward into the groundwater system and toward the lowlands. The rate of water flow from the uplands to the discharge area depends on the rate of recharge (water infiltrating to the water table), the elevation difference between recharge and discharge areas, and the permeability of the soils and rocks through which the groundwater is flowing. If there is a drought, the water table in the uplands declines because water is flowing toward the stream and not being recharged by infiltration at the surface, thus water that is stored in the pores or fractures of the geologic units is released and the water table is lowered. When the upland water table declines, the rate of groundwater flow toward the streams slows, but water continues to discharge to the stream until the water table drops below the streambed surface.

A piezometer is a small-diameter well that is open to the inflow of groundwater over a short section of its length. The elevation of the water surface in a piezometer relative to sea level is known as hydraulic head (often simply called "head"), which is a measure of the potential energy of the water.

Groundwater flows from points with high hydraulic head (high potential energy) to points with low hydraulic head (low potential energy). As water that recharged the water table beneath an upland moves downward and toward lowlands, it loses energy due to friction between the moving water and the aquifer framework so the hydraulic head declines along the flow path as the potential energy is converted to heat, though the heat is too small to be measured.

The flow system on the front face of Figure 12 represents an idealized cross section with flow moving along a section perpendicular to ridges on the left and right to a stream valley in the center. Water infiltrates at the ground surface and percolates down to the water table, then flows in paths with combinations of downward, lateral, and upward components of flow to discharge at the stream. This is an "idealized" view because all the flow appears to occur in the plane of the drawing. That is, flow is two-dimensional with water entering and exiting only at the top boundary and no water moving into, or out of, the plane of the page. In natural settings, groundwater flow is three-dimensional, as illustrated in the schematic of Figure 13. Blue dashed lines in Figure 13 connect locations of equal hydraulic head and solid blue arrows represent groundwater flow moving down the hydraulic head gradient. Conceptually, Figure 12 follows the thick white line cutting perpendicular to the stream in Figure 13. Although Figure 12 indicates that flow is perpendicular to the ridge and stream, in a natural system flow is not perpendicular to them as shown in Figure 13. That is, components of flow enter from the upgradient areas in the foot hills and exit to down gradient areas of the plains.

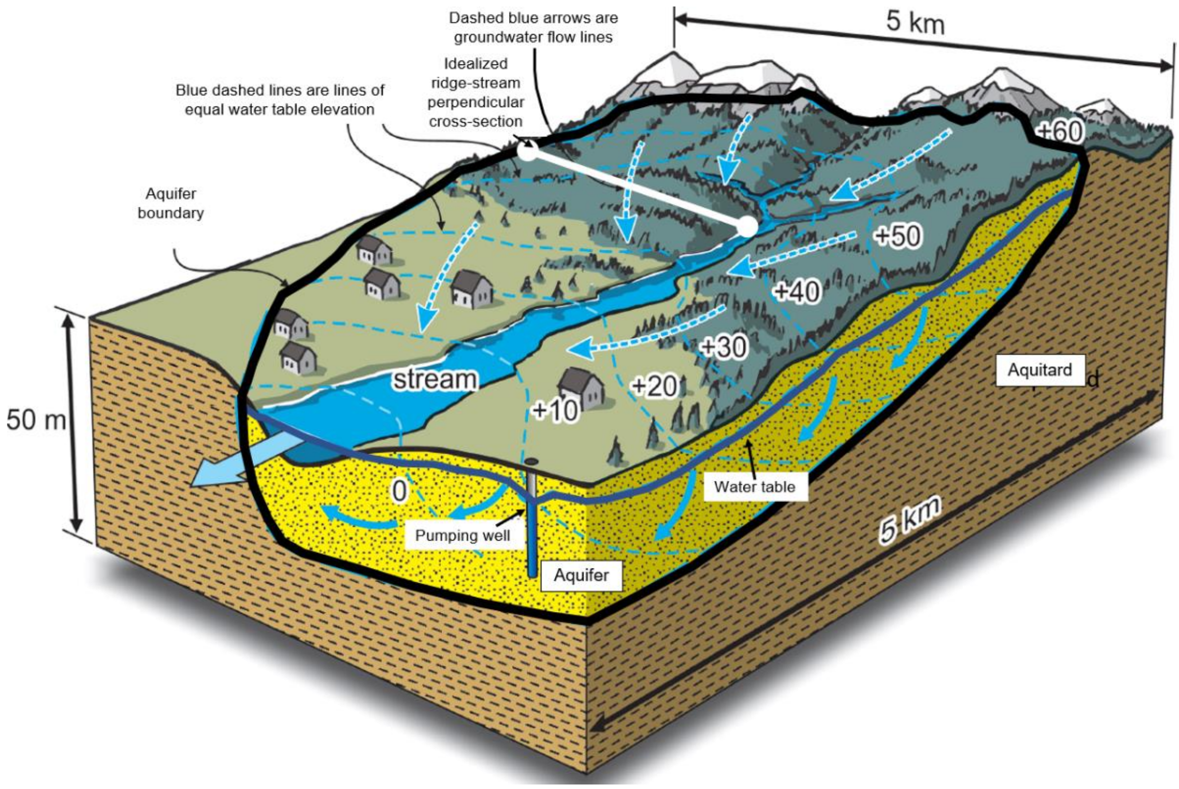

Figure 13 - Groundwater flow is three-dimensional as shown in a groundwater basin (outlined in black, with the water table as a thick dark blue line, thin dashed blue lines of equal hydraulic head in three dimensions, and dashed blue arrows showing groundwater flow directions). The two-dimensional diagram of Figure 12 represents flow along a cross section that is perpendicular to the ridge and stream as indicated by the thick white cross-section line. Although Figure 12 represents the general pattern of flow from ridge to stream, it ignores the flow into and out of the front and back faces of the section in the three-dimensional field setting, thus Figure 12 is an idealized concept of groundwater flow (modified from Rivera, 2014).

This lateral flow from hills to valleys is important. The water table in a valley is closer to the surface than in the uplands and does not rise and fall as much as water tables under uplands, because it is regulated by the recharge over the entire hillslope above it. If it does not rain for many days, the hills may be parched, but the valleys are still receiving groundwater from the uplands, because groundwater flow is relatively slow. In dry times, the groundwater recharge on the hills from many days, or even many years, ago is still "on its way" toward the valleys. Thus, the delayed delivery of groundwater from the hills to the valleys ensures that the valleys will receive water in dry times.

As such, the groundwater system is similar to a bank account, water is stored under the hills as "funds in an account" that steadily sends "cash" to the valleys, through a slow "postal service", arriving in the valley when it is not receiving "cash from local customers". Thus, the valley has a steady income, so it is prepared for lean times. This is part of the reason why trees in the valleys are larger and healthier than the trees on the hills in places that have long dry seasons.

Groundwater Connection with Landscape

The depth of the water table is partly responsible for different plant species occupying different positions along the slopes from hill to valley, as only the drought tolerant plants can live on the hills in arid regions and water tolerant plants live near streams (Figure 14). In lowland discharge areas of arid climates, water is lost to the atmosphere by evapotranspiration causing salt to accumulate. Such settings develop salt-tolerant vegetation.

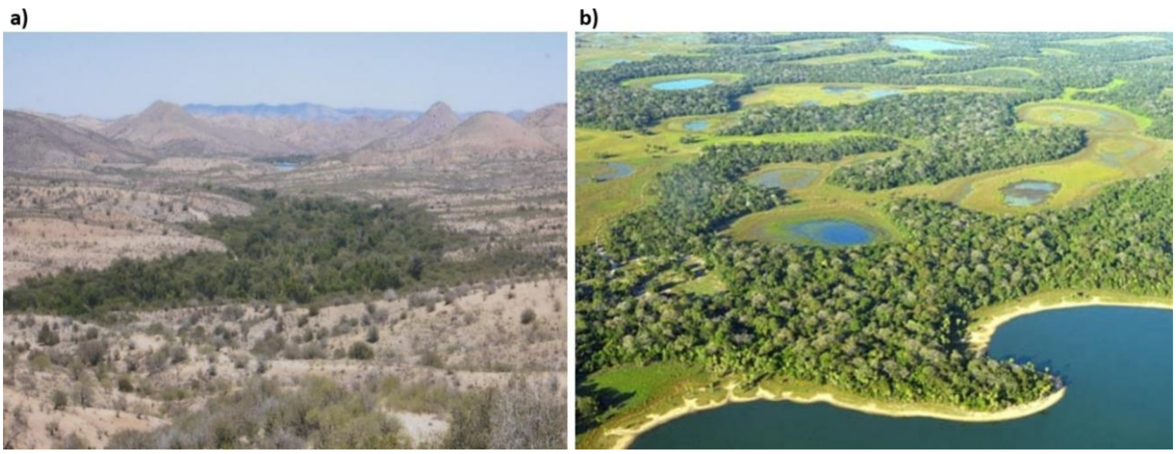

Figure 14 - The depth to the water table can influence the types of vegetation growing in a place. a) In a water-stressed environment such as Arizona, United States (left image), trees grow along the stream corridor where the water table is shallow, while desert shrubs and grass grow on the hills where the water table is too deep for plant roots to reach (The Old Pueblo, 2014. "Riparian Forest along Sonoita Creek, southwest of Patagonia Lake, part of which can be seen in the center of the photo↗" by The Old Pueblo is licensed under CC BY-SA 4.0↗). b) In places with too much water such as the Pantanal wetlands in Mato Grosso do Sul, Brazil, trees are found on hills where their roots have room to grow in the oxygen-rich unsaturated zone above the water table, whereas near the lake shores, the groundwater table is so close to the ground surface that tree roots can't get sufficient oxygen because there is little if any air in the pores of the soil (Wikimapia, 2020. "Pantanal Mato-Grossense National Park↗" by Wikimapia↗ is licensed under CC BY 4.0↗).

The water table occurs everywhere beneath us and when humans change the landscape shape, the vegetation, or purposefully drain groundwater for farming and construction, we change the depth to the water table. This often has problematic consequences for humans and ecological systems. However, we are able to predict consequences before we make changes so as to make informed decisions about our actions. Depending on the predicted consequences, we may decide not to proceed or we may redesign the changes to reduce the adverse effects.

The depth of the water table can have a strong impact on how the land responds to heat. For example, in hot dry areas of Australia where eucalyptus trees are the native vegetation, the natural position of the water table is deeper below land surface than after the eucalyptus trees are cleared for crops. This occurs because the trees consume soil moisture capturing infiltrating water, resulting in minimal groundwater recharge. After the trees are cleared, the crops consume less groundwater so recharge increases and the water table rises. When the water table is near the ground surface, water evaporates leaving dissolved substances behind to form salt precipitates that accumulate in the soil rendering the land unfit for crops. Soil salinization is a cause of cropland loss each year around the globe. In many agricultural regions, management of land use to avoid salinization is key to agricultural productivity.

Another example of water table depth influencing the landscape is the occurrence of wildfires as described by Elbein (2019) in his Pulitzer Prize winning National Geographic article "Tree Planting Programs Can Do More Harm Than Good." He explains that a shallow water table in wetlands can make the difference between normal wildfires and infernos that cause massive destruction. This was the case in the Fort McMurray wildfire in Alberta, Canada, in 2016, which was the costliest wildfire in Canada's history. Mossy bogs, a type of wetland known as a peatland, cover an immense part of northern Canada and Russia. Peat is composed of partially decayed organic material such as moss. Peatlands contain large amounts of carbon that is gradually sequestered from the atmosphere over thousands of years. As peat forms, it supports fewer of the typical trees (black spruce in the Alberta case). With fewer trees, more recharge reaches the water table so the water table moves closer to the surface. The shallow water table makes the peatland resilient after wildfires. Peatlands commonly experience low-intensity fires and are able to recover the carbon lost during the fire in a relatively short period of time because the shallow water table prevents the fire from burning deeply into the peat. When peatlands were drained for the purpose of creating a spruce forest in the Fort McMurray area, an environmental adjustment occurred: the black spruce trees used more water, the water table declined, the shallower peat was replaced by a drier moss species (kindling instead of fire retardant), the large trees became a huge store of fuel, and then the Fort McMurray wildfire ensued. Intensely burned peatlands require long periods of time to recover the carbon released to the atmosphere by the fire (Figure 15). The media attributed this fire to the extremes of nature related to climate change without recognition that human intervention in the shallow groundwater flow system played a key role in the event.

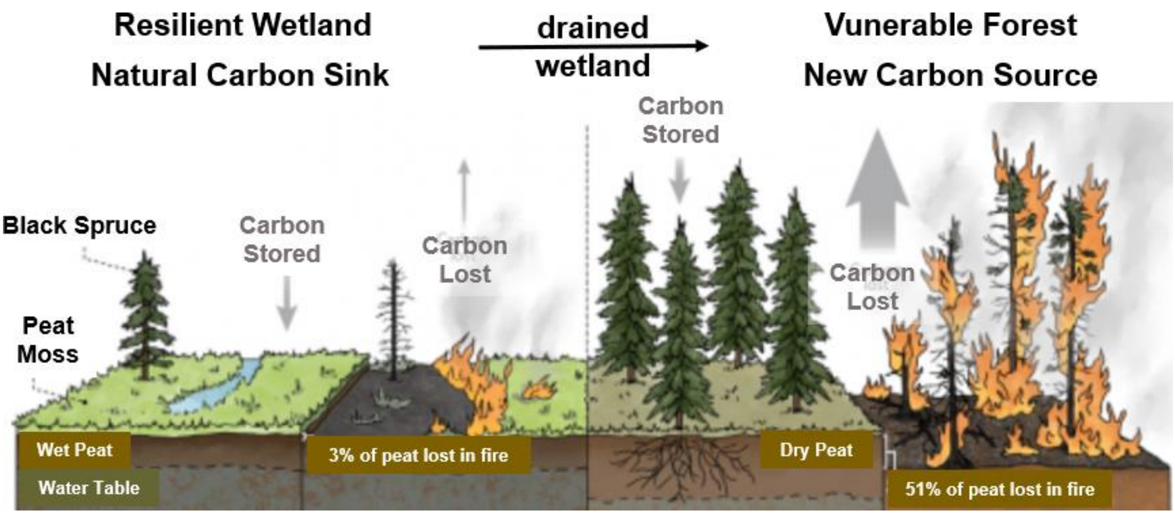

Figure 15 - Scientists studied the landscape after the 2016 Fort McMurray Fire and found that where the water table was lowered by humans beneath peatlands so they could plant a black spruce forest, the fire was more intense and burned deeper, causing large loss of carbon that took 1000s of years to store (after Elbein, 2019; image Wilkinson, 2018).

Groundwater Connection with Streams

The upland to lowland movement of groundwater continues if the water table under the hills is higher than the water level in, or under, the streams. Sections of streams that receive groundwater are called gaining streams (Figure 16a). As seen from the point of view of a rafter floating down a stream, gaining streams carry an increasing volume of water (becoming wider and/or deeper and/or flowing faster) with distance down the stream. This is the primary mechanism for groundwater to discharge to the surface. Water that enters a stream from the groundwater system sustains baseflow of the stream. In locations where the water table is deeper than the elevation of the water surface in the stream, water flows from the stream into the subsurface. Sections of streams where water seeps into the subsurface are called losing streams (Figure 16b and c). From a rafter's viewpoint when floating down the stream, losing streams carry a decreasing volume of water, its discharge decreases with distance down the stream (becoming shallower and/or narrower and/or flowing slower) and may eventually become a dry streambed (Figure 16d). Streams that go dry during some periods, such as arroyos in the southwestern United States, are called intermittent or ephemeral streams. Streams that gain essentially all the time because there is enough recharge to store sufficient groundwater to support outflow to the stream throughout dry periods are called perennial streams.

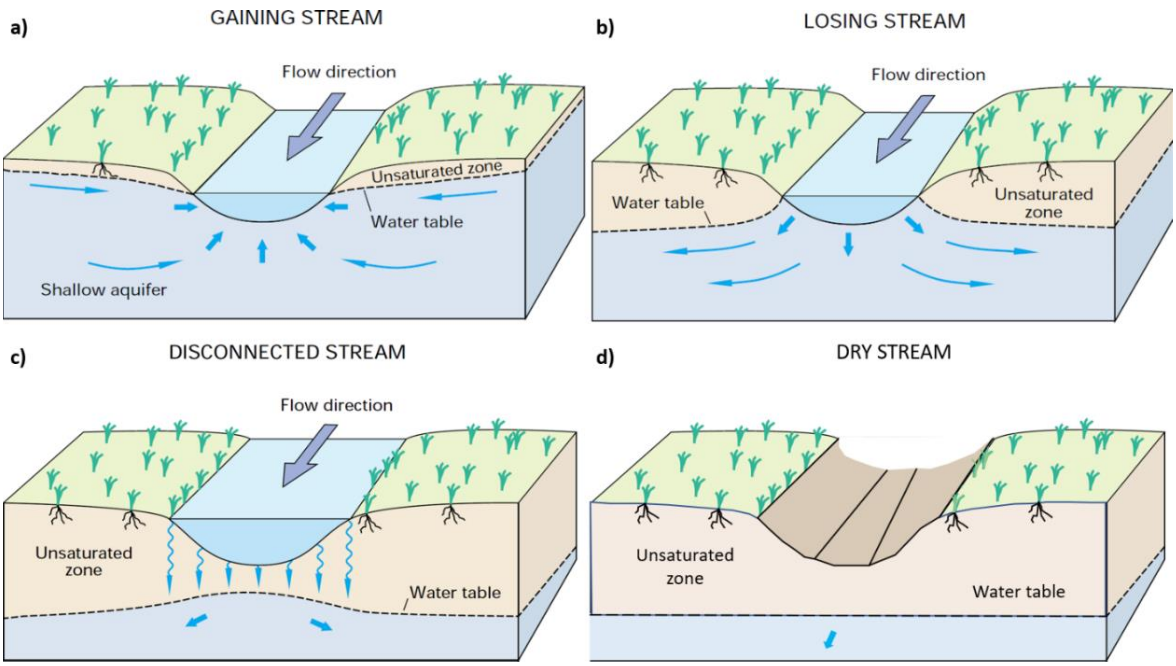

Figure 16 - Schematics of a) gaining, b) losing, c) disconnected-losing, and d) dry streams (adapted from Winter et al., 1998).

Water flowing in streams is a combination of components contributed by:

- precipitation that flowed over land;
- infiltration that flowed through temporarily saturated soil zones above the water table (called interflow or quick flow);
- groundwater discharge; and,
- human activity (primarily flow from storm water sewers, point discharges from industries and water-treatment plants, and agricultural drainage).

Groundwater discharge to streams is the primary reason that streams do not run dry despite days to months without rain. The flow continues because water recharged to the groundwater system long ago and far from the stream, flows slowly and steadily toward the stream.

Although the proportions of natural components of stream flow vary depending on local climate and geology, globally approximately half of the water flowing in rivers is from long-term flow through the persistently saturated portion of the groundwater system discharged to the river, and half is from storm runoff over the surface or through shallow temporarily saturated layers. Some storm runoff occurs over the ground surface, though most storm runoff flows through the shallow subsurface, often initiated in the vadose zone via temporary saturated zones perched on low permeability layers. The zone of the capillary fringe near streams can provide a component of interflow when infiltration reaches the capillary fringe, changing the zone from a state of negative water pressure to positive pressure. In this case the water held in the capillary fringe is mobilized and the water moves rapidly to the stream. This phenomenon is known as the capillary fringe effect.

It is useful to note that some hydrologists refer to the flow in stream channels as runoff, but here we call that flow stream discharge while the term runoff is reserved for storm water making its way to streams either by flowing over the ground surface or through shallow temporality saturated soil layers.

A segment of a stream, such as shown in Figure 16, can be gaining on one day or in one season and losing on/in another, all depending on the relative water level between the stream and the surrounding water table. Conditions along a stream's length may vary between gaining and losing many times. The water flowing at a location in the stream depends on two conditions. First, it depends on precipitation and/or snowmelt that occurred, perhaps many days ago, in upgradient portions of the area drained by the stream that flowed to and then along the stream channel. Second, it depends on the level of the water table directly below the stream. The water table below the stream may be high due to strong groundwater flow or it may be depressed due to drought or to heavy use by phreatophytes near the stream. Therefore, near the stream, the elevation of the stream water and the elevation of the water table can rise and fall for different reasons, and at different tempos, depending on both the local and distant weather, climate, vegetation, and terrain.

The continuous, dynamic, two-way exchange between groundwater and surface water bodies illustrates the close connection between groundwater and surface water. At one moment a water molecule belongs to the groundwater reservoir, and at the next moment, it belongs to the surface water reservoir, only to return to the groundwater again. Appreciating this groundwater-surface water continuity is important for managing our water resources.

Losing streams play an important role in recharging the groundwater reservoir in arid basins. In many arid regions of the world, the surrounding mountains receive more precipitation than the valleys, supplying water to the mountain streams. Upland stream beds are often higher than the water table. Where these streams flow out of the mountains and over sediments on the dry valley floor near the mountain front, they lose their water, thereby recharging the groundwater as shown in Figure 17. The lack of direct precipitation on the valley floor renders groundwater in such areas precious. The shallow water table in these dry valleys can result in gaining streams, as well as support plant and animal life that would otherwise be impossible as shown in Figure 17.

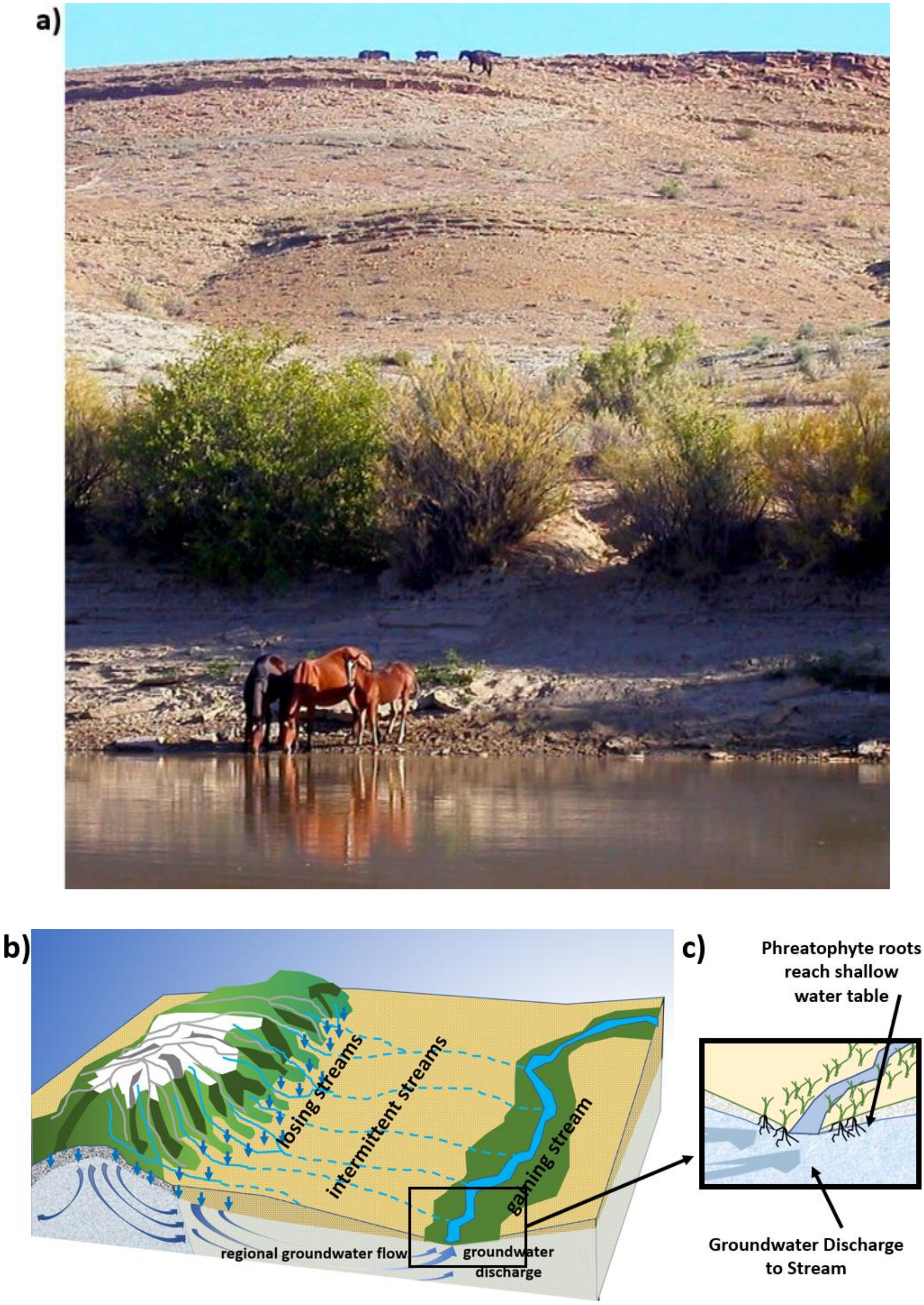

Figure 17 - The shallow water table in dry valleys is the result of discharging groundwater that was recharged in distant uplands. This discharge supports plant and animal life that would otherwise be impossible: a) salt cedar drives roots deep enough to draw water directly from the shallow water table near the river and feral horses are able to survive because of regional groundwater discharge to the Green River in Utah, United States (photo by Leitz, 2009); b) losing streams near mountain fronts contribute recharge to the groundwater system that flows long distances to discharge in the river of this arid region; and c) schematic showing the shallow water table near the river is tapped by the roots of phreatophytes (Poeter et al., 2020, gw-project.org).

Humans in arid areas have tapped into this type of groundwater resource since ancient times by digging shafts into the mountains with long, low-slope tunnels for conveying water to the desert plains and developing large, thriving agriculture-based civilizations (Figure 18). Known as a Qanat or Kariz, these structures were first created about 3000 years ago in the Middle East.

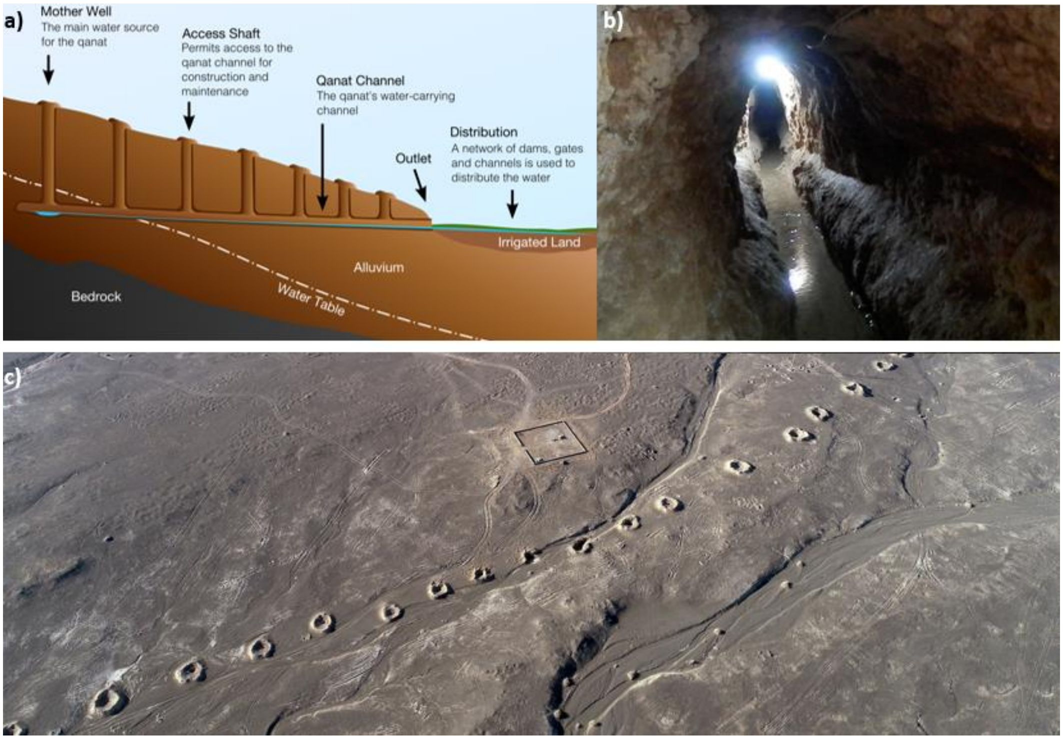

Figure 18 - Ancient cultures constructed Qanats to bring water from the mountains to the desert: a) Qanat schematic (Bailey, 2009. "A cross section of a typical qanat↗" by Samuel Bailey↗ is licensed under CC BY 3.0↗); b) photo inside a qanat (Naeinsun, 2012. "A qanat tunnel near Isfahan, Iran↗" by Naeinsun is licensed under CC BY-SA 3.0↗); and c) Qanat system in Xingjiang, China (panoramastock.com, 2020).

In some places, humans divert water directly from streams, often for irrigation. When water is diverted from a losing stream, the human diversion deprives the groundwater system of recharge that it would have received from the stream.

Groundwater Moderation of Stream Temperature

The delayed arrival of groundwater recharge at streams provides a reliable source of water for the gaining streams of the world. This is important for the health of aquatic ecosystems, because fish and aquatic plants that form the base of the food chain for many animal species would not be able to live in a stream that runs dry as soon as the rain stops. The steady seepage of groundwater into streams also regulates stream temperature, because the groundwater is insulated from daily (and seasonal) heating and cooling of the atmosphere. Consequently, its temperature does not vary as much as the surface temperature as shown in Figure 19.

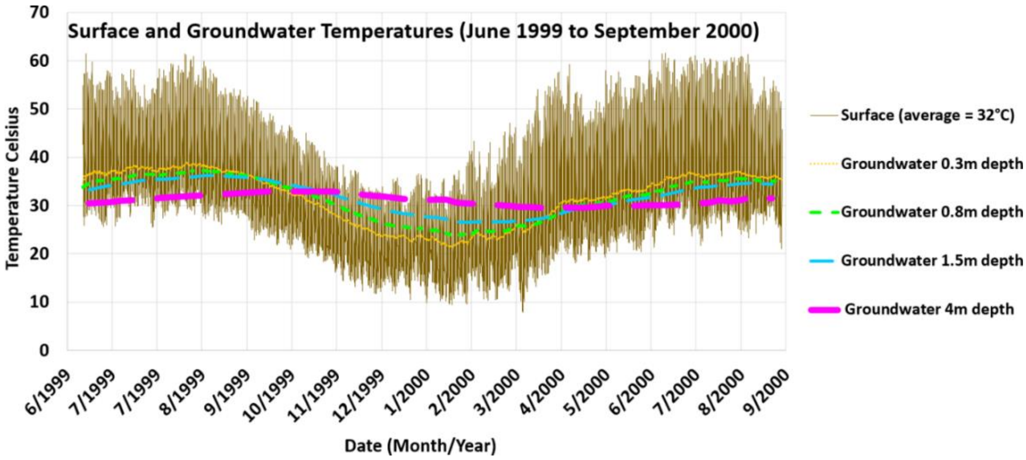

Figure 19 - Shallow groundwater temperature varies seasonally, but not nearly as much as surface temperature. The magnitude of variation in temperature decreases with depth. Also, with depth (from yellow to green, blue, and pink, each with a longer dash), the peak warm and cool temperature of the groundwater exhibits larger delay from the peak surface temperatures. At intermediate depths (e.g. 4 meters, thick, pink) groundwater temperature is fairly constant at a value near the average annual temperature at the surface (32℃ at this location). Generally, the temperature of groundwater deeper than about 10 meters is higher than the mean surface temperature because it is warmed by the geothermal energy emanating from the core of the Earth (Poeter et al., 2020, gw-project.org).

Thus, groundwater discharging to a stream is cooler than the stream water in summer and warmer in winter as illustrated in Figure 20. The warmer groundwater beneath the stream prevents freezing of the stream bottom. Again, this is important to fish and other aquatic life, many of which survive in only a narrow range of temperature. The groundwater seeping in through the bottom of a stream or lake may contain oxygen, and hence be favorable for fish to lay eggs, or the water may be devoid of oxygen (anoxic) and thus unfavorable for fish. Anoxic conditions may develop because of land-use changes in recharge areas such as soil compaction, paving or disposal of organic wastes.

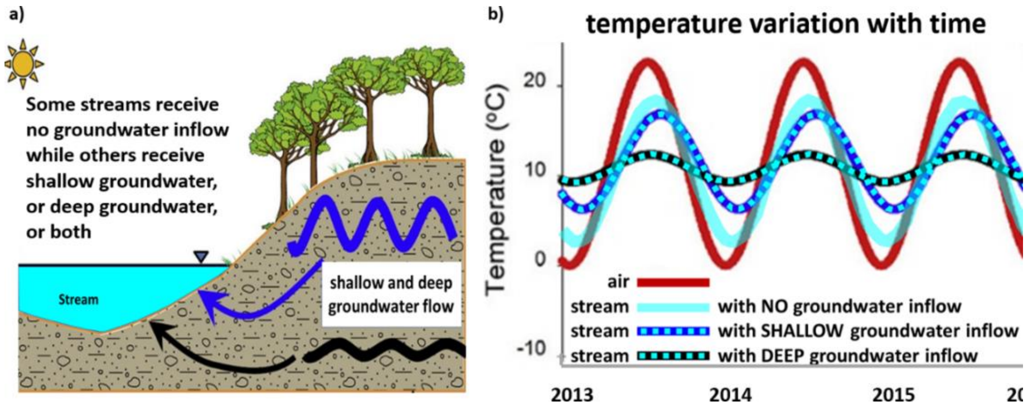

Figure 20 - Schematic of the relationship of air, stream, and groundwater temperatures: a) some streams receive no groundwater inflow, others receive shallow groundwater inflow, or deep groundwater inflow, or both; b) fluctuation of air temperature (red) is more extreme than the water temperatures, with a stream that does not receive groundwater having a slightly subdued fluctuation of temperature (light blue) relative to ambient air temperatures, a stream that receives shallow groundwater inflow having more subdued temperature fluctuations (dashed light and dark blue), and a stream that receives deep groundwater having the most subdued temperature fluctuations (dashed light blue and black) (adapted from Briggs et al., 2018).

Groundwater Connection with Springs

Springs are fed by discharging groundwater. They occur where the water table intersects the ground surface. They may form at a depression in the ground surface along a slope that intersects the water table as in Figure 21a, or they may form where a geologic unit of lower permeability perches (traps) water above the groundwater table as illustrated in Figure 21b.

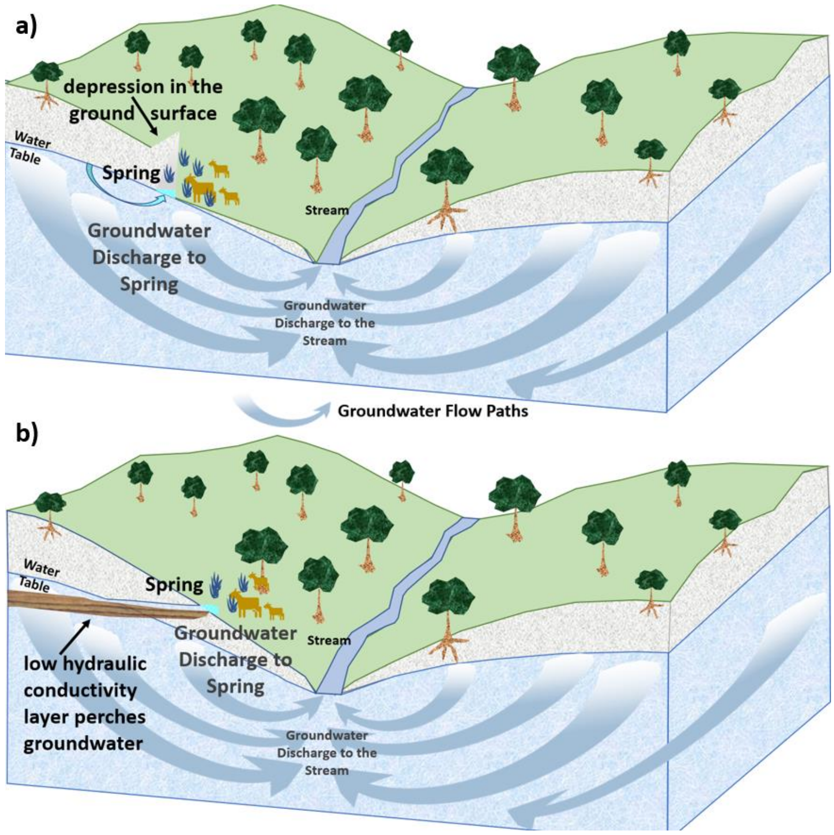

Figure 21 - Springs occur where the water table intersects the ground surface: a) at a depression in the surface topography; or, b) where a geologic formation perches groundwater and outcrops at the surface (Poeter et al., 2020, gw-project.org).

Springs have been an important part of human history, and today springs provide drinking water for more than a hundred million people and to businesses that bottle water. Huge springs supplied water to the aqueducts of early Rome and still supply Rome's water today. Oases (desert springs) were the source of water along much of the Silk Road trading route between China and Europe. The North Silk Road crossed the Badain Jaran Desert in China (the 4th largest desert of Earth) where, even today, over 100 groundwater-fed lakes are springs nestled within the largest sand dunes in the world (Figure 22 and Figure 23). These lakes maintain the vital oases and ecology in the desert. Similarly, long-distance groundwater convergence toward, and discharge as springs in, the Great Rift Valleys of eastern Africa has been hypothesized as the life support system for societies of early human ancestors despite centuries-long droughts.

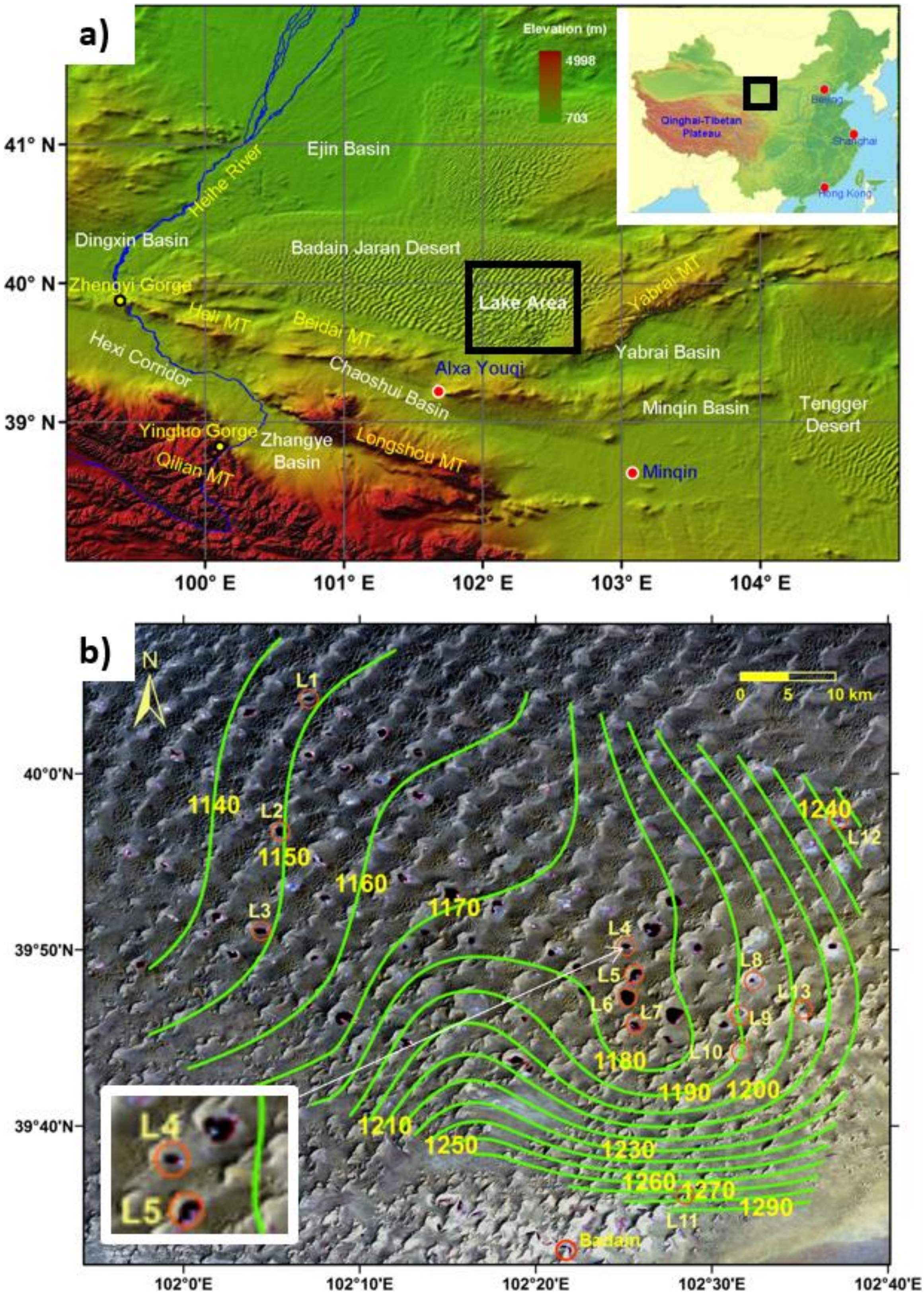

Figure 22 - Groundwater springs form lakes among the earth's tallest sand dunes in the Badain Jaran Desert of China. These lakes range from fresh to extremely saline, and maintain the vital oases and ecology in the desert. a) Location of the Badain Jaran Desert and the lake area (Jiao, 2015); (b) Landsat Thematic Mapper image of the area including most of the lakes in the desert on May 24, 2003, with 10m groundwater contours estimated from ICESat (Ice, Cloud, and land Elevation satellite) data (Jiao, 2015).

Figure 23 - A photo of one of the lakes within the sand dunes of the Badain Jaran Desert of China (Jiao, 2017).

The discharge of some springs is much warmer than other surface waters in the same locale. In these thermal springs, groundwater flows to a depth where it is heated either by molten subsurface rock associated with volcanic activity or by deep rocks that are warmed by heat conducted from the cooling core of the Earth to its surface. Density of the water decreases as it is warmed, so the water rises, and when it reaches the surface it manifests as a hot spring. Hot springs are generally located near geologically recent igneous activity as indicated by their frequent occurrence in the tectonically active western portions of North America as shown in Figure 24.

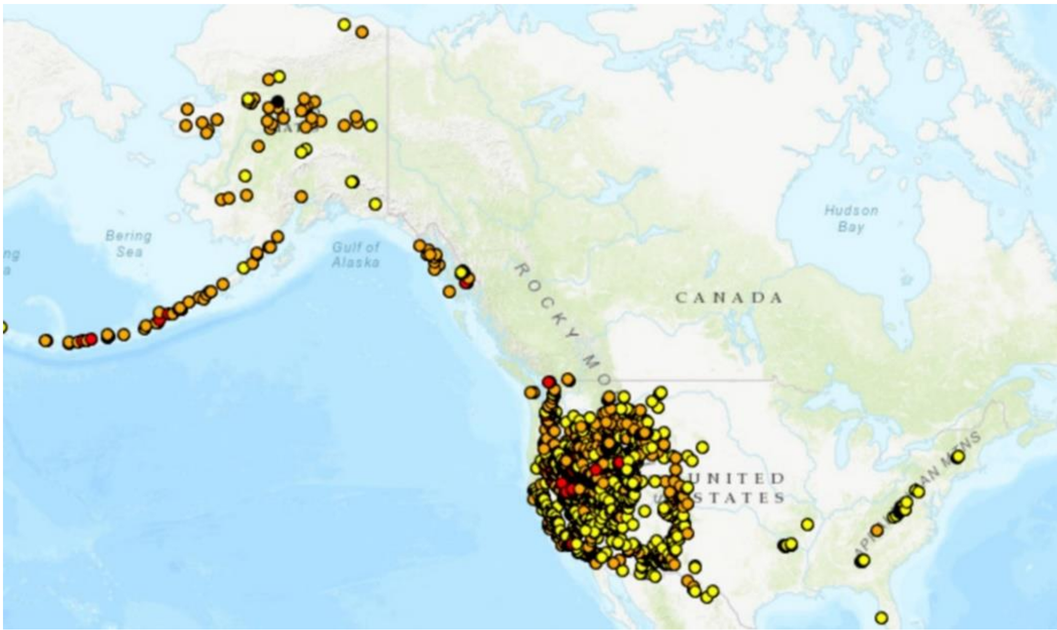

Figure 24 - Thermal springs generally occur near geologically recent igneous activity as indicated by this Google Earth map of thermal springs in North America (map from USNOAA, 2019; data from Berry et al., 1980).

Occasionally groundwater is heated at depth and has a direct conduit to the surface via a zone of fissures or a fault, forming a geyser that periodically ejects a large volume of water. Water cooled by ejection flows back into the reservoir where it is again heated becoming less dense and more pressurized by heated dissolved gasses. At some point the weight of the overlying column of water is insufficient to hold back the water and it erupts. These features (Figure 25) are not as common as thermal springs.

Figure 25 - The famous Strokkur geyser erupting in Iceland (Tille, 1996. "Eruption of Strokkur close by↗" by Andreas Tille↗ is licensed under CC BY-SA 3.0↗).

Groundwater and Wells

Humans bring another factor to the dynamic exchange of groundwater with the surface because they pump water from the subsurface using wells. Pumping lowers water levels near the well, causing water to flow out of storage and toward the well. This lowers water levels farther from the well, creating a cone shaped water level surface around the well. The difference of water level before and after pumping is called drawdown and the cone shaped water level surface is called a cone of depression, or a drawdown cone (Figure 26a and b). If pumping continues, the cone of depression grows until the inflows balance the volume pumped at the well. When the drawdown cone extends to a stream, stream water infiltrates through the stream bed into the groundwater system (Figure 26c).

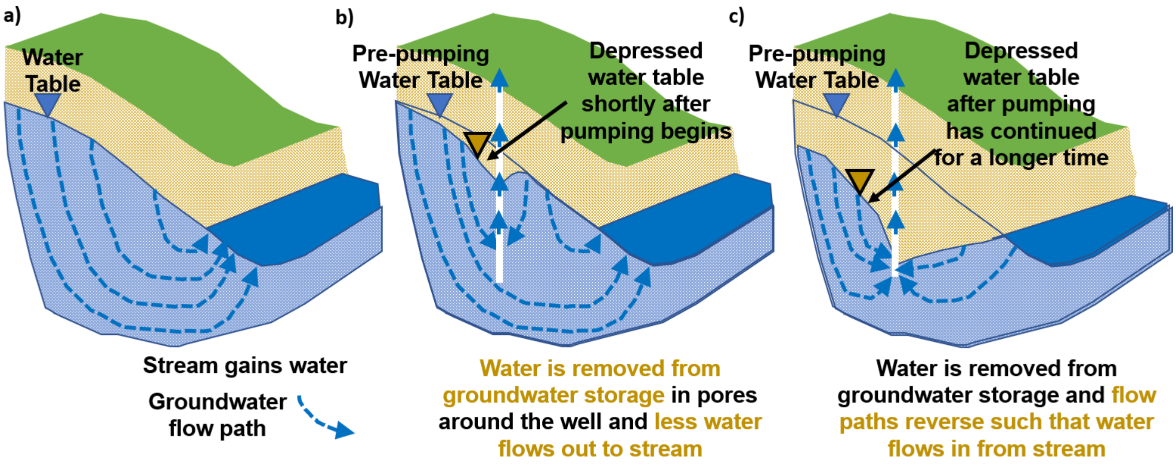

Figure 26 - Schematic showing that pumping water from a well near a stream depresses the water table: a) before pumping; b) shortly after pumping begins water comes from groundwater storage and less water flows toward the stream, decreasing flow in the stream; c) as pumping continues, the water table is depressed to the point that water flows from the stream to the well such that the stream discharge decreases further and the stream surface elevation is lowered (Poeter et al., 2020, gw-project.org).

Groundwater, unlike most other extractable resources, can be renewable. Thus, it is possible to develop a groundwater source that will last indefinitely, which is a highly desirable societal outcome. Groundwater, however, is a shared resource in which usage by one party may be highly beneficial to that party, but harmful to others and/or to the long-term viability of the resource. Thus, societal management is necessary to prevent the "Tragedy of the Commons" (the situation where the collective action of individual users of a shared resource, acting in their own self-interest, behave contrary to the common good of all users by depleting or spoiling the shared resource). The term sustainability has been proposed for such societal management. Sustainability in groundwater development is frequently interpreted as withdrawing less groundwater than is naturally recharged. This management approach is called safe yield. However, the expanding cone of groundwater depression can decrease existing evapotranspiration, induce infiltration from adjacent surface water, and capture water that would have discharged under natural conditions. If groundwater extraction is balanced by these sources, a new equilibrium is achieved and is referred to as sustained yield. Management based on sustained yield neglects the impact of extraction on the water resources that are connected to the system through the larger hydrologic cycle. A change to one part of the hydrologic cycle impacts other parts of the cycle and thus, may have cultural or legal implications.

Groundwater resources cannot be sustained if withdrawal of groundwater exceeds recharge to the groundwater system because groundwater levels will decline, and eventually the groundwater stored in the pores of aquifers and streams in the area will no longer be available. If the amount of water pumped exceeds the amount of recharge, the cone continues to expand and deepen until the aquifer is no longer a good source of water. An example of this is the excessive pumping of groundwater from the Ogallala aquifer in

Kansas, United States. This withdrawal in excess of recharge is called groundwater depletion, groundwater mining, or groundwater overdraft. The overuse of groundwater in Kansas, caused water level declines such that streams in an area of about 20 million hectares went dry as shown in Figure 27.

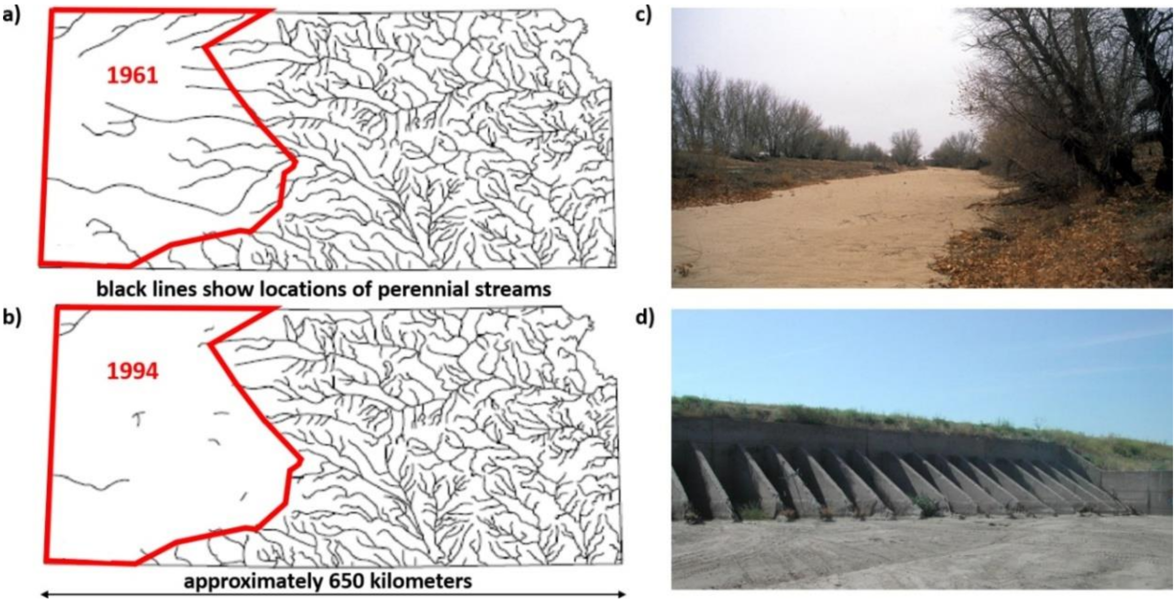

Figure 27 - Pumping of groundwater removed water from storage in the Ogallala Aquifer beneath Kansas, United States, lowering the water table to a level that caused a) perennial streams in 1961 (KGS, 1998) to b) dry up by 1994 (KGS, 1998) as pictured in c) (Charlton, 2018) and d) (USNWS, 2012).

Sometimes humans further complicate the hydrologic cycle by exporting water from one place to another. Occasionally this involves moving water through pipelines that transfers water from one drainage basin to another, but more often humans inadvertently move "virtual" water. Virtual water is the water contained in a product that arrives in one country but was grown, bottled or manufactured in another country, using water pumped from that country.

4.3 The Regional-Scale View

By zooming out further (Figure 28), the three-dimensional, regional, often layered, geologic units containing groundwater systems come into view. The geologic layers occur because: 1) sediments are laid down by water or blowing wind; and 2) sedimentary rocks, which cover about 73% of the upper continental crust, are consolidated so they retain their original layered structure. This layered structure is significant, because both the volume of groundwater storage and ease of groundwater flow differ depending on the porosity and permeability of the layers, creating a sequence of aquifers and confining units.

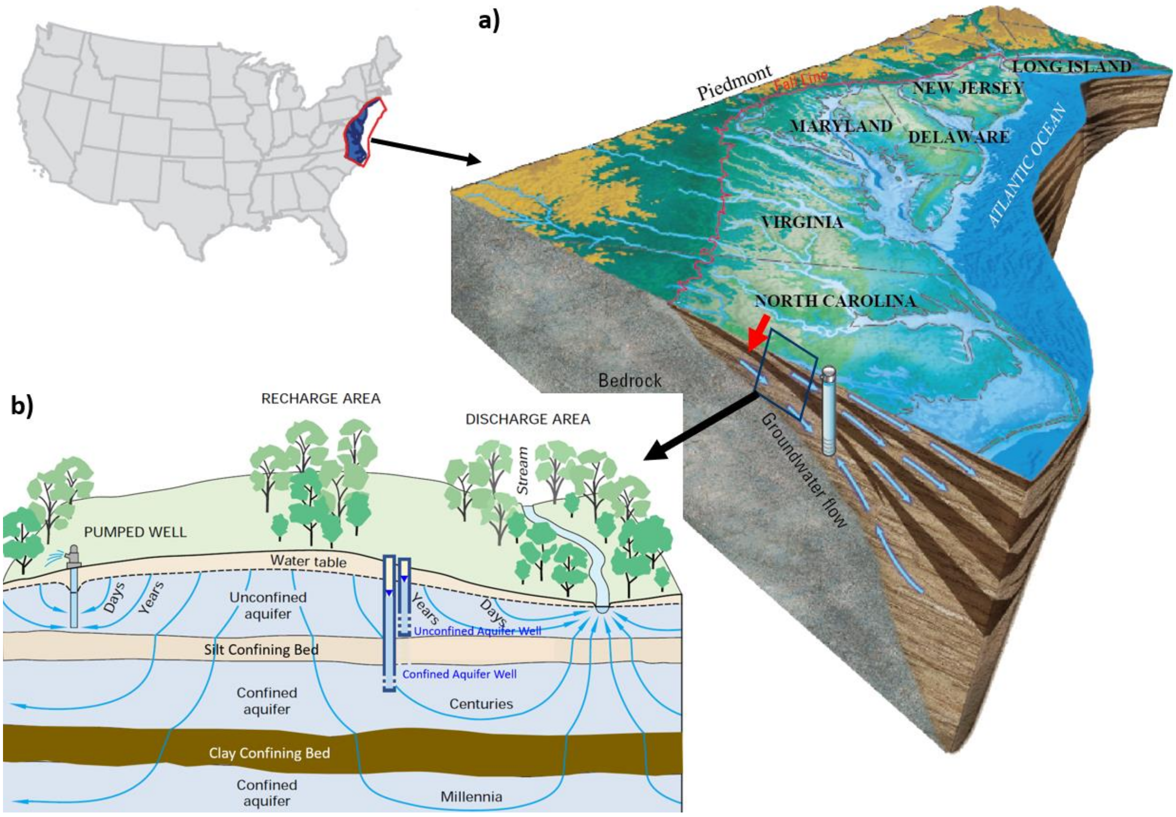

Figure 28 - Regional view of groundwater systems. a) The seaward dipping mid-Atlantic coastal plain sediments of the United States (adapted from USGS, 2019b), with the window framing; b) the local aquifers that are a small part of the larger regional groundwater system and showing layered aquifers and confining units (Winter et al, 1998, as adapted from Heath 1983)..

Aquifers and Confining Units

When drilling a well, at some point, saturated conditions will be encountered. This is the location of the water table, which is the top of the groundwater zone and the top of an unconfined aquifer. This groundwater is stored in an unconfined aquifer, and is labeled in Figure 28b as the aquifer right below the land surface. As drilling continues to greater depth, typically, the top of the first confining bed is encountered (Figure 28b). If the well is sealed with a pipe, so that the groundwater in the unconfined aquifer cannot seep into the well, and water is bailed out of the pipe, there will be an empty pipe with a muddy silt bottom. As drilling continues downward through the confining bed water cannot seep into the well fast enough to fill the pipe because the confining bed is made of low permeability silt or clay. At some point, the drill reaches the bottom of the confining bed and enters the sand layer below. Suddenly, water rapidly enters the borehole, and the water level rises to a level that is higher than the top of the underlying sand bed. This sand bed is another aquifer, because it is porous and permeable, but in this case the water level within the aquifer is higher than the top of the aquifer because the water is under pressure, so it is called a confined or artesian aquifer (Figure 28b). It is confined in the sense that the groundwater in this aquifer is being held in by the silt bed above it. Confining beds are not very permeable, and water moves slowly through them, thus an elevated water pressure is maintained in the underlying confined unit. When the well is drilled through the confining bed, the pressurized water within the confined aquifer flows up into the well casing to the level of the hydraulic head in the confined aquifer (Figure 29 provides a close-up of the wells in the confined and unconfined aquifers). In contrast, the water level in the upper aquifer is not confined by a low permeability bed above, and the water level in the well of this unconfined aquifer rises to the level of the water table. The unconfined aquifer is also called a water table aquifer because it contains the rising and falling water table. The higher water level in the well of the shallow aquifer in Figure 29 relative to the lower water level in the well in the aquifer beneath the confining bed indicates that water must be flowing downward through the confining bed at this location.

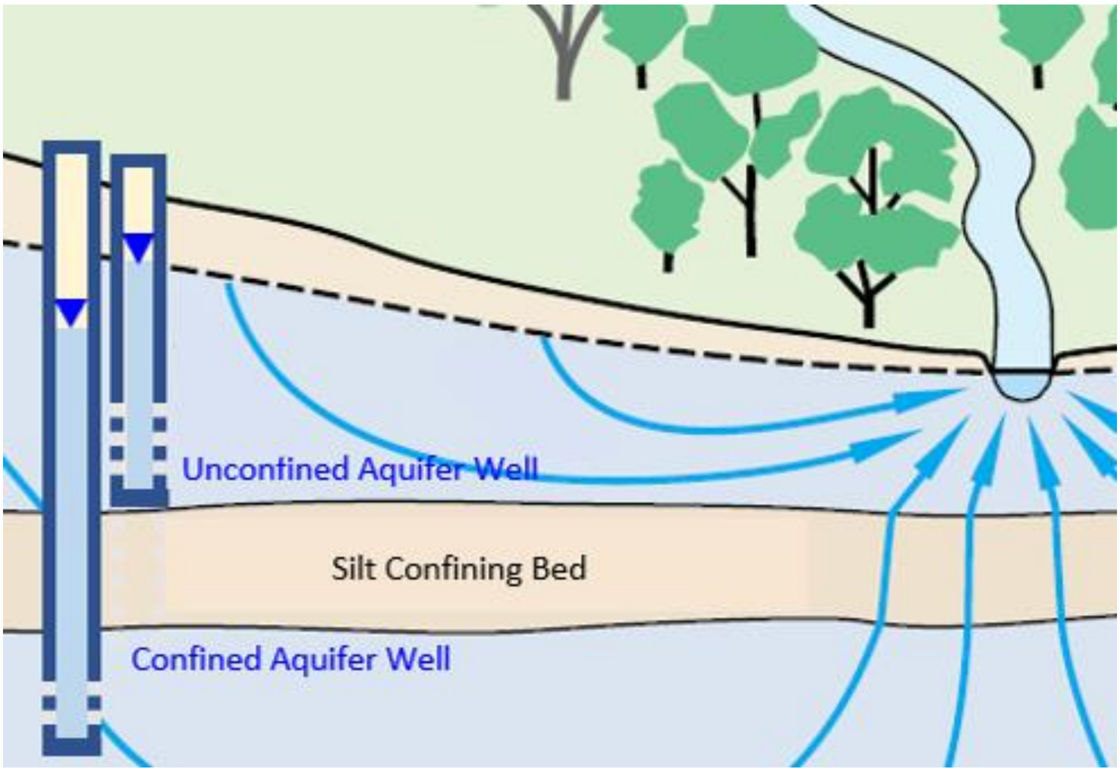

Figure 29 – Close-up of wells shown in Figure 28b. The dashed lines indicate "screened" sections of wells, through which water from the formation can enter the well. The water in the well of the unconfined aquifer rises to the level of the water table, while the water level in the well in the confined aquifer rises above the top of the confined aquifer because of the pressure contained by the confining bed (adapted from Winter et al., 1998, as adapted from Heath, 1983).

To investigate the cause of the groundwater pressure in the confined aquifer, zoom out from Figure 28b to its place in the larger picture shown in Figure 28a where it becomes apparent that the stack of aquifers and confining beds is a small part of a larger groundwater system. The alternating beds of sand, silt and clay are dipping gently toward the sea. This geologic structure of interlayered fine silts and clays with coarse materials like sand and gravel is typical of coastal plains throughout the world. The larger picture reveals that, inland, the confined aquifer slopes upward (toward the left in Figure 28a) and eventually intercepts the land surface. At this location, marked by the red arrow in

Figure 28a, the aquifer is no longer confined because the overlying silt layer is not present, so it is an unconfined aquifer and recharge from precipitation infiltrates to its water table. Since this recharge point is higher than where the well was drilled, that extra height translates into weight of water (pressure) bearing down on the location where we punctured the confined aquifer. This is somewhat analogous to the water supply system in a small town with an elevated water tower where the hydraulic head of the water is highest in the tower so that water will flow to all the houses in town (Figure 30). Although the water supply pipe is below the street level, when the tap is opened on the second floor of the house, water gushes out, because the water level in the tower is higher than the water level at the faucet in the house.

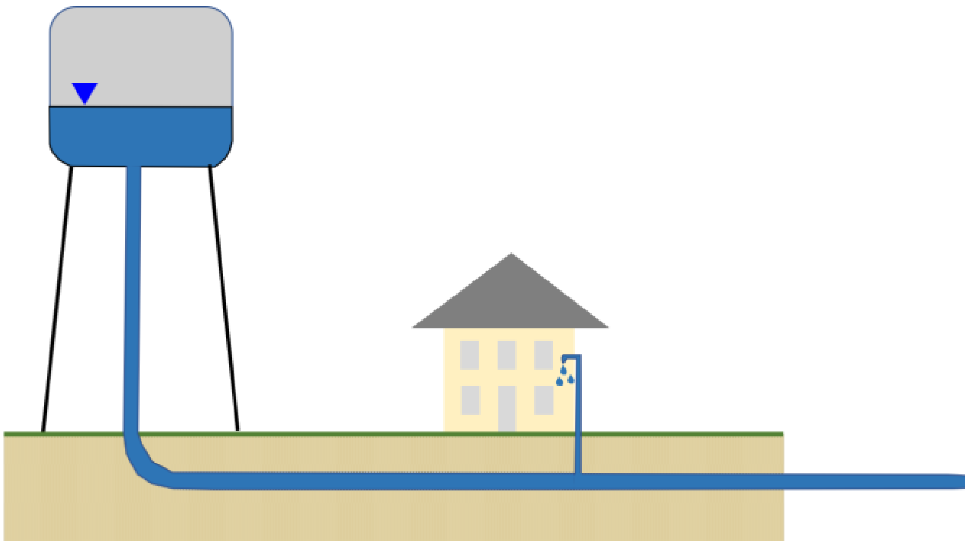

Figure 30 - A water tower higher than a house provides strong water pressure at the water taps, even though the water supply pipe is under the street level (Poeter et al., 2020, gw-project.org).

We say the water tower is "somewhat analogous" to the groundwater system, because, unlike the subsurface groundwater system, the water supply pipe is not filled with porous material. In comparison, water loses substantially more energy as it flows from one point to another in a porous material than in an open pipe. In a groundwater system, even the unconfined aquifer is pressurized at depth in areas where groundwater flows upward toward streams, Furthermore, a well that is open to only the deep portion of the aquifer can have a water level not only higher than the water table but sometimes higher than the ground surface such that the water will flow out of the well without a pump. A well with a water level higher than the surface is called a flowing well. Flowing wells can occur in both unconfined and confined aquifers.

A famous flowing artesian well tapped into a high-pressure groundwater aquifer in 1888 in Woonsocket, South Dakota, United States, causing a "gusher" (Figure 31a). The pressure was created by water recharging the outcrop area of the Dakota aquifer on the west end of Figure 31b, and flowing through the Dakota aquifer beneath the shale of low permeability such that the pressure was not relieved by leakage out of the aquifer along the flow path. When the Woonsocket well was drilled into the aquifer (represented by the red line on the east side of Figure 31b), water gushed out at a high flow rate (Figure 31a). Over time, the volume of water stored in the aquifer decreased so the pressure declined, and the well was no longer a flowing well (that is, the water level in the well declined to below the ground surface). After that time, a pump was needed to draw water from the well. Flowing artesian wells used to be common in many places throughout the world, but are now less common because pumping has reduced groundwater pressure in the aquifer.

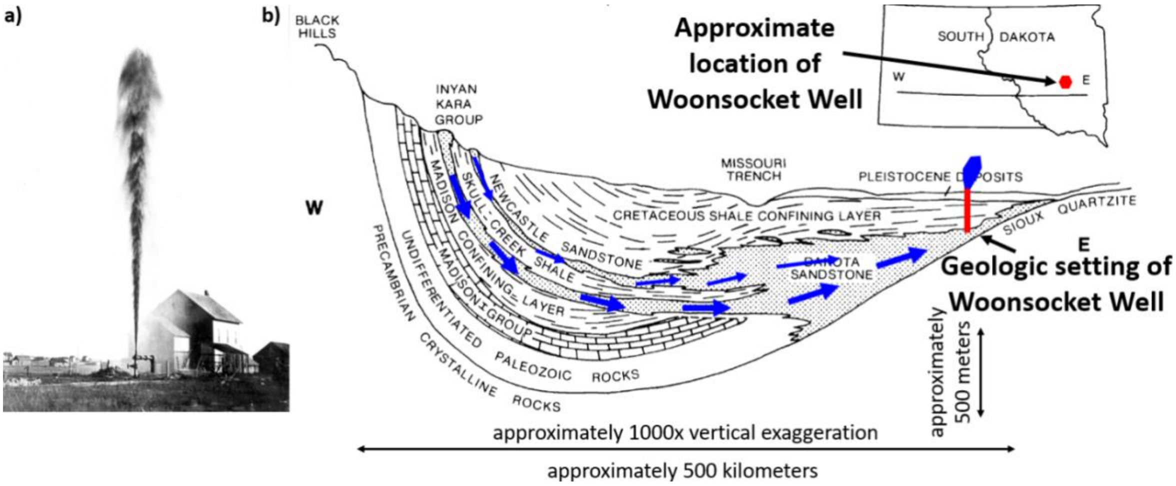

Figure 31 - A flowing artesian well: a) The Woonsocket well of the Dakota aquifer was drilled in 1888 with outflow photographed in 1900. (Darton, 1900); and, b) Cross section of the Dakota aquifer illustrating recharge in the west flowing below the shale confining layer resulting in high pressure in the east (adapted from Bredehoeft, 1983).

The distinction between the unconfined and confined aquifers is important for many reasons. For example, being closely connected to the land surface, an unconfined aquifer is more vulnerable to contamination, and its water level fluctuates more in response to rain and drought. A confined aquifer is somewhat shielded, the water tends to contain fewer contaminants, and the water levels are not as responsive to short-term variations in precipitation. The water in a confined aquifer often has a longer residence time in the groundwater system as shown in Figure 28b. While unconfined water can have a very long residence time in some areas, it is typically on the order of days to years. In contrast, water in confined granular aquifers (not fractured rock) typically has much longer residence times, often on the order of 100s to 1000s of years; that is to say, water in discharge areas fell as precipitation 100s to 1000s of years ago.

Aquifer Storage

Another important distinction between unconfined and confined aquifers is the way they respond when water is pumped from them. When water is pumped from a well in an unconfined aquifer, the pumped water is replaced by air entering the drained pores from above as illustrated in the before and after images of Figure 32. In contrast, when water is pumped from a confined aquifer, air does not enter the pores, rather the water pressure is relieved and the geologic layers compact (especially the clayey layers within or between aquifer layers). This occurs because the high-water pressure has been supporting the particles by bearing some of the weight of the overlying geologic layers and water (Figure 33).

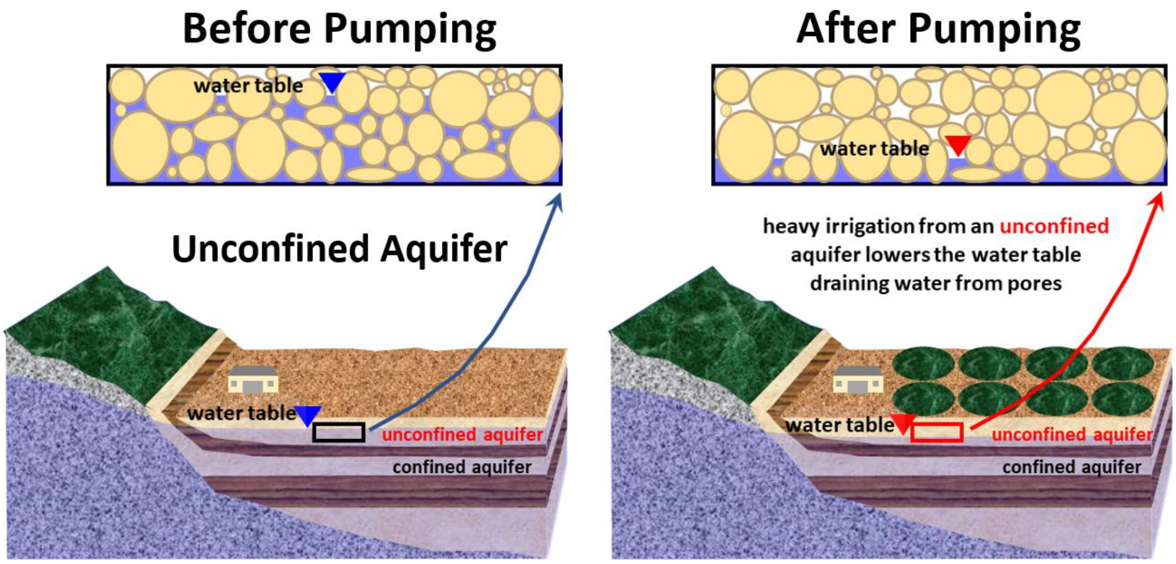

Figure 32 - Schematic showing the change in aquifer conditions before (left) and after (right) heavy pumping of an unconfined aquifer (pores drain) (Poeter et al., 2020, gw-project.org).

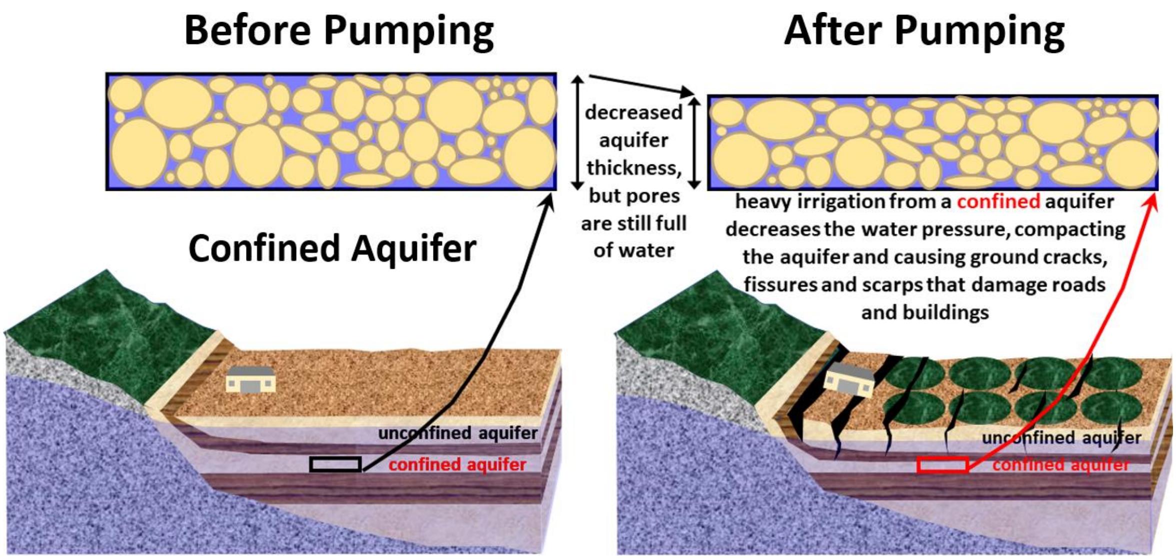

Figure 33 - Schematic showing the change in aquifer conditions before (left) and after (right) heavy pumping of a confined aquifer (pores depressurize and geologic layers compact) (Poeter et al., 2020, gw-project.org).

Because pores drain when unconfined aquifers are pumped and pores depressurize when confined aquifers are pumped, the response to pumping propagates outward much more rapidly in confined aquifers as compared to unconfined aquifers. **Decreasing water levels in response to pumping from a confined well typically are manifested at distances of 100s of meters to kilometers within a few hours or days (depending on the aquifer properties), even though the groundwater near the well may have moved only a few meters in that time.** This is somewhat analogous to a wave in the ocean, the wave travels rapidly while the molecules of water stay in essentially the same location because the wave is a transfer of energy between the molecules of water, not a journey of the molecules.

An important consequence of the difference between pores draining in unconfined aquifers while confined aquifers compress is that **an equal decline of water levels in an unconfined aquifer will yield far more water than that of a confined aquifer.** Typically, a one-unit decline of water level (e.g., 1 m) in an unconfined aquifer will yield 1000s of times more water than the same water level decline in a confined aquifer.

In some regions of the world where large volumes of groundwater have been pumped from a confined aquifer, there has been significant compaction of geologic formations, often revealed as sinking of the land surface called subsidence. An example is shown for the Central Valley of California where decades of groundwater pumping to irrigate water-intensive crops in the hot and dry summers caused the valley floor to sink as much as 10 meters from 1925 to 1977 as shown in Figure 34. Such sinking of the land due to release of groundwater pressure in confined aquifers has occurred not only in the western United States, but in other locales, notably in Mexico City, Mexico; Jakarta, Indonesia; Venice, Italy; and Beijing, China. When subsidence occurs near coasts, it accelerates local saltwater intrusion into coastal aquifers. When the pumping rate is reduced such that aquifer levels no longer decline, the land stops subsiding. However, if further reduction in pumping occurs so that aquifer water levels rise, the subsidence is not fully reversed (that is, the land surface does not rise) because the clay grains cannot return to their prior arrangement as shown in Figure 34c and d.

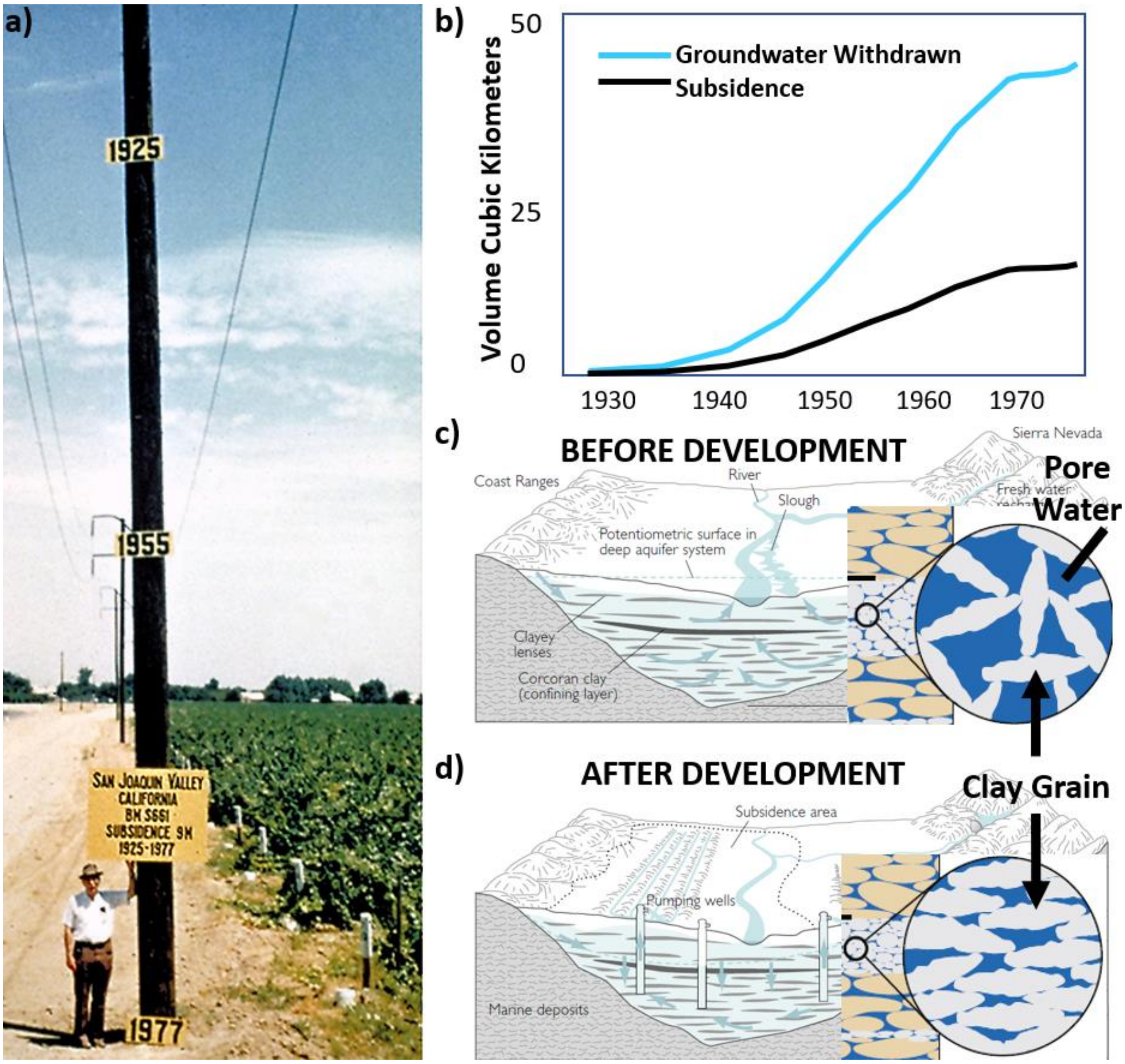

Figure 34 - Subsidence of the San Joaquin Valley, California, USA. a) Photograph of the sinking ground surface due to heavy irrigation from 1925 to 1977. (Poland, 1977); b) Volume of water withdrawn and volume of subsidence over an approximately 2,000 square kilometer area from 1925 to 1977. (Galloway et al., 1999); c) Schematic of valley before pumping, showing arrangement of fine - grain particles in clayey lenses (adapted from Sneed et al., 2018); and, d) Schematic of valley after long - term pumping, showing tight packing of grains in clay lenses after reduction of water pressure due to pumping (adapted from Sneed et al., 2018).

4.4 The Continental-Scale View

Zooming farther out provides an even larger view of the groundwater portion of the hydrologic cycle, extending from the continental divide to the coastal ocean (Figure 35). Broadly, there are two end members of the continental scale system:

- the headwaters in mountainous regions near the continental divide; and,
- the lower basins in flat regions near the coast.

Connecting the headwaters and the lower basins are two, large, continental-scale, terrestrial, water transport systems: one above ground and the other in the subsurface.

- The above ground system is the readily observable stream network, which is concentrated (in channels) and is largely two-dimensional (hugging the land surface). Small upland streams cascade over the surface and converge down-gradient in an orderly manner.
- The subsurface system is the difficult-to-observe groundwater system, which is diffuse (not in channels nor tunnels, except in karst terrain, but rather in pores and fractures of geologic materials), which, relative to the stream network, is three-dimensional (with flow paths that do not necessarily follow the shape of the land surface). Patterns of groundwater flow are less orderly than the stream network because groundwater is driven by multi-scale hydraulic head gradients that are strongly deflected or contorted by complex geologic structures.

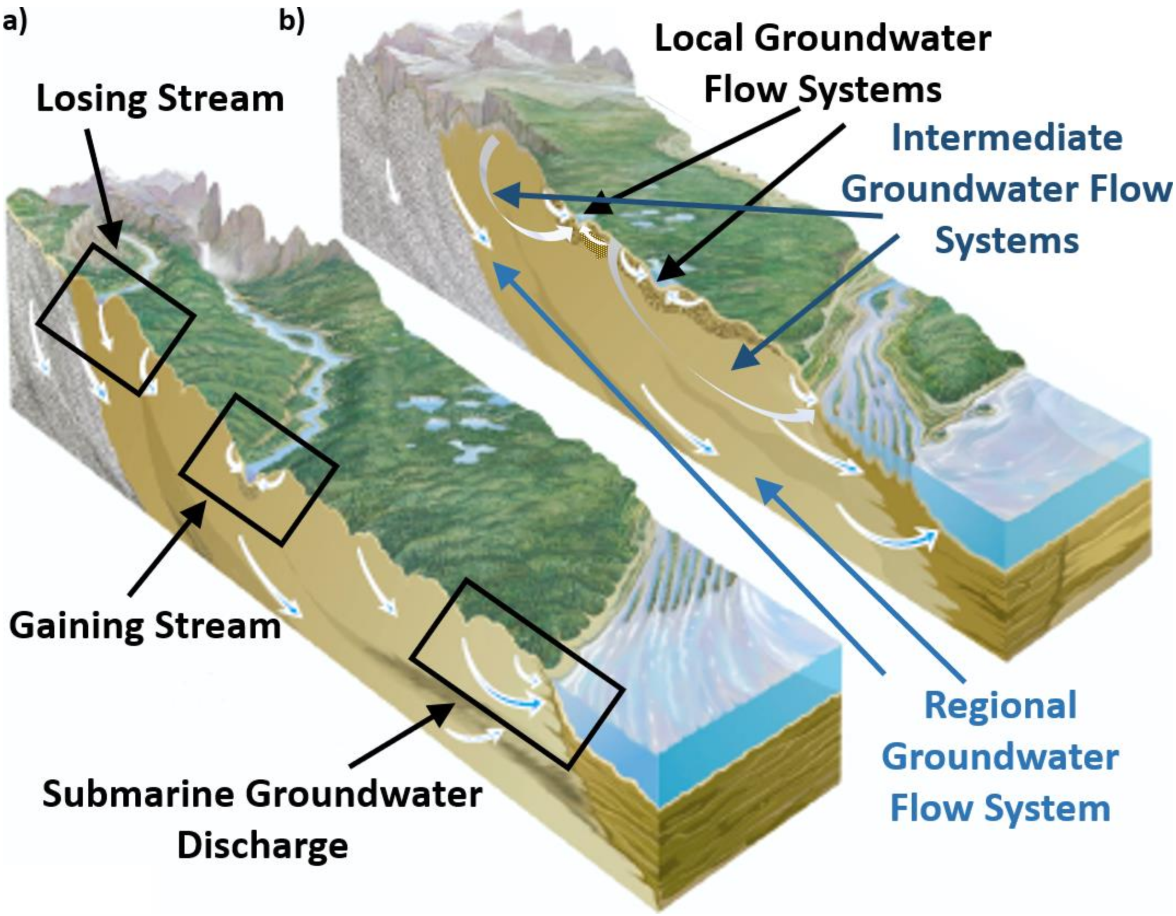

Figure 35 - The continental view, showing the spatial context of: a)both losing and gaining streams as well as submarine groundwater discharge; and, b) the multi-scale nature of groundwater flow systems with shallow, local flow systems nested within deeper intermediate systems which are nested in regional flow systems. This illustrates the long-distance hydrologic connectivity of the surface and subsurface water system through exchange between rivers and groundwater, and discharge of rivers and groundwater to the ocean (adapted from Winter et al. 1998).

Water is exchanged between the surface and subsurface as illustrated by gaining and losing streams and submarine seeps (Figure 35a), and local and regional groundwater flow systems develope (Figure 35b). The <u>local systems tend to be shallow and short</u>, and respond to short-term rain events and seasonal changes in climatic conditions. The regional systems are deeper and longer. Regional systems tend to "record" the climate conditions from decades to centuries to millenia ago. For example, a gaining stream in the lower reaches of a basin that is supplied by regional groundwater flow may never run dry, even after long droughts because the groundwater was recharged thousands or tens of thousands years ago when the climate was different.

As shown in the large-scale continental view of Figure 35, groundwater can directly discharge into the ocean along the coast of the continent. This is referred to as submarine groundwater discharge. Such features were understood and utilized by sea-faring people to locate fresh water long ago as illustrated in Figure 36. Much submarine groundwater discharge occurs close to shore such as in bays and estuaries.

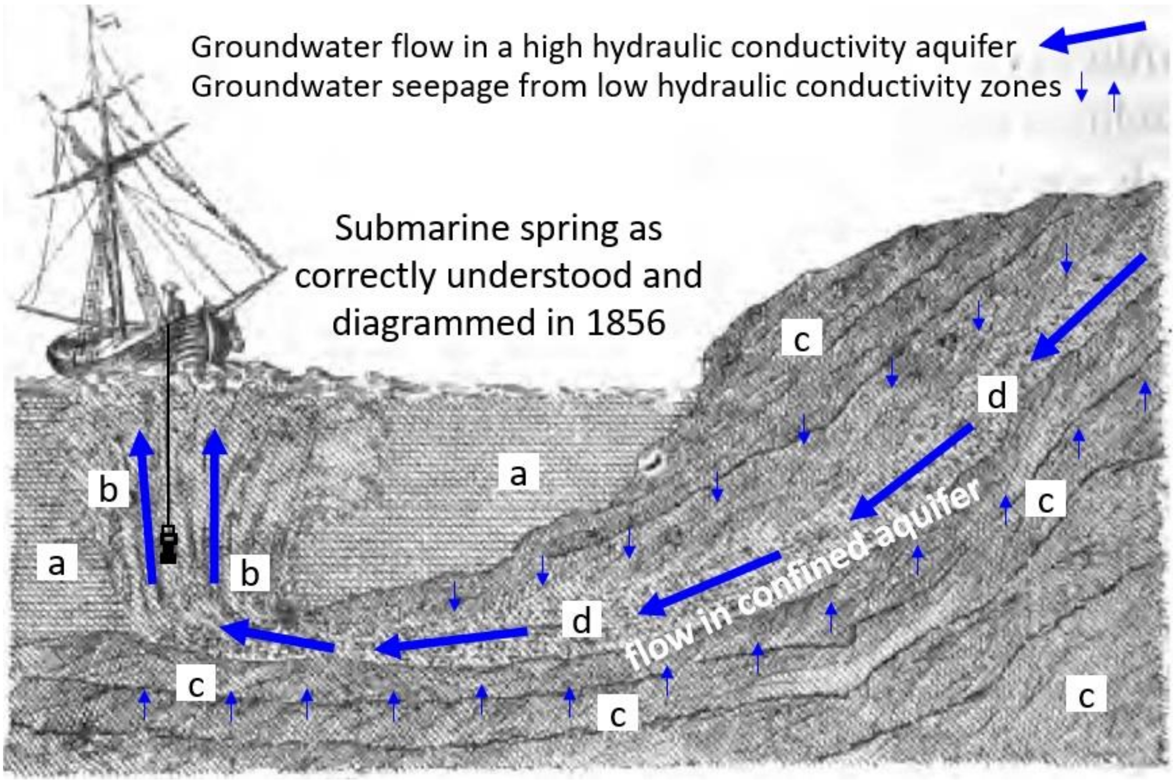

Figure 36 - Submarine springs were correctly understood and utilized for drinking water by seafaring people long ago: a) salt water; b) fresh water; c) low permeability geologic layers; and d) permeable geologic layer. (after Humboldt (1825) who drew the submarine spring diagram as published in the translation by Thrasher in 1856).

In summary, there are **three continental-scale water transport systems**:

1) The **atmosphere;**
2) The **stream networks;** and,
3) The **groundwater systems.**

These continental-scale systems are not isolated. They do not simply deliver continental rainfall back to the ocean in parallel flow systems, rather they are intimately connected and exchange water many times along the way (Figure 37).

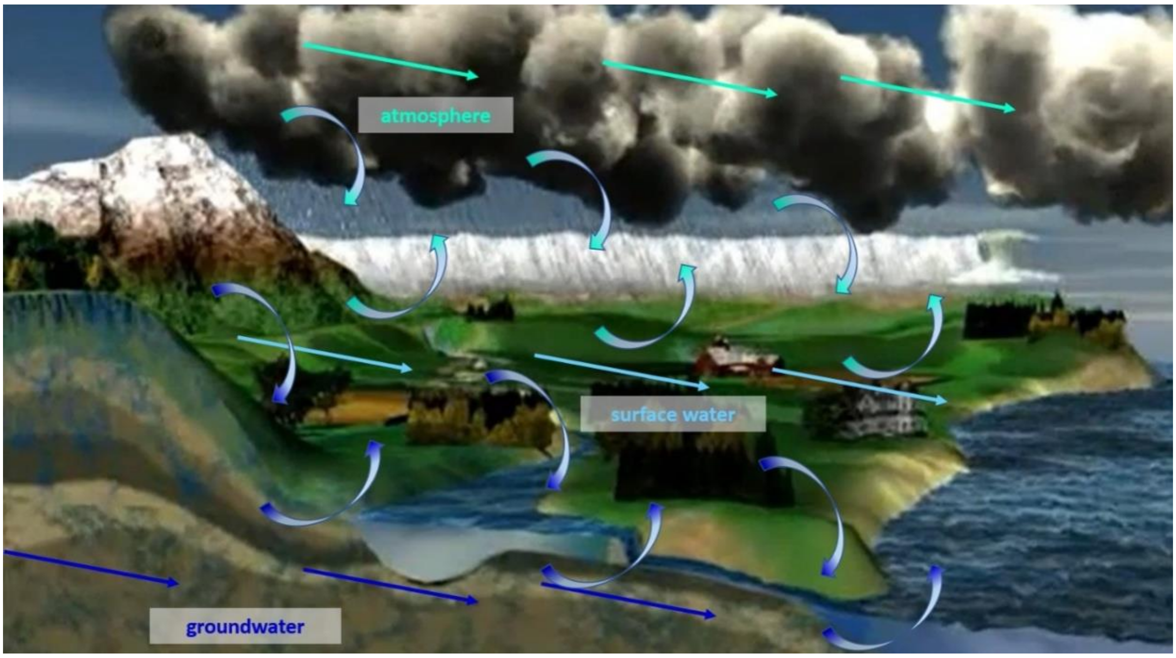

Figure 37 - Three continental-scale water transport systems: air circulation in the atmosphere, stream networks on surface, and groundwater in the subsurface are intimately connected and exchange water many times along the way (adapted from NASA, 2020).

The mechanisms of these exchanges involve water transfer from the atmosphere to the surface and subsurface, and back from the subsurface to the surface and the atmosphere; through precipitation, infiltration, evapotranspiration, and precipitation recycling, as well as through gaining and losing streams. These three transport systems periodically "switch roles" with respect to which one is transporting a particular drop of water from where it first falls on the continent to where it arrives in the ocean. **These interactions "power" the global water flow system.**

5 Groundwater Residence Time

Groundwater moves slowly relative to surface water, so it is useful to consider the time it takes for water to travel through the groundwater portion of the hydrologic cycle (Figure 38). The time required for a water molecule at any point along a flow path in a groundwater flow system to reach another location along the flow path is called groundwater travel time. The time it takes for a water molecule at the water table in a recharge area to travel to where it exits to the surface (the stream in the case of Figure 38) is referred to as groundwater residence time because that is the time the water molecule "resides" in the groundwater portion of the hydrologic cycle. Labels on the curved arrows of Figure 38 show that groundwater flowing along longer, slower and deeper paths spends more time in the subsurface, so it has a longer residence time when it reaches the stream. As shown in Figure 38, water enters a groundwater system at many locations over a wide area, but generally the flow paths converge to discharge on a smaller area. Thus, groundwater discharging to a stream will include water with a wide range of residence times.

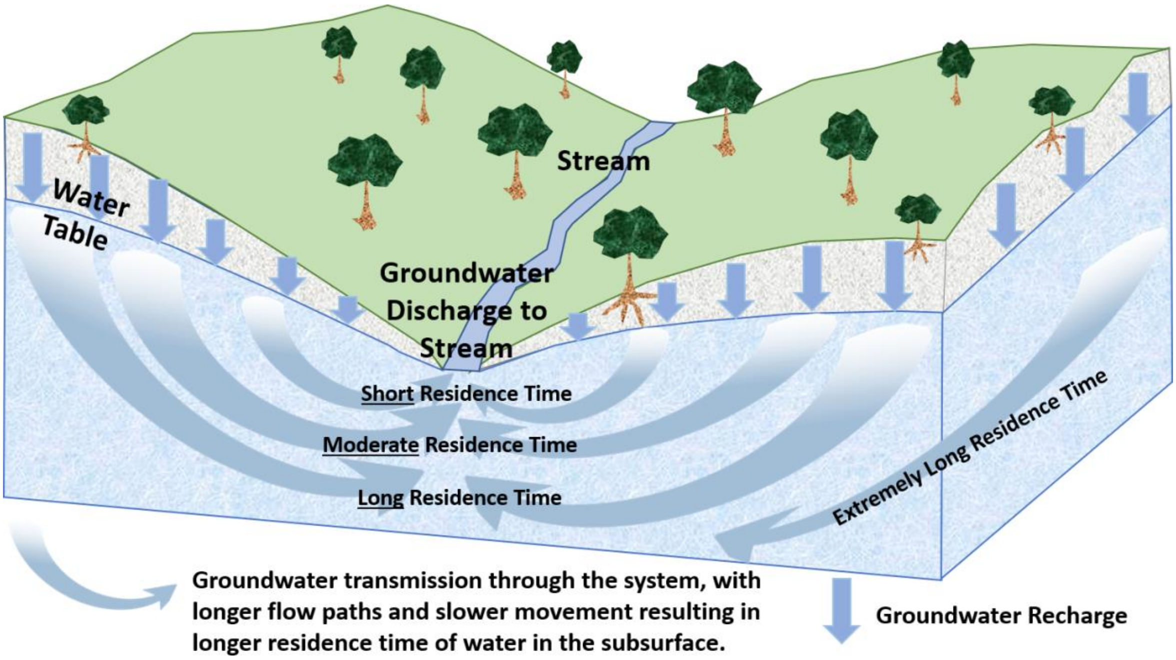

Figure 38 - Groundwater flowing along longer, slower and deeper paths spends more time in the subsurface, so it has a longer residence time when it reaches the stream. Water enters the groundwater system at many locations over a wide area, but the flow paths converge to discharge on a smaller area such that the water discharging to a stream has a wide range of residence times (Poeter et al., 2020, gw-project.org).

The nature of geologic material strongly influences the velocity of groundwater flow and thus influences the travel and residence time. Velocities in the three broad classifications of geologic materials (granular sediments, fractured rock, and cavernous karst) are generally much different from one another. Velocity varies widely even in similar types of geologic material because the velocity is a combination of the ease with which water can pass through the material as well as the driving force created by the water level difference. Given that caveat, at shallow depths typical velocities are on the order of 0.01 to 1 m/day in granular aquifers, 0.5 to 50 m/day in fractured rock, and 10 to 500 m/day in cavernous karst material. Again, considering the residence time of groundwater in the flow system shown in Figure 38, if the geologic material was sand, groundwater residence times may be on the order of years to decades, but if the geologic material was silt and/or clay, which is much less permeable than sand, the residence times would be much longer, such as decades to many millennia.

Residence time of water in the groundwater portion of the hydrologic cycle is much longer than in other compartments of the hydrologic cycle such as the surface water compartment or the atmosphere. The residence time of the water in the groundwater zone is more like that of water molecules that make up large glaciers than that of liquid surface waters. Residence time in any compartment of the hydrologic cycle is estimated as the volume of water in a compartment divided by the average flux of water into and out of that compartment. The exact values are uncertain, but their order of magnitude is easily estimated. For example, the average residence time of a molecule of water in the atmosphere is on the order of 10 days, while a molecule spends about 1 year in the vadose zone, roughly tens to hundreds of years in lakes, about several thousands of years in the ocean, and on the order of hundreds of 1000s of years in the ice caps (Figure 39). In contrast, residence times of water in the fresh water part of the groundwater water zone range from years from hundreds to thousands of years, while residence times of deep, saline water beneath the fresh water zone are much longer, on the order of millions of years. Most of this deep water does not exchange with the hydrologic cycle except during geological upheavals which occur at a frequency on the order of tens of millions of years. The depth to this deep saline water varies with locale depending on topography and hydraulic conductivity, but generally occurs between a depth of 200 to 1000 meters.

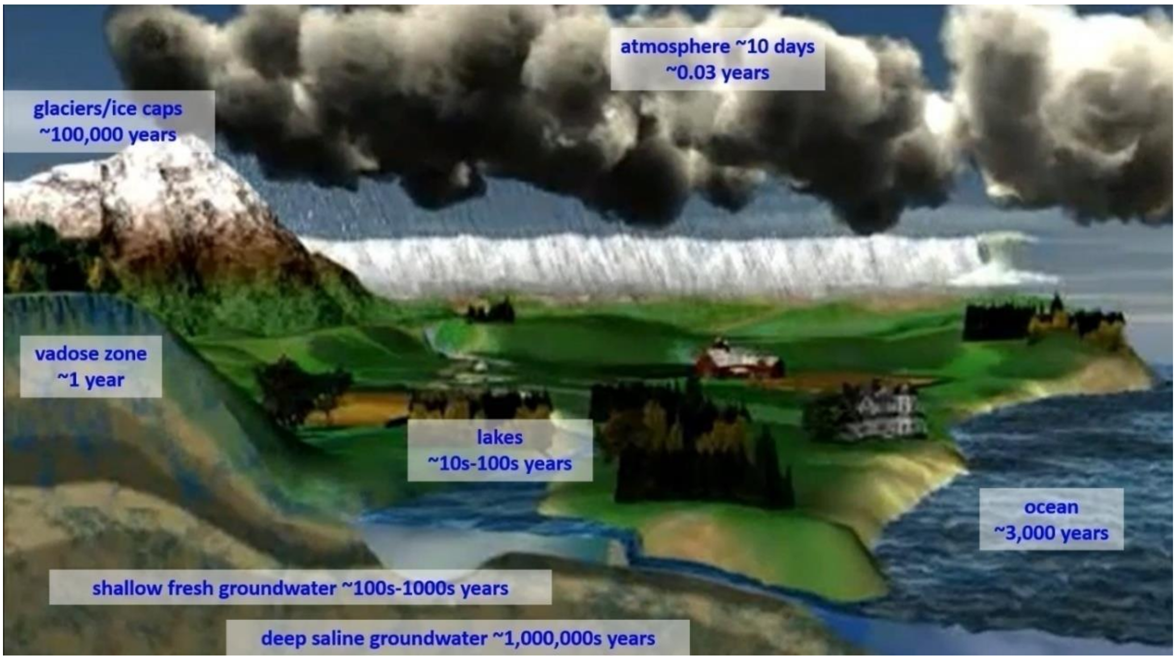

Figure 39 - Relative time a drop of water resides in compartments of the hydrologic cycle (adapted from NASA, 2020).

Water dissolves minerals from subsurface materials as it flows through the pores of those materials, so generally, the longer water resides in the groundwater system, the higher the concentration of dissolved minerals. Consequently, given the potentially broad range of residence time for water discharging to streams and the varying character of the subsurface materials that the water passes through, the discharging groundwater can have a wide range of chemical compositions.

Travel times and residence times are important with respect to the movement of contaminants in groundwater. If contaminants enter the recharge areas and are not readily assimilated by the geologic materials, nor broken down by subsurface microbes, it may take years or decades to arrive at the stream (thus threaten the stream within a human lifetime) or it may take centuries to millennia (thus only become a threat to the stream in the long-term future).

Groundwater has a long-term "memory", because it takes a long time to fill and empty a large reservoir, thus water has a long residence time in the subsurface. In fact, some of our aquifers contain waters that were recharged during the wetter and cooler periods of Earth's history through the glacial-interglacial cycles over the past to tens-of-thousands to hundreds-of-thousands of years. Such groundwater is called fossil groundwater, owing to the fact that it is not being replenished similar to fossil fuels that we extract from the subsurface.

After the discussion of groundwater systems thus far, it is useful to consider examples of groundwater in various settings to help the reader become more familiar with groundwater around the Earth. To that end, the following section illustrates how groundwater occurs in some unique terrains including mountains, karst (i.e., locales with caves), and permafrost settings.

6 Groundwater has a role in all of Earth's Terrains

Groundwater plays a role in all of Earth's terrains. To illustrate the variability of groundwater conditions in differing terrains, this subsection provides a glimpse in groundwater conditions in a few of terrains: mountains, karst and permafrost.

6.1 Groundwater in Mountain Settings

Springs have long been the source of water for mountain inhabitants where cultures developed around terrace agriculture that sustained civilizations such as the Incas in the Andes Mountains of South America (Figure 40), who engineered structures around mountain springs and canals to carry the water through the terraced agricultural area and into the city to fountains where residents could obtain water.

Figure 40 - Terrain formed by historical terrace agriculture (Graber, 2011).

Approximately 12% of the world population lives in mountainous areas today and, to a large extent, depends on groundwater as their source of water. Most mountains exhibit steep terrain and are comprised of fractured rocks with minimal capacity for storing water. Consequently, groundwater typically circulates rapidly, often discharging to springs on the mountain slopes where the water table intersects the ground surface or to mountain streams. Forested mountains have soil formed from the forest ecosystem that prevents rapid storm runoff, thus promoting groundwater recharge and water storage in the groundwater zone with slow release to streams. Deforestation reverses this and promotes drying mountainous terrain and less availability of water to support stream flow and ecology. Although mountain hydrology is important to more than a billion people in the global population, it is not well studied because of difficulties associated with drilling wells in mountainous terrain.

6.2 Groundwater in Karst Settings

With carbonate bedrock forming about 15% of Earth's ice-free surface as shown in Figure 41, more than 25% of the world's population either lives on, or obtains its water from, karst aquifers.

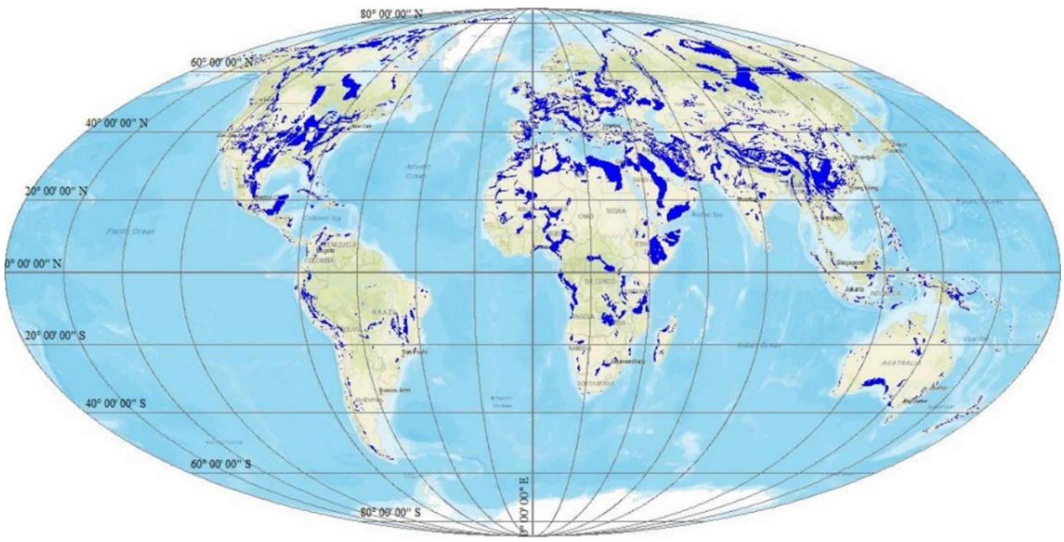

Figure 41 - Outcrop of carbonate and evaporite rocks forming karst aquifers around the world (Kuniansky, 2020, created from World Karst Aquifer Map spatial data set of Chen et al., 2017).

Karst aquifers consist of large openings in the subsurface connected by caves and sinkholes (features where the land surface overlying a cave has collapsed into the cave) as illustrated in Figure 42. They are formed over geologic time scales by acidic water in the vadose zone dissolving substantial amounts of the minerals in limestone and dolomite that groundwater carries away. Later, the process of creating openings in the subsurface is halted as the dissolved minerals neutralize the acidity of the water and the water loses its capacity to further enlarge flow paths. Subsequently, when climate becomes more arid and/or sea level falls, the water table declines, and the acidic infiltration water creates additional caverns at deeper levels. During wetter periods and/or when sea levels rise, the caverns fill with water creating a saturated karst aquifer. Fluctuating water tables over geologic time produced deep karst aquifers in many locales throughout the world.

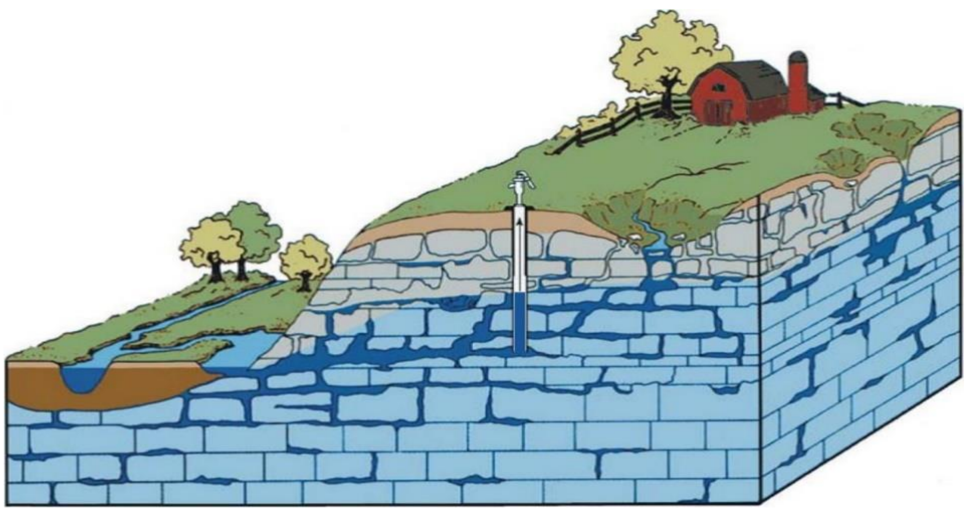

Figure 42 - Large, well-connected openings in karst results in rapid groundwater flow and short groundwater residence time, making them prone to contamination (Iowa Geological Survey, 2020).

Recharge water flows more rapidly through connected karst openings to discharge at springs and streams than through other types of sedimentary aquifers. Given the large connected openings of karst, groundwater flow is more similar to flow in streams than to flow in sediments or fractured rock. Finding sufficient supply of surface water is often difficult in karst terrains because water infiltrates rapidly. The rapid movement of water through karst aquifers makes them prone to extensive contamination.

Karst is the only landscape where humans can explore large distances into the subsurface on foot through dry connected caves or using scuba gear in water-filled caves. In addition to their value for water supply, they support tourism where majestic caverns are adorned with mineral "jewelry" of cones and columns that are formed when the groundwater contains more minerals than it can carry and the minerals precipitate from the water (Figure 43).

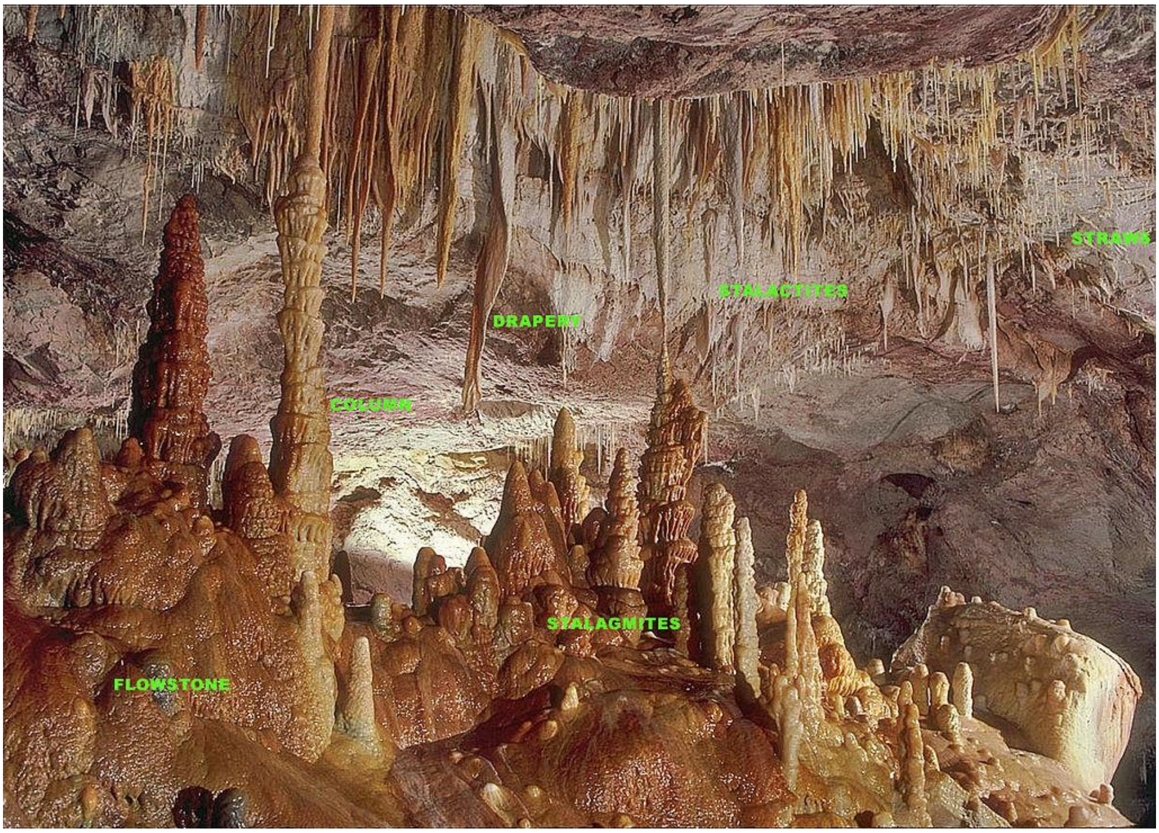

Figure 43 - Underground cave photo showing common structures formed by precipitation of minerals from groundwater (Dave Bunnell, 2006. "Photo by Dave Bunnell showing the most common speleothems↗" by Dave Bunnell↗ is licensed under CC BY-SA 2.5↗).

6.3 Groundwater in Permafrost Settings

At the cold extremes of the globe, permafrost forms in groundwater systems (Figure 44). Permafrost can be soil, rock or sediment that is saturated or unsaturated, but by definition is frozen for more than two consecutive years.

Figure 44 - World map of the cryosphere (the frozen water part of the Earth system). The distribution of permafrost is shown in purple hues (Ahlenius, 2007).

Where the surface is free of ice, permafrost occurs beneath the "active layer" which is soil, rock or sediment that freezes and thaws each year. Active groundwater flow occurs above and below the permafrost layer which is essentially impermeable. This obstacle to downward drainage causes the surface to be boggy. When substantial volumes of water flow into the groundwater system, areas of unfrozen ground occur within the permafrost (Figure 45).

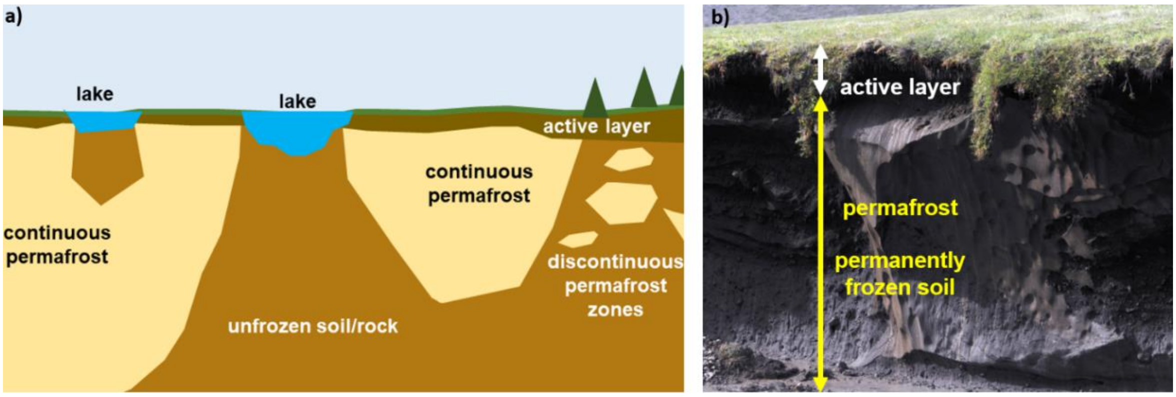

Figure 45 - Permafrost is frozen portions of subsurface near the Earth's surface: a) schematic of the variable distribution of frozen and unfrozen material with less frozen material where surface water seeps into the subsurface or forest cover insulates the ground; b) photo of a thin active layer above the permafrost on the North Slope of Alaska (photo by Kling, 2012).

7 The Unique Functions of Groundwater in Earth's Hydrologic System

The groundwater compartment of the hydrologic cycle is a large, slow moving reservoir of fresh water (in its shallower realms), that reacts chemically with geologic materials along its flow paths, and interfaces with the water transport systems of rivers and the atmosphere. This vast groundwater reservoir serves as: 1) a regulator of the fresh-water hydrologic cycle by mediating the flow of continental surface waters; 2) a chemical factory and conveyor belt for processing Earth's material and transporting it from the continents to the oceans; 3) a waste repository/processing plant; and, 4) a global life-support system.

7.1 Groundwater as a Hydrologic Regulator

The relative sizes of Earth's water reservoirs are shown in Figure 46. The largest bubble shows the volume of all the liquid water on the surface, under the surface, and in the atmosphere of Earth relative to the total size of the planet (Figure 46a). Only 2.5% of that water is fresh and most terrestrial life depends on that fresh water. Of the total fresh water on Earth, about 70% is locked up in polar ice inaccessible to terrestrial life (Figure 46b). The 99:1 relative size of groundwater to surface waters has great significance. Using the bank analogy that was presented earlier, the ready cash flow (surface water) is only 1% of the bank balance. This is good news for hydrologic "financial" security, because streams, lakes, wetlands, and all life that depends on them, has reserve funds available in the groundwater reservoir. That is, surface waters will not go dry if the rain stops for a while because the large groundwater reservoir keeps discharging water into them as baseflow. In this sense, by its sheer volume the fresh groundwater reservoir serves as a buffer to maintain rivers and wetlands through variations of weather and climate. However, when we change the landscape to allow more water to run to the oceans and less to recharge groundwater (for example through deforestation, urbanization, or heavily irrigated agriculture) there is less groundwater to support the fresh water cycle.

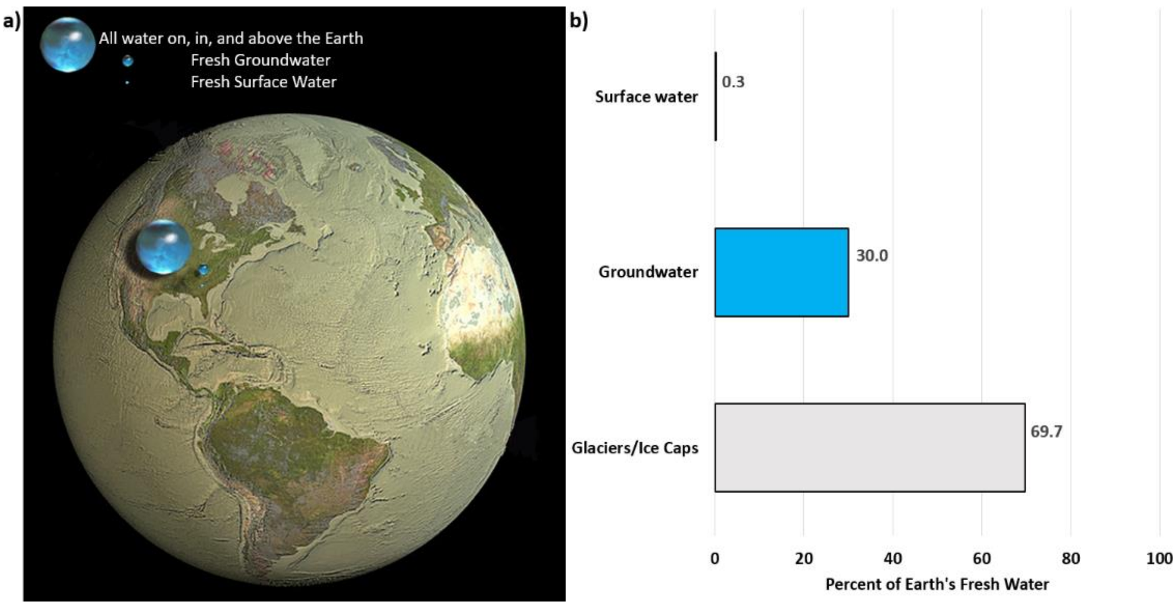

Figure 46 - Proportional volumes of a) water on earth (adapted from USGS, 2019c) and b) percentages of Earth's fresh water stored as ice, groundwater, and surface water. (Poeter et al., 2020, gw-project.org, based on values from Shiklomanov, 1993).

As discussed earlier, the groundwater levels are not only impacted by variations in weather and climate, but also by humans pumping water from wells. Again, the groundwater reservoir's vast size and capacity to store water provides a buffer when water levels are lowered by pumping wells, because water is first drawn from groundwater storage, due to lowering of the water table as water flows to the well, before it decreases groundwater flow to streams, or draws water from streams. In addition, in some areas, the lowered water table decreases the amount of evapotranspiration (Figure 47), thus enhancing recharge to support groundwater discharge to wells and as baseflow to streams. This is yet another way that the groundwater system buffers surface water flows. Of course, new water is not created, so vegetation dependent on that evapotranspiration will die and be replaced by plants that require less water, and surface water bodies in the area of the lowered water table may decrease in size or go dry. In effect, water is "stolen" from other portions of the hydrologic cycle.

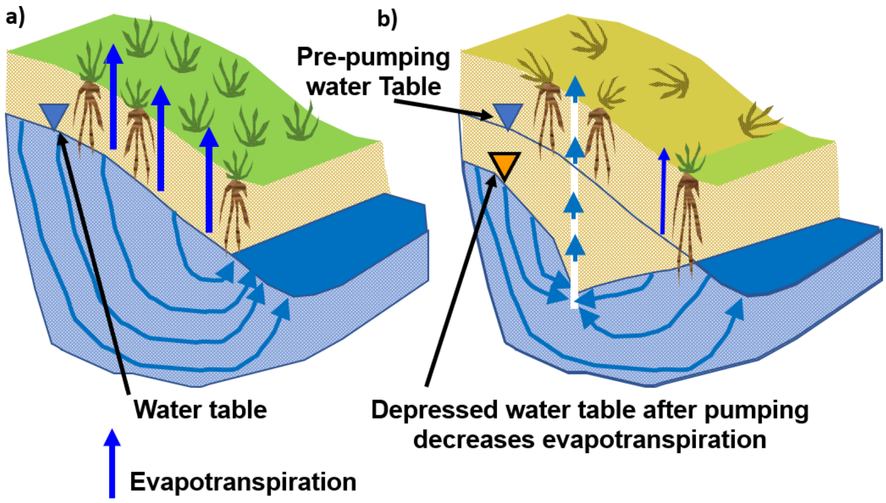

Figure 47 - Drawdown around pumping well can lower the water table and decrease evapotranspiration. This enhances recharge and that supports groundwater discharge to wells and baseflow to streams without further depression of the water table. The decreased evapotranspiration due to the lowered water table can cause vegetation to die off (Poeter et al., 2020, gw-project.org).

Around the globe, continual decline of groundwater levels indicates groundwater is being pumped more rapidly than it is being recharged. Groundwater depletion is estimated to be on the order of 283 cubic kilometers (km^3) per year plus or minus about 40 km^3 (Wada, 2016) and this has global implications. When extraction of groundwater is larger than natural recharge, the volume of water on the Earth's surface increases as the volume in the subsurface decreases. This increased volume of surface water as a result of over-pumping has made a substantial contribution to sea level rise, contributing approximately 0.8 +/-0.1 mm/year to ocean rise, which is about 25% of the current 3.1 mm/year rise of the oceans (Wood and Hyndman, 2018).

One example of extreme groundwater decline is found in the North China Plain (Zheng et al., 2010), an area of about 40,000 km², where since the 1950s groundwater levels declined over 90 meters in some wells with a spatially averaged decline of 15 meters as the result of unsustainable groundwater pumping (Figure 48). The depressed water levels have resulted in dry streams and land subsidence.

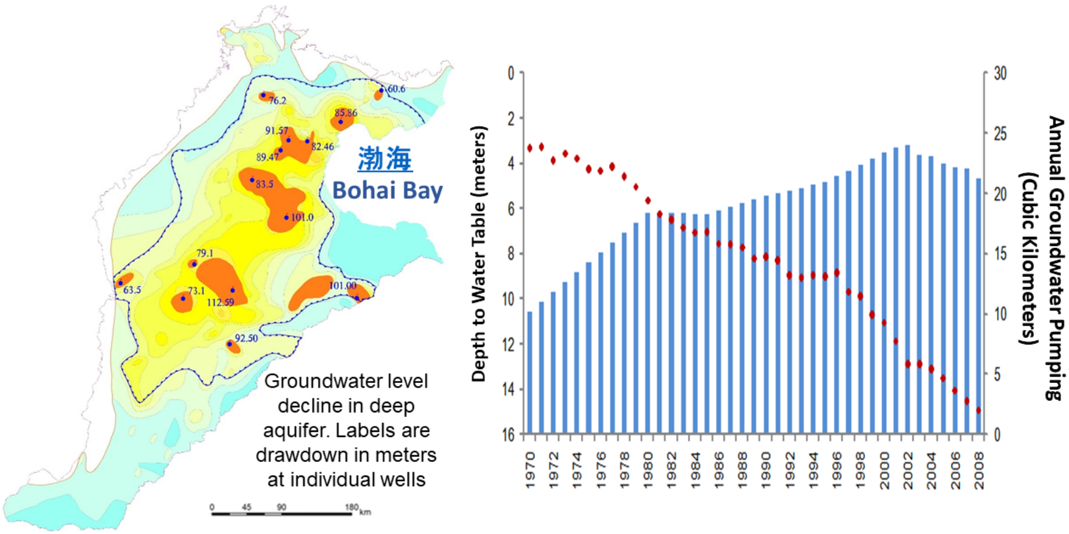

Figure 48 - The North China Plain has a large cone of groundwater depression due to unsustainable groundwater pumping, mostly for agriculture: a) decline of water levels in meters since the 1950s with the largest declines at individual wells on the order of 90 meters and a spatially averaged decline of 15 meters (Zheng et al., 2010); and, b) spatially averaged depth to groundwater and annual volume of pumping from 1970 through 2008 (Zheng, 2020).

Given that aquifer depletion throughout the world is reducing river baseflows and causing sea level rise, geoengineering interventions in the hydrologic cycle are being implemented in an attempt to reverse these negative impacts by managing water table elevation in some watersheds. Management requires less pumping, more groundwater recharge, or both. To achieve higher average recharge over a span of many years, more of the precipitation must reach the water table while less precipitation escapes as shallow runoff from the aquifer catchment. The specific procedure for enhancing recharge varies from place to place, but may include: landscape engineering to impede and capture runoff; infiltration of treated wastewater through engineered wetlands or spreading basins with permeable bottoms; and/or use of wells to inject storm water or treated wastewater into aquifers. Managed aquifer recharge programs are becoming more common for reduction of aquifer depletion because the alternative, which is less groundwater extraction, is so difficult to achieve in a world of increasing population accompanied by agricultural and industrial growth. However, such programs rely on available aquifer storage capacity and the only aquifers that offer much storage capacity are unconfined aquifers where the added water fills unsaturated pore space.

To achieve a sustainable groundwater supply, groundwater levels (and thus groundwater storage) may fluctuate substantially from year to year, but the average must be constant over the long term. In wet years, the groundwater reservoir receives more recharge, so its storage is replenished. This can balance the depletion of water from storage in dry years, if the long-term average rate of pumping is managed properly over many years (or decades) to accommodate the long-term cycle of droughts.

One example of such management was implemented in 1968 in an effort to halt the groundwater overdraft in the San Fernando Basin which provides drinking water for the city of Los Angeles, California, in the United States. Water levels had been measured since 1929 and were used to estimate the amount of water stored in the aquifers of the basin (Figure 49). Development caused declining water table elevations from 1945 into the 1960s, this large depletion of groundwater storage prompted the management plan. The plan requires approximately 0.44 km^3 of groundwater to be stored in the aquifer (green dashed line of Figure 49). To account for wet and dry periods, it was specified that the minimum storage could be as much as 0.18 km^3 less than the required storage (lower red dashed line of Figure 49) to provide storage space for adding water to the aquifer in wet years. The maximum storage could be as much as 0.26 km^3 more than the required storage (upper red dashed line of Figure 49) to prevent water levels rising to the point that groundwater would be lost through discharge to adjacent groundwater basins. As shown in Figure 49, with only a few brief exceptions, the amount of storage has rarely fallen in the targeted range. However, the depletion has stopped, and the community continues to develop recharge facilities to increase the amount of water that can be added to the system.

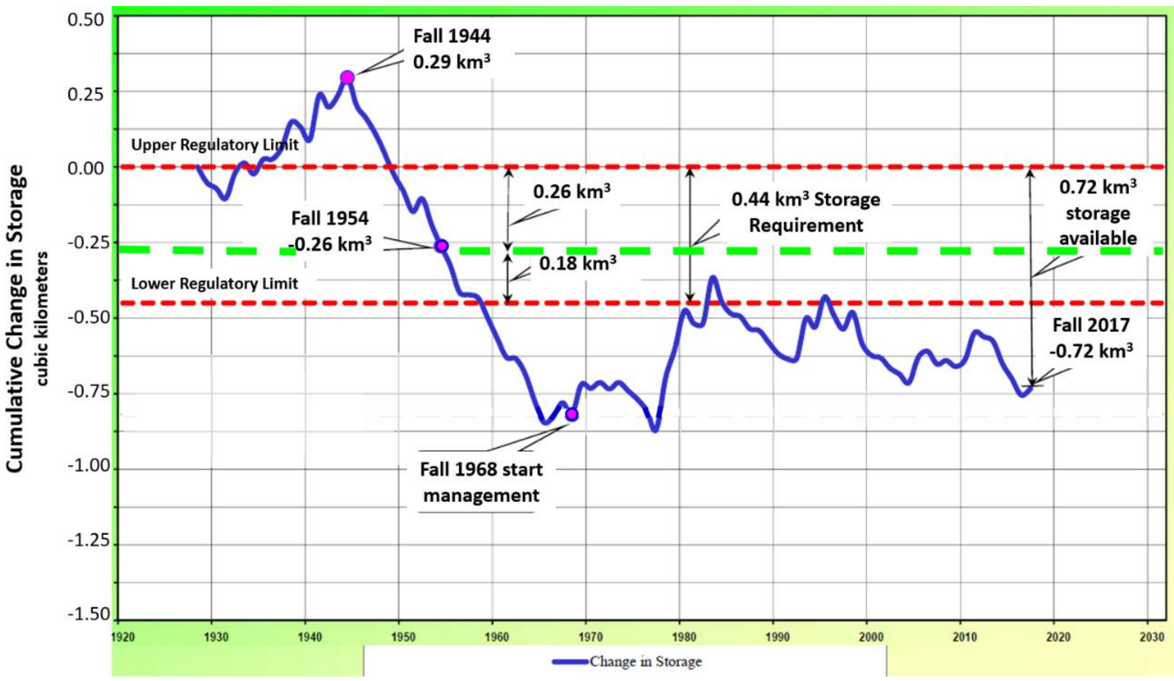

Figure 49 - Cumulative change in groundwater storage in the San Fernando Basin aquifer that supplies drinking water from wells to the city of Los Angeles, California, USA. The thick solid blue line shows the change in groundwater storage from 1929 to 2016. The volume in storage in 1929 is referenced as zero change in storage. The management plan is to control usage while also introducing water through infiltration ponds to maintain about 0.44 km^3 of groundwater in the aquifer (thick, long-dashed, green line) with an acceptable variation between the upper and lower red, dashed lines (modified from ULARA Watermaster, 2018).

Stored groundwater represents "savings" put into the "bank" by nature over a profoundly long period of time. But, like fossil fuels, we are "withdrawing" and "spending" that long-term savings over an extremely short period relative to the time required to put the water into storage. In many agricultural regions of the world, water that resided in aquifers for tens of thousands of years has been depleted within the last half century. Such "spending" of long-term reserves, be it ancient groundwater that entered the subsurface tens-of-thousands of years ago, or coal beds and petroleum reservoirs that were formed by ancient plants buried hundreds-of-millions of years ago, means that we continually leave less of these resources to future generations.

7.2 Groundwater is a Geochemical Factory and Conveyor Belt

All fresh groundwater contains dissolved constituents and all fresh groundwater is in motion conveying its dissolved load through the flow system towards discharge areas. This process has been going on throughout geologic time. The type and magnitude of these dissolved constituents render the groundwater either useful or not useful for drinking, agriculture and industrial processes. The main features of Earth's surface, as it exists today, were formed by geologic events in the past, millions to billions of years ago when forces deep in Earth's crust formed mountains while erosion and deposition of sediments created valleys and plains. In the north and far south, glaciers gouged the landscape and smeared mixtures of geological material over the land to form today's shallow geologic layers. The hydrologic cycle was established long ago in synchrony with the climate and landscape, evolving together over geologic time.

Water flowing on Earth's surface is the main agent controlling the evolution of the landscape through erosion and deposition. Leopold et al. (1964) wrote that "Rivers are the gutters down which flow the ruins of continents", in reference to the mass of sediments transported by the riverine systems to the ocean. This pithy statement could be adapted to "Groundwater is the enigmatic web through which flows the decimation of rocks", in reference to the mass of solute discharged to the ocean by groundwater.

Flowing groundwater is the foundation that provides the ongoing supply of water to the surface water system through both wet and dry periods and occasionally alters the landscape through development of salt flats in arid areas and the formation of caves with associated sink holes in karst areas. Approximately half of the water flowing in rivers is from long-term flow through the persistently saturated portion of the groundwater system discharging to the river, and half is from storm runoff. Some storm runoff occurs over the ground surface, though most flows through the shallow subsurface, often initiated in the vadose zone through the capillary fringe or via temporary saturated zones perched on low permeability layers.

Natural Chemical Constituents in Groundwater

Natural waters contain dissolved elements known collectively as Total Dissolved Solids (TDS), nearly all of which are natural inorganic salts. Water with less than 1000 milligrams per liter (mg/L) of TDS is considered fresh, while water with more TDS (>4000 mg/L) is classed as brackish, water with higher TDS (>10,000 mg/L) is saline (sea water ~ 35,000 mg/L), and brine (>35,000 mg/L) is extremely salty. Table 1 summarizes the terms used to describe the TDS levels of water. When a well is drilled just about anywhere on the globe, the shallow groundwater has low TDS (is "fresh") and is good for drinking if it is not excessively impacted by chemicals from human activities. At greater depth, the water is brackish, deeper yet it is saline and below this, the water is typically brine. This change of water with depth from fresh to brackish to saline to brine is nearly universal, except in a few places where there is no fresh or brackish water at any depth because all the groundwater is salty.

Table 1 - Terms for varying degree of dissolved solids in water.

Total Dissolved Solids (milligrams/liter)	Water Description
< 1,000	fresh
1,000 - 4,000	lower end of this may be drinkable
> 4,000 - <10,000	brackish
> 10,000 - < 35,000	saline
35000	sea water
> 35,000	brine

Natural fresh groundwater contains dissolved elements in three categories: major constituents; minor constituents; and trace constituents. The amounts of major, minor, and trace elements in the groundwater depend on the climate in the recharge areas, the chemical conditions of the vadose zone and the geology of the groundwater system through which the water flows. It is useful to know the types of elements that might be present in groundwater because it is not feasible to measure every element of the periodic table in a water sample. Typically, only 8 or 9 elements constitute over 95% of the mass of dissolved solids in groundwater. Regardless of the setting, some elements are so pervasive that they are always part of a basic chemical analysis of groundwater.

TDS in groundwater is mostly in ionic form (i.e., positively or negatively charged ions). $H^+$and OH^- ions are always present in water because water molecules, H_2O, dissociate into H^+ and OH^-. This seemingly simple phenomenon is actually fascinating and complex, although only some basic concepts and terminology are discussed here. The amount of H^+ ions in a particular water sample is usually expressed as pH. As you may know, a pH of 7 in pure water is called neutral, which is a condition in which the H^+ and OH^- ions are balanced. The pH of natural groundwater varies. Figure 50 lists the variation of pH as 6 to 9, with 7 to 8 a more typical range. For a pH of 7 in pure water there are 0.0001 mg/L of H^+ ions. Although present at very low concentrations compared to the other species, $H^+$and OH^- are very important to a multitude of reactions that occur in groundwater, including weathering, dissolution, precipitation, and microbiological and abiotic transformations.

Many chemical constituents are dissolved in groundwater as illustrated in Figure 50. The six constituents typically present at highest concentrations in groundwater are known as major ions: including positively charged ions called cations (sodium, Na^+; calcium, Ca^{2+}; magnesium, Mg^{2+}) and negatively charged ions called anions (bicarbonate, HCO_3^-; sulfate, SO_4^{2-}; chloride, Cl^-). These usually make up nearly all the mass in the measured TDS value. The minor constituents that may be present include: potassium, K^+; manganese, Mn^{2+}; iron, Fe^{2+}; silicon, Si^{4+}; nitrate, NO_3^-; fluoride, F^-; and dissolved organic carbon, DOC. These minor constituents, generally have a concentration in the range of 0.1 to 5 mg/L. Many trace elements are present at lower concentrations, sometimes below our ability to detect them with commonly used analysis methods.

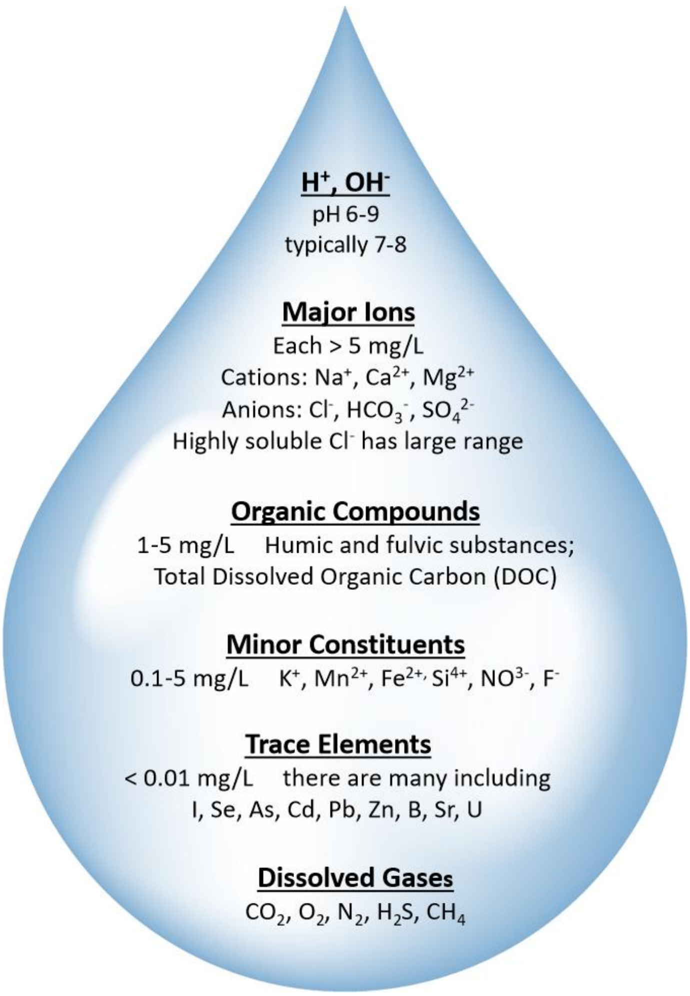

Figure 50 - Natural fresh groundwater has many dissolved chemical constituents known as major ions, minor constituents, and trace elements as well as organic compounds and dissolved gases. Most dissolved chemicals are in the form of positively or negatively charged ions (Poeter et al., 2020, gw-project.org).

The amounts and types of constituents in these major, minor and trace categories give water the chemical portion of its natural "quality". Other components of water quality are temperature, color, odor, turbidity and microbial content. Some of the natural constituents in groundwater can be harmful at higher concentrations, but contribute to good health when at lows concentrations (e.g., iodine, fluoride, and selenium).

Nearly all fresh groundwater that has no significant contamination from human activities is safe to drink but there are important exceptions, most notably where natural groundwater contains excessive amounts of arsenic or fluoride or in Karst systems. Drinking water with excessive arsenic causes many health problems including cancer. Arsenic occurs naturally at harmful levels in groundwater in more than 60 countries, affecting more than 150 million people. While low levels of fluoride (on the order of 1 to 2 mg/L) have been shown to reduce the occurrence of dental cavities, excessive fluoride causes dental fluorosis, or worse, crippling skeletal fluorosis. It is estimated that more than 200 million people consume water with high fluoride concentrations including people in China, India, United States, Canada, and parts of Africa and South America.

Although safe levels have been established for many other naturally occurring elements, such as cadmium, mercury, lead and silver, these rarely occur at harmful concentrations in natural groundwater. The occurrence of harmful levels of arsenic and fluoride results from a combination of two factors: the presence of arsenic- or fluoride-rich minerals in geologic materials and chemical conditions that facilitate their dissolution and release into groundwater.

In countries relying heavily on domestic wells for supply such as Bangladesh, arsenic may cause harm. If a well is drilled in a geologic formation where arsenic-bearing minerals are present and oxygen is absent, dissolved arsenic and iron will be present in the extracted groundwater. Water in shallow wells typically has enough dissolved oxygen that iron minerals precipitate, removing arsenic from the water. However, other health hazards may be of concern for shallow hand-dug and poorly constructed drilled wells, such as bacterial contamination from surface runoff.

Arsenic and fluoride in groundwater have caused and continue to cause severe health effects in many rural areas where poverty prevents avoidance. But they also threaten health in wealthier areas where millions of private domestic well owners consume groundwater rich in arsenic or fluoride without awareness because private wells are not included in government testing and regulation. The locales known to have excessive amounts naturally occurring arsenic and fluoride are shown in Figure 51a and b.

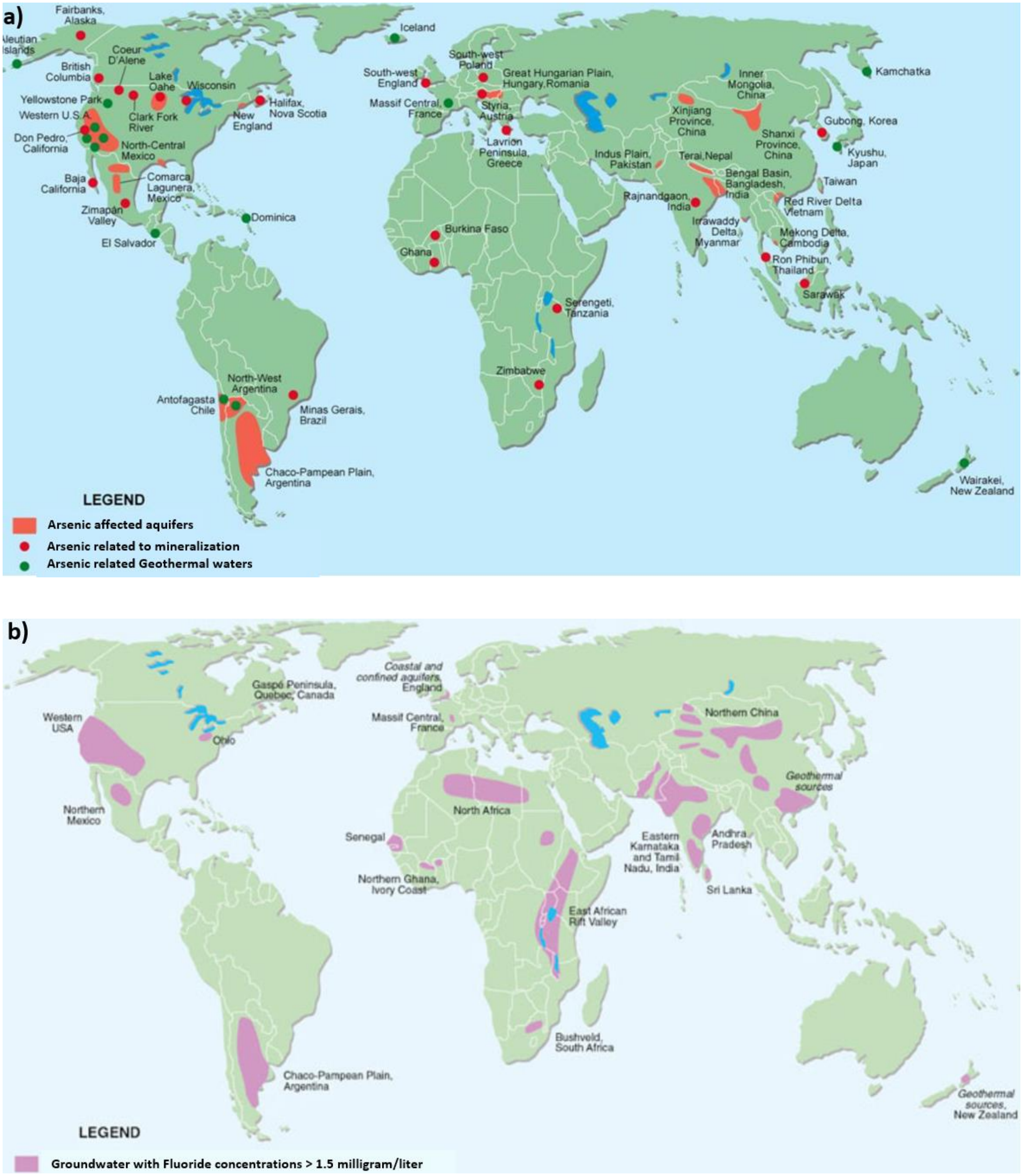

Figure 51 - The natural occurrence of excessive amounts of arsenic or fluoride are examples of why groundwater may not be safe to drink even where there is no significant contamination from human activities: a) distribution of documented problems with arsenic in groundwater (>50 μg/L) and related to mining and geothermal activity (BGS, 2020a); b) locations of documented occurrences of high fluoride groundwater (>1.5 mg/L) (BGS, 2020b).

Origin of Dissolved Constituents in Groundwater

The dissolved chemical load in groundwater comes not only from interaction with the geologic materials it flows through, but also from the constituents in the atmosphere that the recharge water was exposed to before infiltrating. Precipitation that infiltrates through the vadose zone to form groundwater recharge carries wet and dry aerosols that the atmosphere transports over the continents. These aerosols are from ocean spray, smoke, volcanoes, continental dust, and lightning, as well as chemicals from human activities such as burning of fossil fuels and application of agricultural herbicides and pesticides. Owing to their small sub-micron size and the acidic nature of rain due to the presence of carbon dioxide (CO_2) in the atmosphere, dry aerosols are dissolved in the precipitation water. This dissolved material includes many of the elements in the periodic table in very low concentrations. The concentration of each element in the atmosphere varies with distance from its source. For example, the distribution of chloride precipitated on the United States as shown in Figure 52 indicates higher amounts of chloride near the coasts and the Great Salt Lake as a result of aerosols in spray from those water bodies.

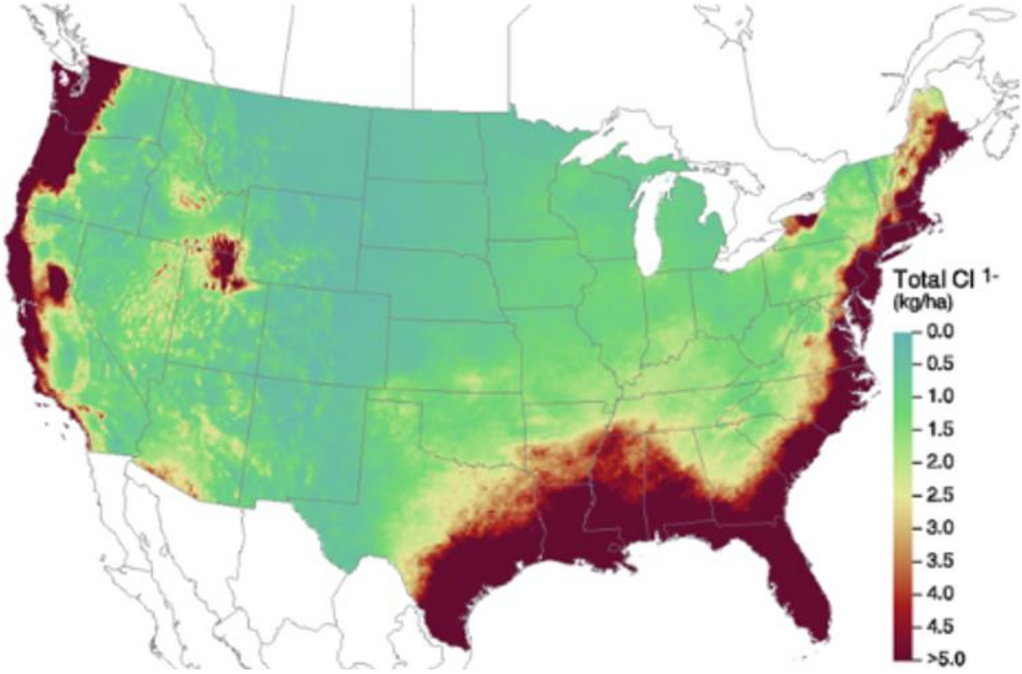

Figure 52 - Map of wet flux particles of chloride precipitated from the atmosphere on the continental United States in 2016 (kilograms/hectare/year) with low concentrations in green and high in red (NADP, 2019).

Although the chemistry of natural groundwater starts off with the contribution of dissolved constituents from the atmosphere, nearly all groundwater takes on additional dissolved mass of constituents as the water infiltrates through the vadose zone, as represented schematically in Figure 53. The chemistry of infiltrating water is altered in the vadose zone in two ways: by amplification related to evapotranspiration and by geochemical reactions (Figure 53). Even if the vadose zone were chemically and microbially inert so as to contribute no chemical mass to the recharge water, the chemical concentrations in the infiltrating water would increase substantially (increasing the TDS) because of the evapotranspiration amplification effect.

Evapotranspiration transfers much of the vadose zone water to the atmosphere (the global average is about 70%), but substances dissolved in that water remain behind in the soil water, so the concentrations of dissolved substances in the water that is left behind increase compared to those in the precipitation. In arid and semi-arid areas most of the solutes are derived from precipitation. However, the vadose zone is not inert; it is chemically reactive because oxygen enters from the atmosphere and carbon dioxide (CO_2) is produced within the vadose zone from microbial decay of organic matter in the soil and from respiration of plant roots. The combination of these reactions and the evapotranspiration amplification effect uses the CO_2 content of gas in the vadose zone to be 10 to 100 times higher than that of the Earth's atmosphere in drier climate regions, and 2 to 5 times higher in wetter climates. This CO_2 dissolves into the water, forming carbonic acid, and the acidic soil water dissolves minerals. In many regions, the vadose zone has minerals containing sulfur, such as iron-bearing minerals like pyrite, and these minerals are oxidized in the presence of oxygen gas to produce sulfuric acid, further increasing acidity of the soil water and its ability to dissolve minerals. This process of minerals dissolving in the vadose zone is an important part of landscape weathering (the breaking down of rock). The presence of oxygen and carbon dioxide in the vadose zone make the vadose zone especially reactive geochemically.

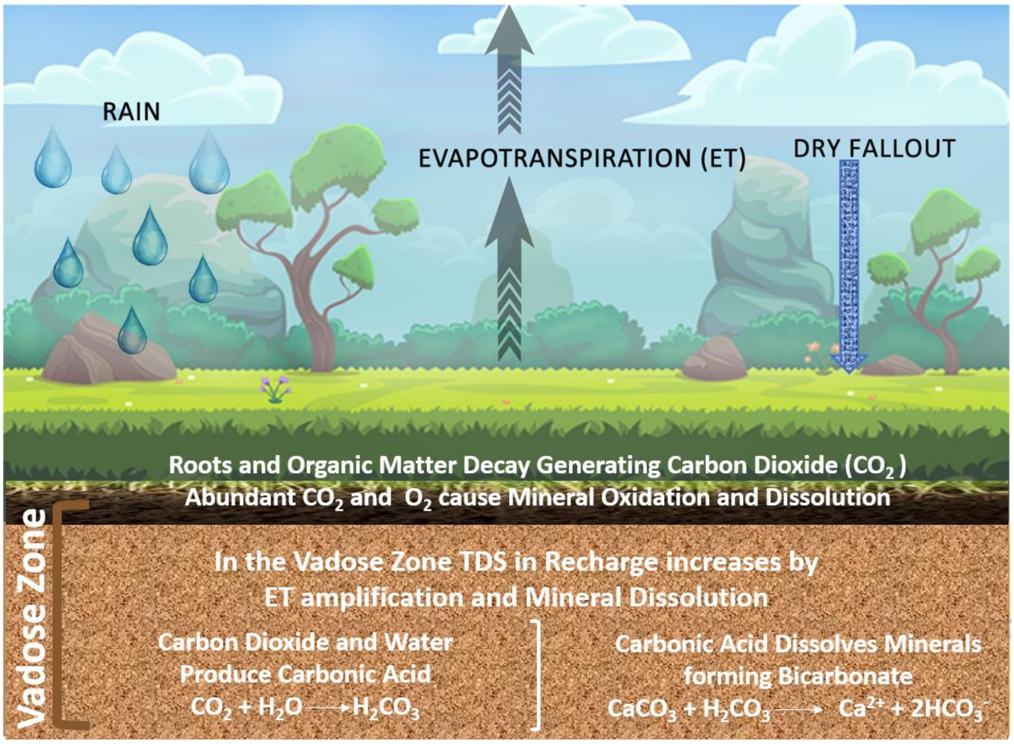

Figure 53 - The vadose zone is particularly active geochemically because of the generation of carbonic acid (H_2CO_3) that enhances mineral dissolution resulting in production of bicarbonate (HCO_3^-) and dissolution of minerals like calcite ($CaCO_3$) (Poeter et al., 2020, gw-project.org).

Almost without exception, the TDS of groundwater increases as groundwater moves along the flow path from the recharge to discharge areas (Figure 54). This increase occurs largely from the release of relic salinity from low permeability zones within which groundwater is nearly stagnant. Relic salinity includes solutes that remain from past geologic eras when sea water was present in the geologic formations. Some minor amounts of solutes may be acquired from additional weathering, but most are from relic salinity and underlying brines.

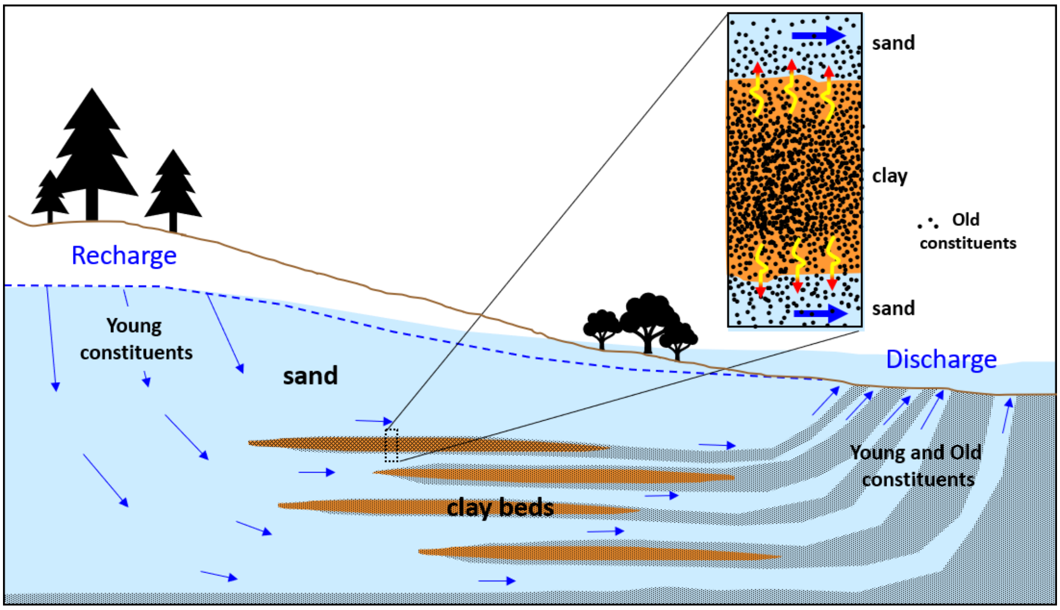

Figure 54 - Schematic showing how low permeability beds comprised of clayey materials (orange/brown zones) can contribute dissolved constituents to the active groundwater flow (blue arrows) in the more permeable parts of the groundwater flow system. Low permeability geologic units with almost no active flow (e.g., clay beds) can release old dissolved constituents (e.g., relic salinity, represented here as gray shading/dots) by diffusion (twisted yellow arrows with red points in the close-up) from nearly stagnant pore water in the clay to zones of active groundwater flow in high permeability materials (e.g., sands, with young constituents, represented as pale blue). Thus, groundwater outflow in discharge areas is a mixture of young and old dissolved constituents. Here, only a few large clay beds are shown for clarity, but typically there are many smaller beds such that the discharging groundwater includes water from zones of different geochemical reactivity with different groundwater residence times (Poeter et al., 2020, gw-project.org).

Older geologic landscapes become less geochemically reactive over geologic time as the soluble minerals are flushed out by groundwater flow. In humid areas, groundwater in these exceptional landscapes has relatively low TDS even after traversing long flow paths with large groundwater residence time because sources of soluble constituents have been diminished by millions of years of groundwater flushing. In contrast, geologically young landscapes typically have higher TDS groundwater because there has not been sufficient time to flush the soluble components from the geologic materials. For example, areas glaciated during the past few hundred thousand years such as in Canada, parts of the northern United States, northern Europe and much of Russia, are geologically young landscapes formed by glaciers. Generally, these geologic materials are comprised of minerals and rock fragments that have been exposed to groundwater for only 10,000 to 15,000 years after the most recent glaciers receded from the mid latitudes. As a result, substantial amounts of readily soluble minerals such as calcite, dolomite and pyrite, among others, are available for dissolution by infiltrating water and in some of those areas even groundwater with short residence time has elevated TDS, causing them to be brackish.

Groundwater moves more slowly in deep zones, so there has been less flushing, and thus, in general, deeper water is saltier. In arid areas, groundwater tends to contain more dissolved solutes owing to concentration by evaporation.

Generally, flow paths that are short and well flushed have bicarbonate (HCO_3^-) as the dominant anion and usually calcium (Ca^{2+}) as the dominant cation (Figure 55). This composition is primarily the result of processes that occur in the vadose zone as shown in Figure 53. As discussed above, the vadose zone is especially geochemically active because root respiration and microbial decay produces abundant CO_2 that dissolves to form carbonic acid (H_2CO_3), which enhances mineral dissolution thus producing bicarbonate (HCO_3^-). Even if there are no reactive minerals in the vadose zone, some HCO_3^- is produced in this zone. The groundwater that makes up nearly all the baseflow to streams and rivers is from local groundwater systems in which the dominant anion is HCO_3^-. On longer flow paths more typical of intermediate flow systems, sulphate (SO_4^{2-}) often exceeds HCO_3^- as the dominant anion (Figure 55), but there are many exceptions. In some groundwater systems, SO_4^{2-} declines due to natural microbiological processes (sulphate reduction) that consume sulphate and produce CO_2 that causes a rise in HCO_3^- and a decrease in pH. The regional flow systems (Figure 55) generally have chloride (Cl^-) as the dominant anion and sodium (Na^+) as the dominant cation because these longer flow paths have more opportunity to be influenced by releases of halite (sodium chloride) from low permeability zones and underlying formations. Also, common chloride minerals have the highest solubility of all the major minerals. The lower solubilities of major minerals that produce HCO_3^- and SO_4^{2-} keep those ions at low- to moderate- concentrations.

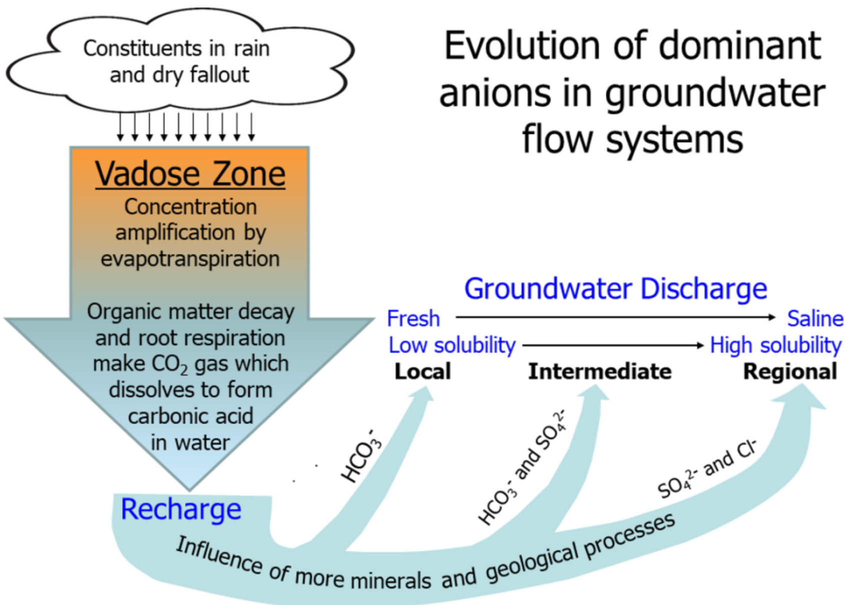

Figure 55 - The anions occurring at highest concentration vary along groundwater flow paths depending on the geologic circumstances between the recharge and discharge areas (Poeter et al., 2020, gw-project.org).

Chloride minerals are so soluble that over geologic time chloride is removed from the higher permeability zones that have been flushed by large volumes of fresh recharge water. But chloride commonly lingers as "relic chloride" in low permeability zones and in deep flow systems (Figure 56). In general, the longer the flow path, the more likely zones of slow flowing groundwater will release relic chloride into zones of active flow.

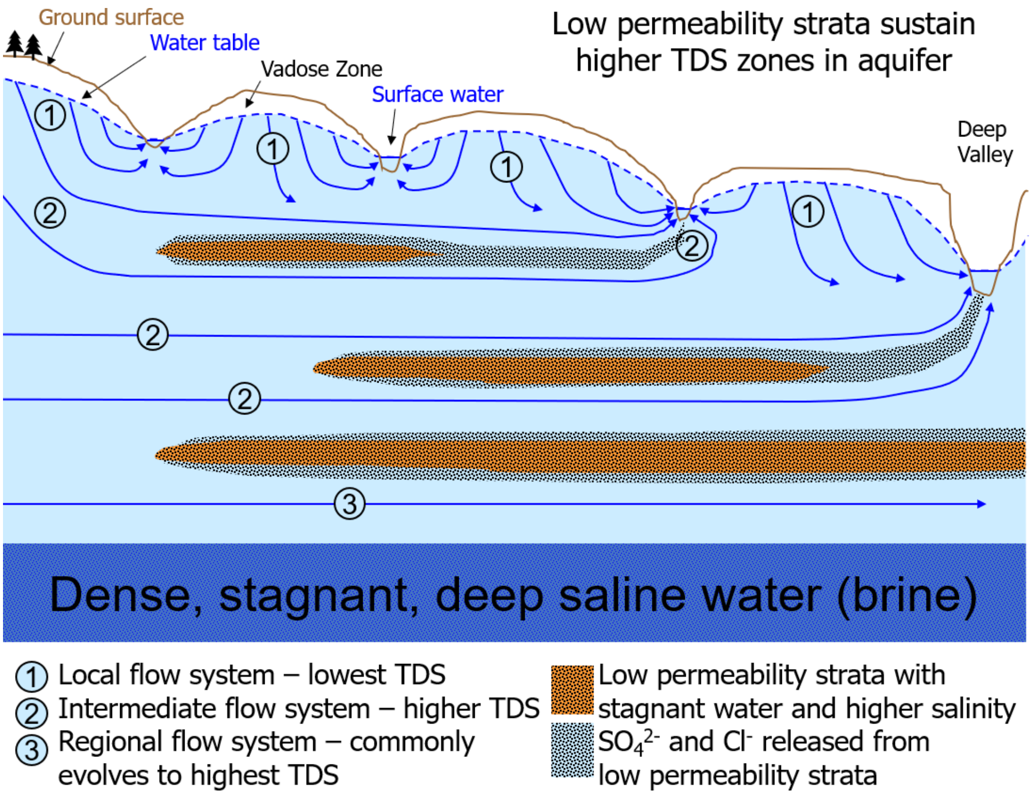

Figure 56 - Schematic summary of the distribution of TDS with depth in groundwater (Poeter et al., 2020, gw-project.org).

Occurrence of Salty, Mineral-rich Groundwater

Salty groundwater is common in all deep groundwater zones. Fresh groundwater is the norm for shallow zones, although salty groundwater is common in shallow zones of arid climates.

After the flushing of relic chloride over long periods of geologic time, today's shallow fresh water zone extends to substantial depth around the globe as a result of eons of groundwater flushing. There are many regions where groundwater is fresh to depths of 500 meters or more (Bierkens and Wada, 2019). Below these depths, groundwater is most likely brackish of saltier. The depth of the bottom of the fresh water zone (i.e. to the top of the brackish water zones) varies greatly around the globe. To illustrate this, the estimated depth to brackish water in the continental United States is shown in Figure 57.

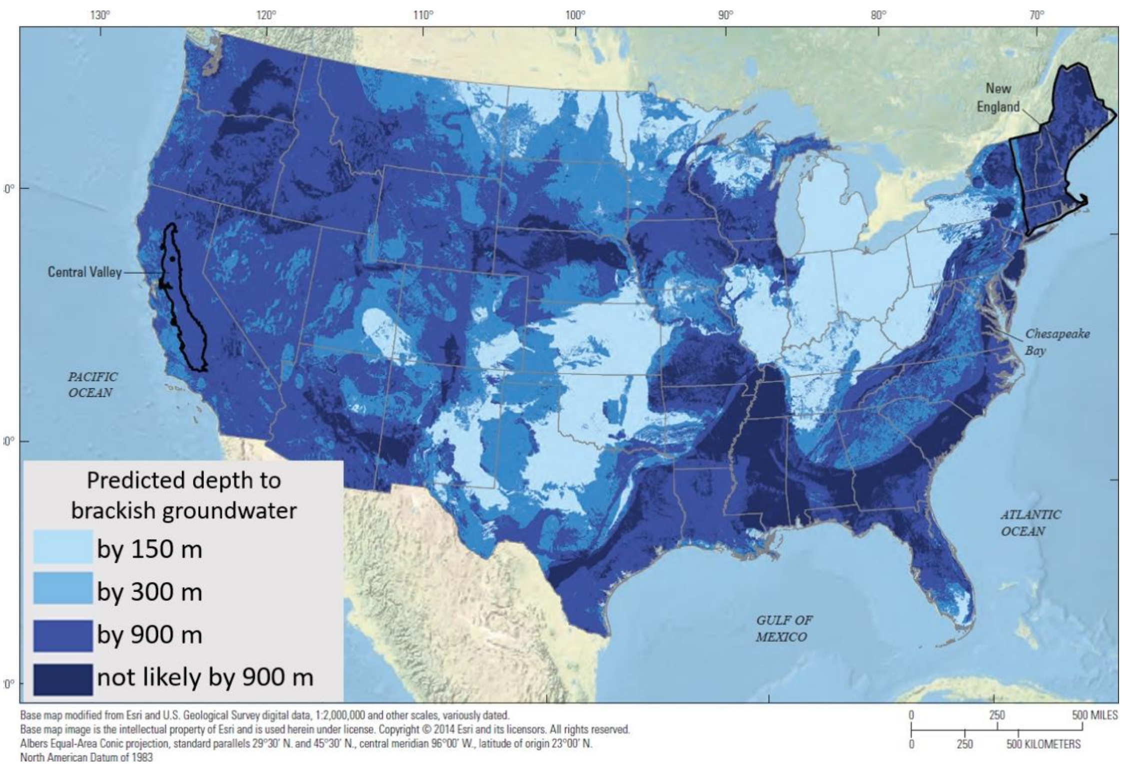

Figure 57 - Estimated depth to brackish water on the continental United States. In lightest blue areas it is likely that brackish water will be encountered at less than 150 m depth, whereas in the darkest blue areas it is likely that brackish water will be encountered only at depths greater than 900 m (adapted from Stanton et al., 2017).

Unanticipated occurrences of fossil freshwater have been discovered under the ocean floor off the northeast coast of the United States. This indicates that much remains to be discovered about the extent and character of groundwater in some areas of the globe (Gustafson et al., 2019).

Where the groundwater flow system discharges to the surface, the chemical constituents end their groundwater journey and enter the above-ground portion of the hydrologic cycle. In regions with a humid climate, this journey ends as seepage into streams, rivers, wetlands and lakes, ultimately reaching the oceans. In arid and semi-arid regions, the journey ends as seepage to lowland flats and dry valleys. Evaporation from such areas can concentrate the solutes in shallow groundwater by hundreds to thousands of times, leaving the areas unsuitable for agriculture. In short, the chemistry of the groundwater discharge governs both the chemistry of most surface waters and the accumulations of salts on land and in soils of arid regions.

In arid climates vegetation is sparse, recharge is minimal, water tables are generally deeper, hydraulic gradients are low, and groundwater residence times are long. As a result, the dissolved constituents in groundwater of arid areas differ from, and concentrations are generally higher than, those where groundwater recharges in humid areas and flushes the geologic units. Most constituents in groundwater originating in arid climates are from atmospheric aerosols that are concentrated by evaporation and accumulate on the surface until a rare, major recharge event flushes them down to the water table. The lack of vegetation reduces the amount of carbon dioxide in the recharge zone; thus, chemical weathering of the aquifer material by carbonic acid is slower and concentrations of constituents produced by chemical weathering are lower. As a result, the groundwater includes more sodium chloride, calcium sulfate or sodium carbonate and less calcium carbonate than groundwater originating in humid zones. In addition to these differences, the slower groundwater flow allows time for constituents from relic and underlying saline aquifers to migrate into the shallow groundwater system, further increasing its salinity.

In some arid places where groundwater discharges to the surface, open water is not visible; instead the water evaporates at the surface and salt deposits form. This occurs in many places on Earth. A study of the Abu Dhabi salt flats illustrates water evaporating from the capillary fringe that intersects the surface forming a salt flat covering about 36,000 km^2 (Figure 58). Much of the dissolved chemical constituents originate from groundwater seeping to the surface creating a concentration that is about 10 times that of sea water. The sparse, or absent, vegetation in arid areas permits aeolian (wind) processes to act in concert with the water table to develop unique landforms such as sabkhas (Arabic, for salt flats). With minimal vegetation, aeolian activity erodes deeply into the surficial sediments, but cannot move material below the capillary zone, as it is fully saturated, and thus not lifted by the wind. In such a place, the Earth's surface reflects the shape and slope of the underlying water table. These surfaces then become large, flat, discharge areas where evaporation causes salt accumulations that form salty crusts (Figure 58).

Figure 58 - Salt flat (sabkha) Emirates of Abu Dhabi, United Arab Emirates. Although this photo may appear to be of low-resolution, it is not; rather the grainy appearance of the image is due to the extremely high surface temperature of 65 °C (photo by Wood et al., 2002).

Alkaline (high pH) springs sometimes referred to as "Blue Pools" because of their deep blue color, are found in areas where high temperature minerals from the Earth's mantle have been brought near the surface by tectonic activity of the Earth (Figure 59). These minerals were formed at high temperature and pressure and are unstable in the near surface environment, thus are easily weathered. Weathering, in this case without carbon dioxide, involves splitting of water molecules with removal of a hydrogen ion (H^+) to form silicic acid (H_4SiO_4) and hydroxide ions (OH^-) that increase the alkalinity (i.e. raise the pH). When the water is discharged to the surface, the calcium ions in this alkaline water react with carbon dioxide in the atmosphere and the mineral calcite ($CaCO_3$) precipitates in very thin sheets on the water surface. These sheets then sink to the bottom of the pool forming a soft, fluffy-white sediment. The pools are blue because water absorbs the red part of the light spectrum leaving colors in the blue part of the light spectrum for our eyes to see, and this effect is enhanced by the shallow water overlying the white calcium carbonate bottom. In many such pools inorganic methane and hydrogen gas bubbles can be observed rising to the surface.

Figure 59 - A blue pool in Northern Oman formed where minerals from the Earth's mantle reached the surface and weathered, creating alkaline water that reacts with the atmosphere to precipitate thin white calcite sheets on the surface of the pool. The sheets settle to the bottom of pool forming a soft, fluffy-white sediment that enhance the blue color (photo provided by Warren Wood, 1990).

Geochemical Factories and Conveyor Belts in Dry and Wet Climates

In summary, with some exceptions, groundwater evolves from a nearly pristine state (low concentrations of dissolved species) where precipitation falls on the earth and the concentrations of dissolved species increase as water travels through the vadose zone. In the vadose zone, carbonic acid is generated by dissolution of CO_2 gas from roots, decaying organic matter and microbes. The carbonic acid dissolves minerals, which increases the total dissolved solids (TDS) in vadose zone water. Evapotranspiration further increases the TDS because water molecules are released into the atmosphere while all salts are left behind in the water feeding the underlying groundwater flow system. While moving along the flow paths in the groundwater zone, the water may undergo little or no increase in TDS before it discharges to the surface, as is often the case in local groundwater flow systems, or it may acquire much higher TDS as is common in regional flow systems. **The groundwater in motion provides conveyor belts for the dissolved constituents that carry the dissolved load from recharge areas to discharge areas.**

There are two categories of conveyor belts (Figure 60). First, there are those operating in dry climates, where all of the groundwater discharge evaporates or evapotranspires while the salts are left behind to accumulate in saline soils, salt flats, or salt lakes such as the Great Salt Lake in North America, Lake Eyre in Australia, Lake Titicaca in South America, and Lake Chad in Africa. The chemical nature of the groundwater discharge zone in the dry climates is influential, perhaps the dominant influence, on the ecology of surface vegetation and aquatic systems. In contrast, the second, wet climate conveyor belts discharge their chemical loads into surface water bodies such as springs, streams, rivers, marshes and swamps and much of this water eventually discharges into the oceans.

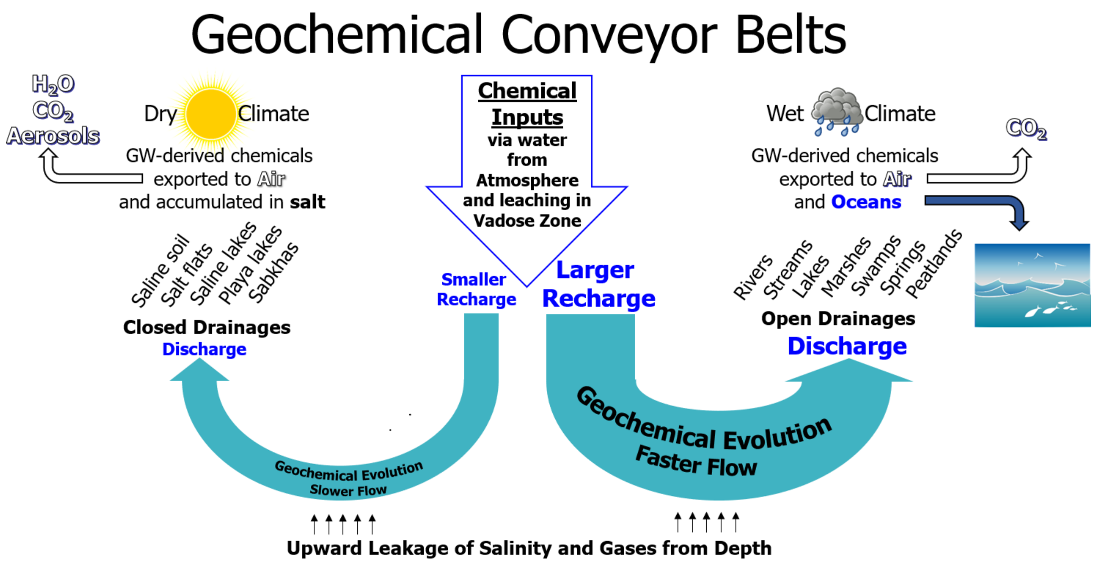

Figure 60 - In recharge areas, aerosols enter the vadose zone with infiltrating water, bicarbonate (HCO_3^-) is created in the vadose zone, and the dissolved constituents enter the groundwater zone. In dry climates, when groundwater rich in HCO_3^- ions discharges to closed drainages, HCO_3^- and CO_2 are released and mineral deposits form during evaporation. Wind erodes the mineral desposits introducing aerosols into the atmosphere. In humid climates, when groundwater rich in bicarbonate (HCO_3^-) ions discharges to surface-water bodies, CO_2 is released to the atmosphere and calcite ($CaCO_3$) is formed, some of which is deposited on stream bottoms and the rest is transported to the oceans as fine suspended sediment along with dissolved HCO_3^- (Poeter et al., 2020, gw-project.org).

When considering flow rates and the distribution of hydraulic head, groundwater systems are generally in balance with the present-day hydrologic conditions on today's landscape. In other words, the distribution of water pressures in the groundwater zone are in a near-steady condition established by the average conditions of today's climate, except where there is excessive groundwater pumping. However, this is not the case for the chemical composition of groundwater, which, nearly everywhere, is not in a steady condition and generally not in geochemical equilibrium with the minerals the groundwater encounters along the conveyor belts. In locations that have not reached geochemical equilibrium, geochemical processes combine with groundwater flow to continually extract chemical mass from the geology for discharge at the surface. In contrast, in parts of the world that have been geologically stable for tens of millions of years, the geochemical factory and conveyor belts have extracted essentially all of the available soluble materials. In those places, the groundwater is fresh, even as deep as one or two kilometers. This fresh groundwater has exceptionally low TDS, influenced primarily by the chemical load contributed from the atmosphere.

7.3 Groundwater as a Waste Repository (Out of Sight, Out of Mind)

On much of the Earth where there is some form of human activity generating chemical constituents that enter the subsurface causing changes in groundwater chemistry. Millions of different chemical compounds have been produced around the globe and many more are developed each year. As a result, many different chemical compounds have leaked into the subsurface in the past 100 years but only several thousand of these are currently known to cause detectable groundwater contamination. Figure 61 displays the types of chemical constituents that cause degradation of groundwater quality. Chemical constituents originating from human activities are known as anthropogenic compounds to distinguish them from the natural elements (geogenic elements) in groundwater. Most changes in groundwater chemistry are not detrimental to humans or ecological systems; however, those that can harm human health and the environment have become immense problems in many regions. The first recorded discovery that groundwater contamination can cause much human illness and death was made by a physician, John Snow, who in 1854 traced the cause of a cholera epidemic in London, England to a water well that was contaminated with human sewage. Although groundwater has been more protected since that time and causes fewer epidemics, illness and death due to groundwater contamination is widespread around the globe.

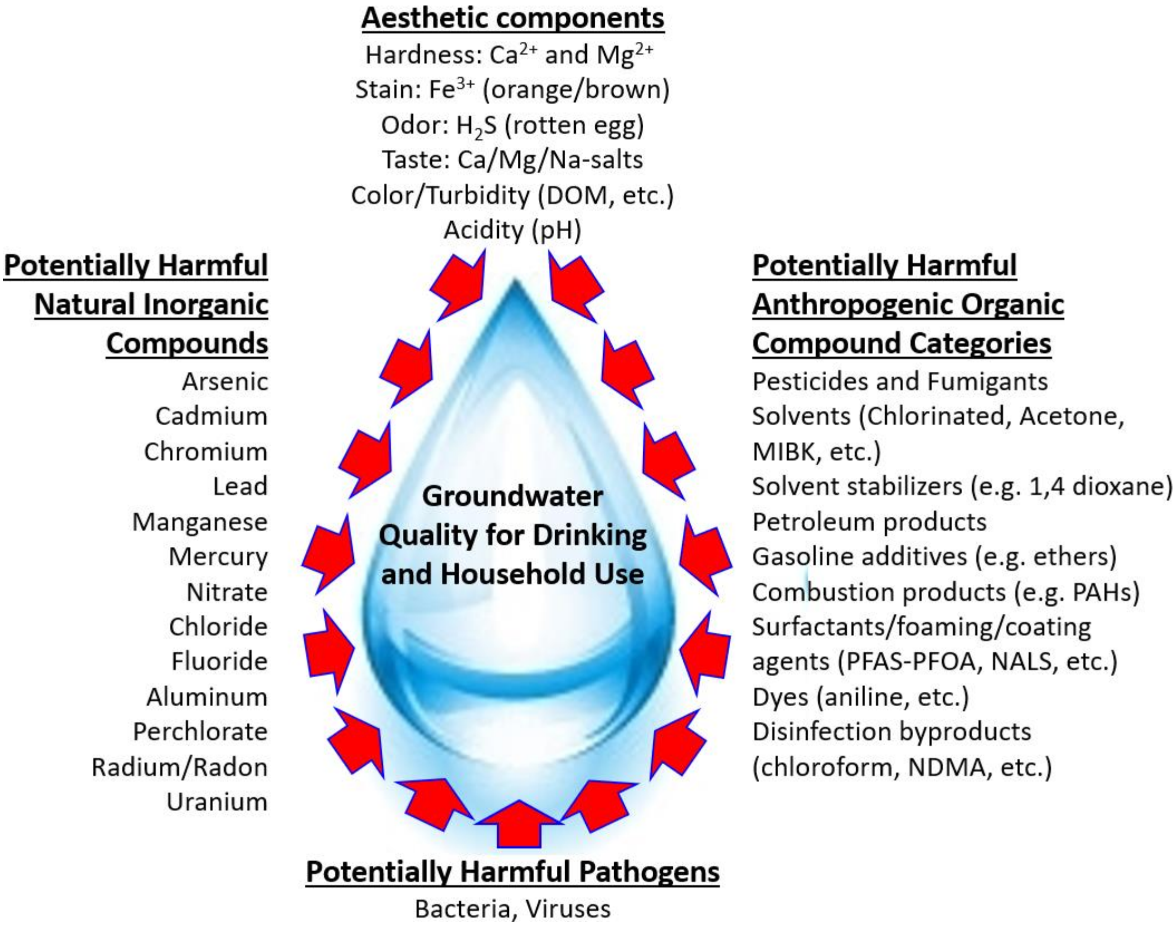

Figure 61 - Categories of chemical compounds that cause degradation of groundwater quality (Poeter et al., 2020, gw-project.org).

Figure 62 shows many of the activities and sources of chemicals in cities and rural areas that commonly cause groundwater contamination. In addition to the contaminants shown in Figure 62, urban areas have networks of sewers which often leak at joints and breaks. Suburban and rural areas have septic tanks that contribute to groundwater contamination. Each of the categories of contamination shown in Figure 62 results in a zone of groundwater contamination that extends away from the source in the direction of groundwater flow and, owing to its shape, it is known as a plume. Like the natural constituents in groundwater, the anthropogenic compounds migrate from recharge areas to discharge areas or to water wells. Some plumes travel to their discharge areas within a few years or decades, while others travel much longer paths with groundwater residence times of centuries or more. These longer and deeper flow paths are illustrated in Figure 35 and Figure 38. Some plumes disappear due to natural degradation or assimilation by subsurface chemical and/or microbial processes, or by dilution. However, contaminants in other plumes may not be removed or may be converted by chemical or microbiological processes into other contaminants that persist and continue migrating along the flow path until they are discharged.

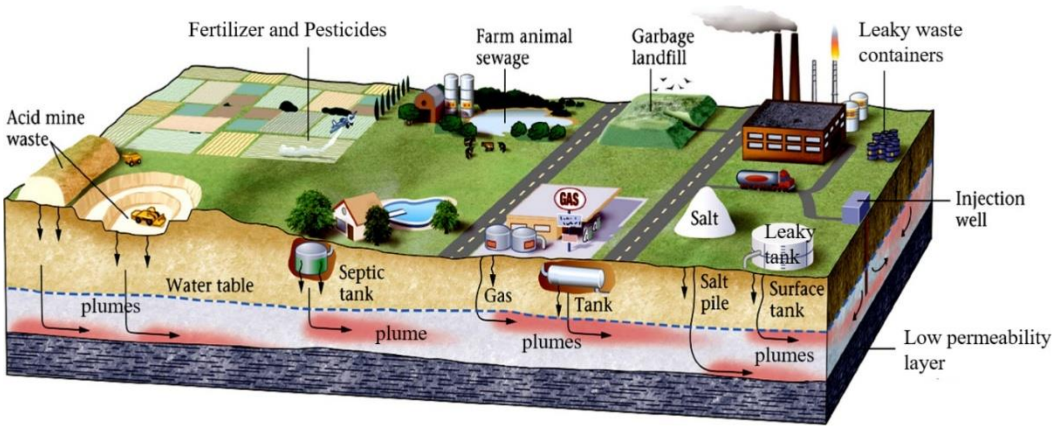

Figure 62 - Chemical constituents from anthropogenic activities enter the subsurface, changing the chemistry of groundwater and creating contaminant plumes in groundwater (adapted from Marshak, 2005).

Before the Industrial Revolution two centuries ago, the chemical constituents from human activities entering the subsurface were mostly natural nitrogen and organic compounds from humans and the waste of their animals. These chemicals rarely caused harm because they were readily assimilated or degraded by natural processes. In general, the subsurface has a huge capacity for assimilation (ability to clean itself) of many anthropogenic chemicals, which provides protection from most of the chemicals produced in our modern industrial society. However, in recent time we have released sufficient anthropogenic chemicals to overload the subsurface system to the point where the assimilative capacity for these compounds has been exceeded. Beginning during the Industrial Revolution of the early nineteenth century, with its capability to extract useful substances from coal and other geologic materials, new varieties of compounds were released into groundwater, including metals and coal tars. These were of limited societal concern at the time owing to low population density, limited use of groundwater, and sparse industrial activities.

Groundwater contamination sufficient to cause concern began in Europe and North America in the 1950s when:

1) increased industrial production created the consumer society and the ubiquitous releases of chemicals to the subsurface;
2) municipalities started spreading sewage sludge on land and using dumps for solid and liquid wastes, which evolved into engineered landfills;
3) the "green revolution" led to the development and expansion of machine-dependent agriculture with chemical fertilizers, herbicides and pesticides;
4) industries began manufacturing complex organic chemicals for use in cleaning, fire protection, personal care products, pharmaceuticals, and other applications, which became used ubiquitously, some being released directly to the environment (e.g. during firefighting) and others present in wastewater, which

commonly leaks from sewers or is released directly to the subsurface via septic tank leach fields; and,
5) use of groundwater increased to avoid using water from polluted rivers and lakes.

Most of the millions of manufactured organic chemicals are either not mobile in groundwater because they bind to mineral surfaces or are quickly degraded by natural bacteria and have little impact. Some, however, now known to total a few thousand, are mobile and degrade slowly if at all (are refractory) or are converted by natural processes to other more harmful contaminants. Many of these contaminants can be conveyed by groundwater flow and, in most industrialized countries, there have been 50 to 70 years of migration of mobile refractory contaminants in groundwater, leading to long plumes (100s to 1000s of meters in length).

We can determine the location of groundwater that entered the subsurface during that era by analyzing for the presence of low-level concentrations of tritium (radioactive water molecules) that were released to the atmosphere in the 1950s and early 1960s from above-ground nuclear testing and dissolved in precipitation which then recharged into the groundwater. In most industrialized countries, nearly all of the important aquifers now show the presence of atmospheric tritium and at least trace concentrations of other anthropogenic chemicals. Generally, more and more types of chemical compounds continue to be found in groundwater, but the long-term consequences of this trend are not known, especially with regard to the impacts of mixtures of different types of contaminants on human health. In our densely populated and industrialized world, most fresh water resources including rivers, lakes and groundwater are receptors for the increasing diversity of chemical contaminants. This increases the challenge in determining the requirements for water treatment to make water safe for drinking.

One of the features that sets groundwater apart from surface waters is that contamination of groundwater has a much longer residence time. If we were able to "wave a wand" and cease all further releases of contaminants into groundwater, the contaminants already in groundwater would eventually be flushed out or completely assimilated because most plumes are part of dynamic groundwater flow systems with assimilation capacity. But for many plumes, the time required for flushing or assimilation will be centuries or millennia. One example is the fumigant dibromochloropropane (DBCP), whose use in farming areas in the U.S. was banned in the 1979, yet DBCP was still widely detected in California groundwater as late as 2017, 38 years after its use was stopped. In contrast, flushing and attenuation in rivers and lakes typically requires only weeks or months after inputs cease. Therefore, given that groundwater contamination can persist for long periods of time, an important goal is to prevent more contamination from entering groundwater so that contaminants do not start the long groundwater journey.

Much of the reason that groundwater has become degraded is because humans often have an "out of sight-out of mind" perspective. However, even when groundwater was on our minds, there were errors in our assumptions about groundwater and thus unrealistic expectations of what would happen when wastes were released into the subsurface. For example, consider on-site sewage treatment and disposal systems (septic systems) that are used to dispose of household sewage. Septic systems are wastewater-treatment installations that are emplaced underground. Typically, a septic system has a tank and a drain field with horizontal perforated piping for the wastewater to infiltrate through the vadose zone into groundwater (Figure 63). While septic systems provide the first line of defense against the spread of disease because they generally remove pathogens (bacteria and viruses), they are not designed to remove the nitrogen and many other contaminant types derived from household chemicals and pharmaceuticals. Figure 63 shows a septic system and its plume in the groundwater shortly after the septic system was installed. With time, the plume of refractory compounds becomes longer and longer until it reaches a receptor such as a well, river, lake or ocean estuary.

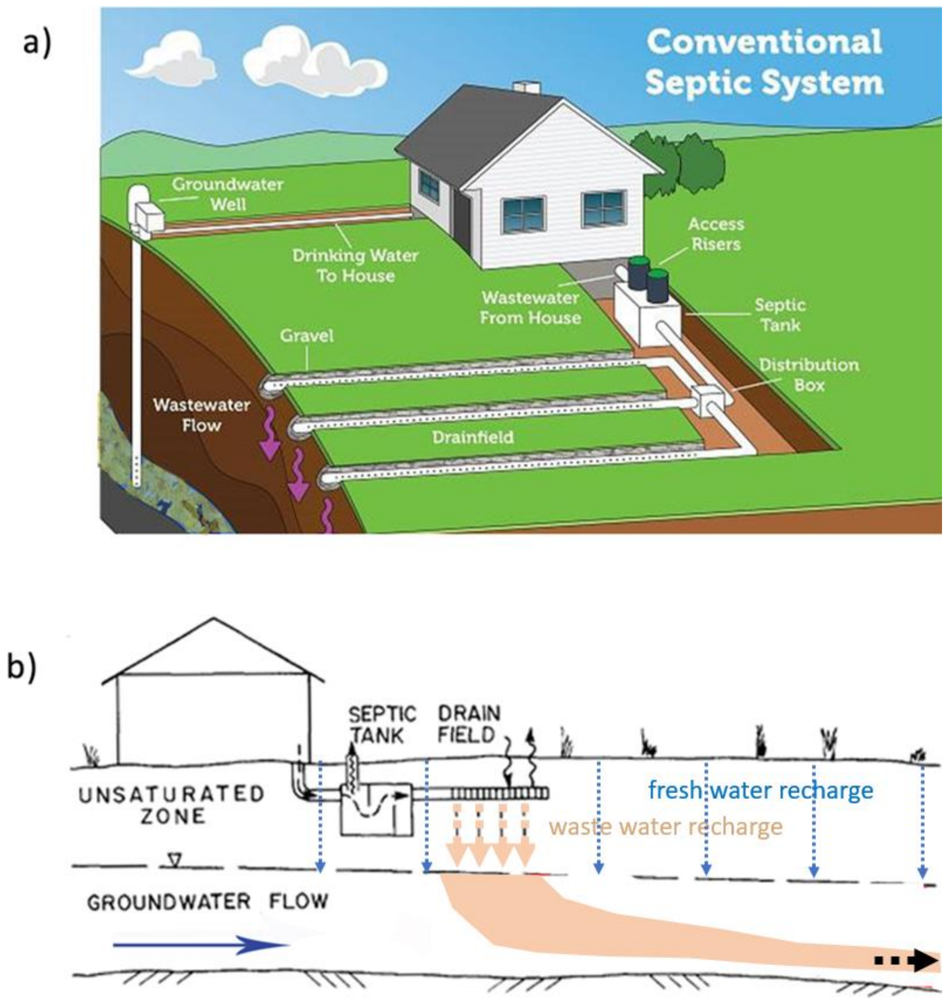

Figure 63 - Diagram of: a) a typical residential septic system with a domestic well nearby; and b) the associated plume, established not long after the system began operating (adapted from Wilhelm et al, 1996).

About one-fifth of households in the United States, Canada and the European Union have (on-site) septic systems. Septic plumes contain nitrate and phosphorus, as well as chemicals from pharmaceuticals, personal care products and food additives. In the 1950s, septic systems became a standard household feature of many areas in the rapidly developing suburban areas of the United States. This was based on engineering analysis, but the analysis assumed a strong degree of plume attenuation by strong assimilative capacity of the subsurface. The septic plumes were not expected to extend far from each septic system and the occurrence of persistent nitrate, phosphate, pharmaceuticals and food additives in plumes was not anticipated. In fact, most households with septic systems also have a water well on the property (Figure 63) and often not far enough removed from the septic systems to avoid capture of chemicals in the plume from the septic leach field. Overall, the magnitude of impacts of septic system contaminants in groundwater on human health are poorly understood, but what is not poorly understood is that septic system contamination is damaging the water quality and ecology of many lakes, rivers, estuaries and bays because the discharge of nitrogen and phosphorus to these water bodies causes eutrophication. These effects are also caused by plumes from leaky city sewer systems.

Likely the main problem for human health from human and animal sewage going into groundwater is contamination by pathogens, for example some strains of Escherichia coli (E. coli) bacteria and viruses. Bacteria are generally not mobile in sand aquifers because they are large enough to be filtered out by the sand, but can be mobile in gravel aquifers, karst and fractured rock aquifers, and as viruses are much smaller, they are more mobile than bacteria in aquifers. Harmful viruses can remain active for as long as three years and may travel many kilometers in high permeability aquifers. E. coli are bacteria that are easy to detect in water samples and their presence is an indicator of the potential presence of viruses. Although there are now effective methods for sampling and analysis of viruses in well water, such testing is rarely done, so that the frequency of illness attributable to viruses in groundwater is poorly known. E. coli are commonly found in household wells.

The so-called green revolution in food production is another global example of how new science was to bring large benefits, but inadvertently brought immense adverse groundwater side effects. This started in the 1940s with large changes in crop genetics (plant cross breeding), but that aspect of the revolution soon ended when agriculture became highly mechanized and dependent on manufactured fertilizers, herbicides, and pesticides. A significant amount of the nitrogen in the fertilizer ends up in groundwater as nitrate (NO_3^-), where it is harmful to human health and detrimental to ecosystems. As a result of chemical agriculture and sewage leaching into groundwater, nitrate is now the most common contaminant in groundwater around the globe.

When charting the history of groundwater contamination over the past 70 years, one finds that the development and production of new chemical products often has unintended negative consequences for groundwater quality (Figure 64).

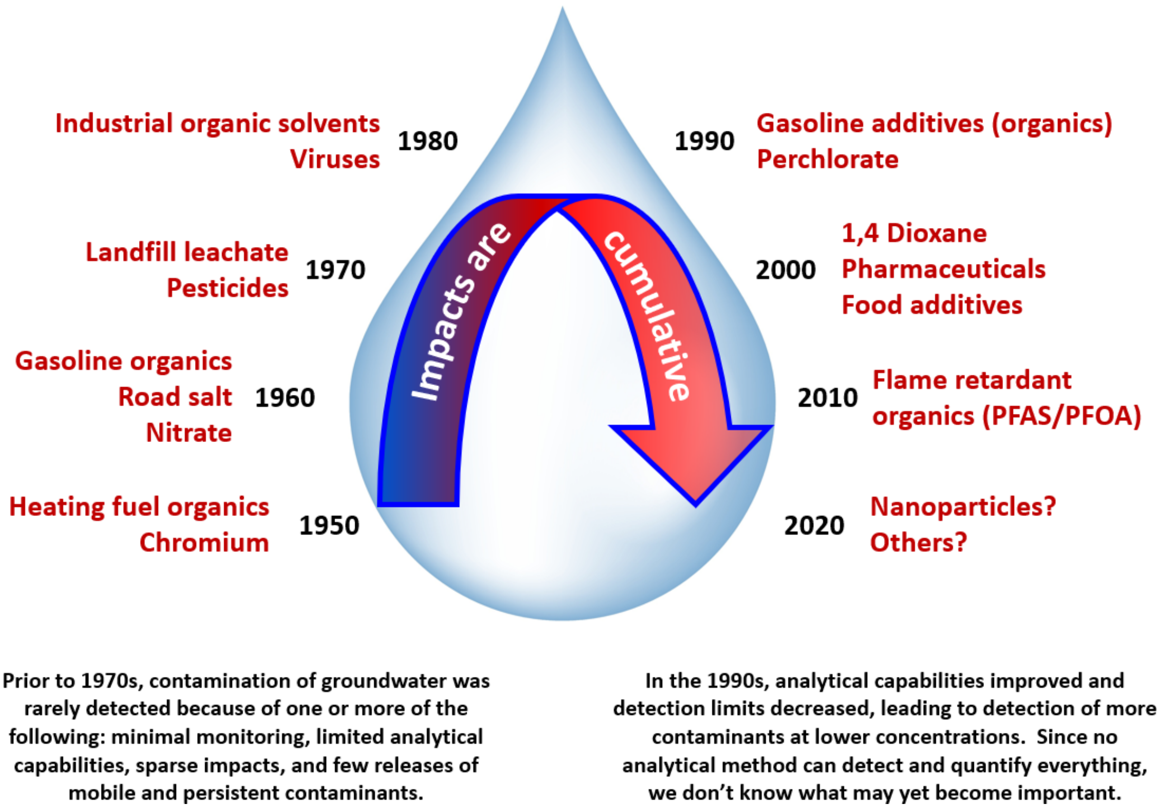

Figure 64 - Evolution of sources of contaminants entering groundwater in past 100 years. Examples of some of the contaminants are given in Figure 65 (Poeter et al., 2020, gw-project.org).

The most recent example of a scientific advance that was designed to improve everyday life having a negative impact on groundwater is the development of several thousand fluorinated organic chemicals known collectively as PFAS (per- and poly-fluoroalkyl substances) as shown in Figure 65. These are essential to producing modern commercial products such as Teflon, Gore-Tex, fire-fighting foams and flame-retardant clothes and bedding. They are widespread globally in groundwater, where they are mobile and persistent. They bioaccumulate (accumulate in tissues of organisms exposed to them) so now most human beings and many other animals on Earth have PFAS in their blood and cells. Accumulation of PFAS in humans and animals has been related to problems such as disruption of the immune and metabolic systems, complications in neurodevelopment and cancer (Sunderland et al., 2019).

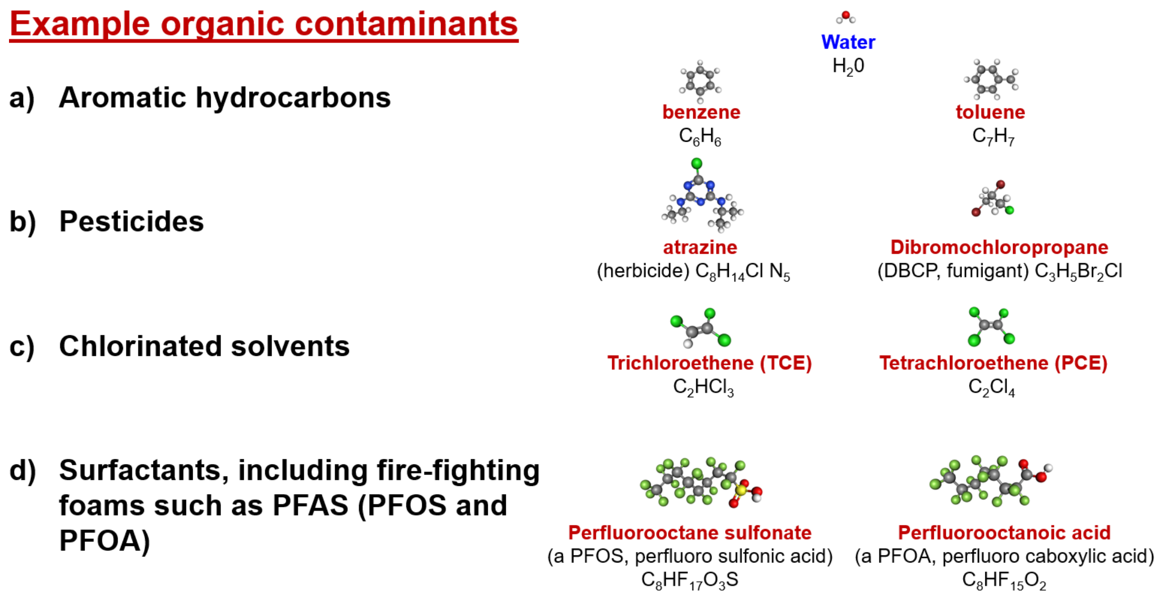

Figure 65 - A few examples of classes of organic contaminants detected in groundwater (only two shown for each class, though many others are discussed in other Books of the Groundwater Project): a) aromatic hydrocarbons from gasoline spills; b) pesticides (a herbicide and fumigant); c) chlorinated solvents; and, d) surfactants, including fire-fighting foams. A water molecule is shown at the top for comparison of size and structural complexity. Note that the PFAS examples are but two of several thousand PFAS compounds created for a multitude of everyday-use products (Poeter et al., 2020, gw-project.org).

Another scientific advance that may negatively impact groundwater is the development of nanoparticles which are used in the manufacture of many products including scratchproof eyeglasses, crack-resistant paints, anti-graffiti coatings for walls, transparent sunscreens, stain-repellent fabrics, self-cleaning windows and ceramic coatings for solar cells. Nanoparticles are in our waste and will likely be found in groundwater. If nanoparticles are found to be common in groundwater, we do not know what the consequences will be.

In this discussion of groundwater contamination, the outcomes have all been negative, but there is a concept for using the groundwater zone as a waste repository aimed at positive outcomes. This is the development of deep geological repositories (DGR) for high-level nuclear waste. This waste needs to be contained for a million years. Therefore, the objective is to entomb the waste in deep zones where the radioactivity will be contained on a geological time scale. In other words, store the waste where the groundwater is not part of the active hydrologic cycle under current conditions. Many countries are designing and some are operating DGRs in very low permeability geologic layer sat depths on the order of 450-600 meters below ground surface where the groundwater is saline, stagnant and shows evidence of having resided in these layers for millions of years (Figure 66). There are many other types of hazardous wastes with chemicals that are not radioactive but degrade slowly and DGRs are also an option for isolating some of these wastes from the environment.

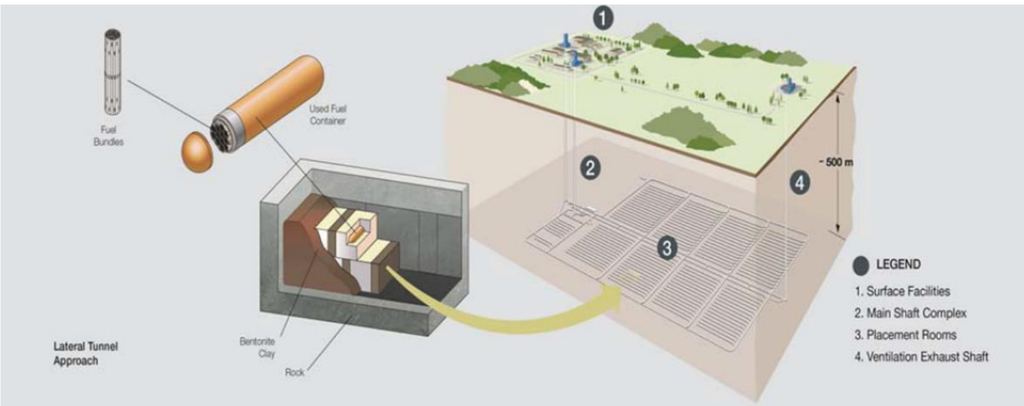

Figure 66 - In a deep geologic repository for solid nuclear waste, the waste is entombed in mined cavities in solid, extremely low permeability rock (Faybishenko et al., 2016).

7.4 Groundwater as a Global Life Support System

The presence of fresh liquid water makes life possible on Earth. The quest for signs of extra-terrestrial life in our solar system and beyond is fundamentally a quest for signs of liquid water.

Groundwater for Agriculture and Drinking Water

In 2017, the World Bank estimated that, globally 70% the percentage of freshwater is used for agricultural activity that feeds the human population of Earth. In 2019, The Global Agriculture Organization estimated the percentage of freshwater used for agricultural in major regions of the world as shown in Figure 67, also estimating that globally 70% of freshwater use is for agriculture. Groundwater provides drinking water entirely or in part for as much as 50% of the global population and accounts for 43% of all of water used for irrigation (UNWWAP, 2015). Worldwide, 2.5 billion people depend solely on groundwater resources to satisfy their basic daily water needs (UNWWAP, 2015).

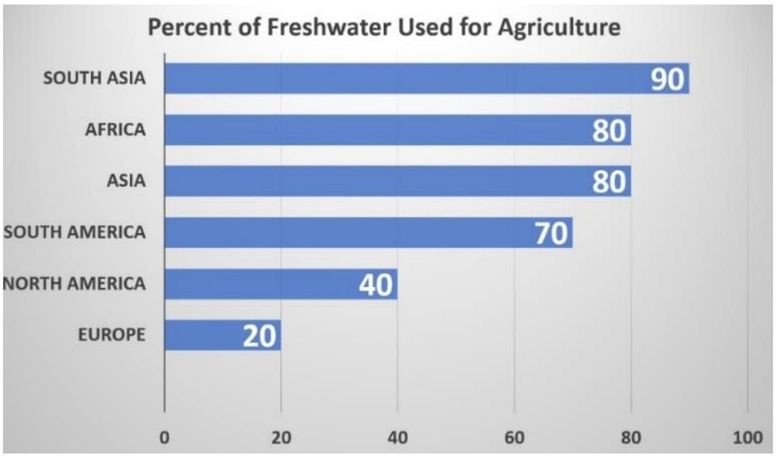

Figure 67 - Percentage of freshwater use that is dedicated to agriculture in major regions of the world (data from Global Agriculture, 2020).

The groundwater is critical to production of food needed to support Earth's current population, and has served humanity reasonably well for centuries, but is now under great stress. At present, as much as 10% of the world's food is produced by depleting groundwater systems and the number of people to feed is rising rapidly. Irrigated agriculture is generally twice as productive as dry land farming, however, there is only a limited amount of accessible water that is not already allocated.

The world population of nearly 8 billion in 2020 is projected to be near 11 billion at the end of the 21st century. The food supply of many countries is threatened. The advances made by the Green Revolution are fading and, in some regions, there is a decrease in the amount of food production due to soil erosion and salinization. China, with 19% of the world's population (1.4 billion people) but only 7% of the arable land, is soon to complete the largest water diversion project in the world in order to end decades of groundwater depletion in the North China Plain. Water from the Yahtzee River is being diverted 1,000 kilometers northward where much of the water will be used to replenish the vast aquifers. In contrast, India, with a population projected to exceed that of China in 2024, has an even greater need for more water, but the prospects for a solution are much less. India uses twice as much groundwater as China, with 89% of the water used to irrigate crops. Much of the current groundwater use in India is depleting aquifers, thus the use is not sustainable. Large areas of India have substantial rainfall, but much of the rainfall quickly makes its way to the oceans without being used to produce food. Climate change is projected to bring even more challenges to many of the countries already in a state of water stress and water insecurity.

As this book elucidated, surface water bodies in all types of terrains are sustained by the steady release of groundwater (Figure 68). This is the primary reason that our streams do not run dry despite days to months without rain. Also, groundwater does not heat or cool quickly, despite the fluctuating air temperature, thus its inflow to streams provides a stable habitat for aquatic plants and animals. Along the edges of streams and lakes, as well as in lowlands and on coastal plains, unique environments called wetlands (which include marshes, bogs, swamps and peatlands) occur as the transition zone between the lowland aquatic and the upland terrestrial environments. They exhibit unique dynamics of water and air availability; hence, they support life specialized in "making a living" in wet places with minimal oxygen.

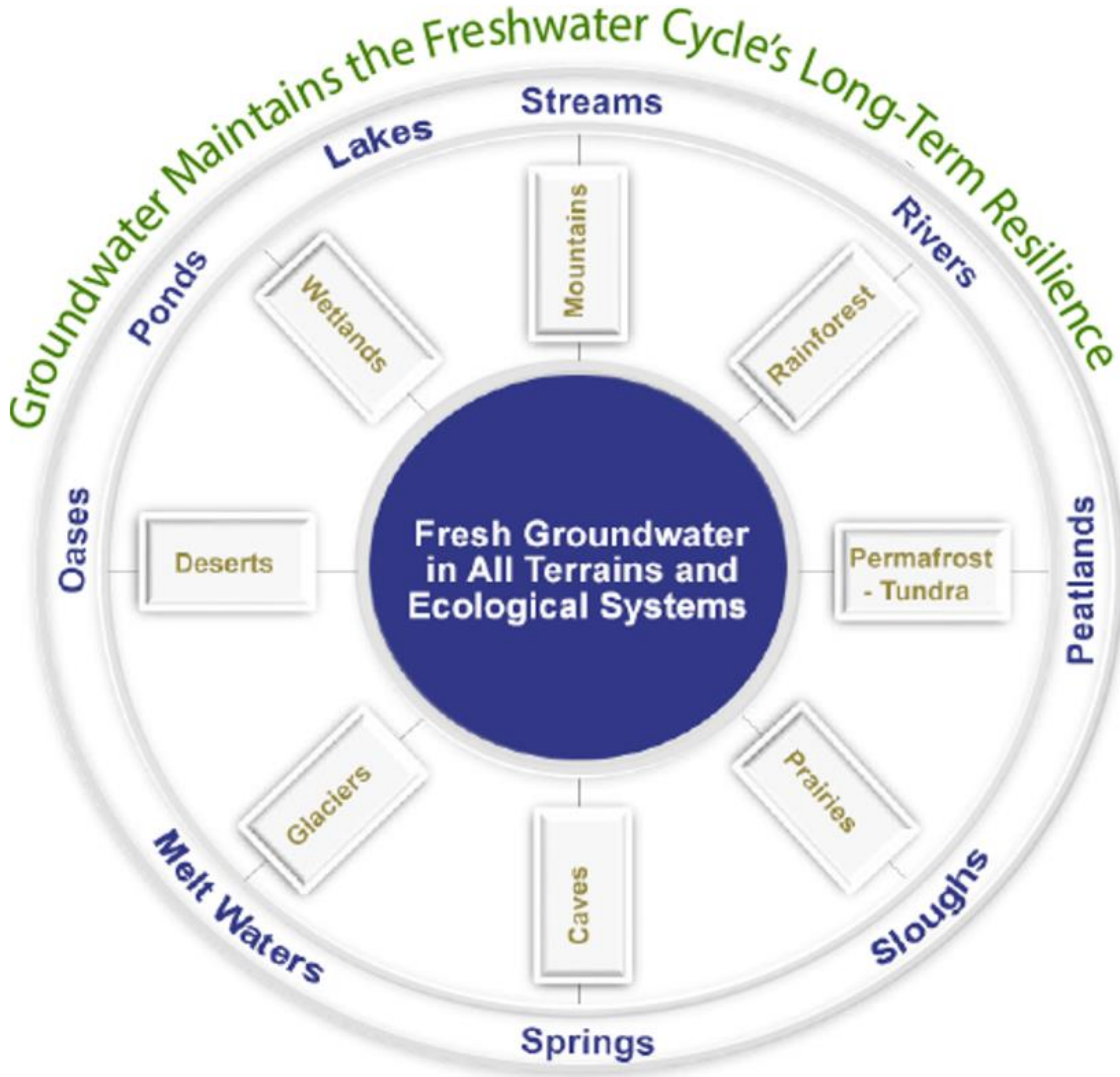

Figure 68 - Many types of surface water bodies in many different of terrains are sustained by the steady release of groundwater (Poeter et al., 2020, gw-project.org).

Wetlands are dispersed throughout the globe and cover over 12 million km^2, an area almost as large as Greenland. Natural wetlands are in long-term decline around the world, having decreased in area by 35% between 1970 and 2015, which is about three times the rate of forest loss. Wetlands exist not because more rain fell on their locations, but because they are located in an area with a shallow water table within the reach of plant roots. In other words, it is shallow groundwater that creates and maintains wetland habitats. Further upland, where the water table is deeper and plant roots can respire, but where the water table is shallow enough to be within reach of large plants with deep roots, groundwater provides much needed water during dry seasons when the shallow subsurface dries out.

Groundwater provides multiple services by regulating surface water flow, supporting ecosystems, and providing water for humankind. In short, groundwater is the Earth's life support system. In 2019, van der Gun grouped groundwater service according to the Millennium Ecosystem Assessment classification of ecosystem services as shown in Figure 69.

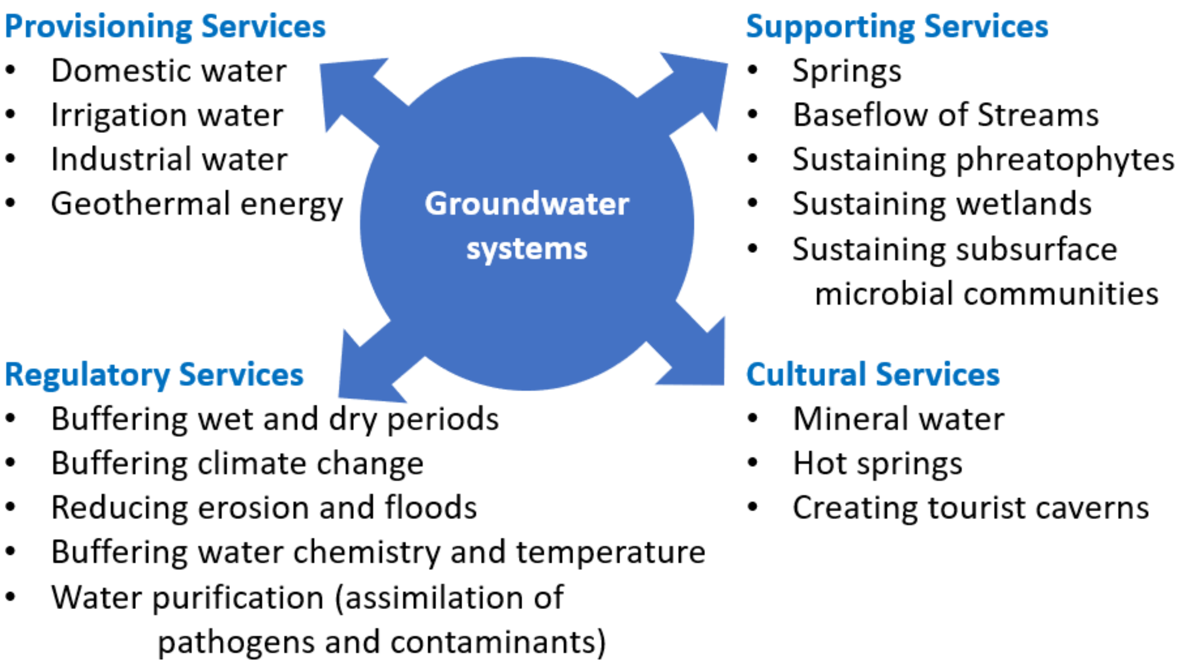

Figure 69 - Overview of important services provided by groundwater systems, grouped according to the Millennium Ecosystem Assessment classification of ecosystem services (adapted from van der Gun, 2019).

In summary, groundwater provides vital water supplies for human societies, directly for drinking water, and indirectly through large-scale irrigation for food and fiber production. Like natural ecosystems, humans require sustainable sources of water. Long-distance groundwater convergence toward, and discharge to springs has provided life support for our species for millions of years. The difference today is that humans have the unprecedented power to withdraw large volumes of groundwater and have the power to transport that water over long distances, in many places surpassing the capabilities of the natural hydrologic cycle. Therefore, modern humans are using much more groundwater and withdrawing it much faster than nature can replenish, while also introducing anthropogenic chemicals faster than nature can assimilate them. There is no question that our lives depend on groundwater, and as the human population grows, more demand will be placed on this vast, but finite, resource. The need for understanding our groundwater systems and for managing them in a thoughtful manner within the constraints of the hydrologic cycle, is greater than ever.

8 Disappearing Groundwater

Earth has many thousands of aquifers, but only a few dozen aquifers are categorized as major. Thanks to a decade (2003 to 2013) of satellite data collected by a unique NASA Earth-observing mission called the Gravity Recovery and Climate Experiment (GRACE), much is now known about the depletion of many of the major aquifers. Unlike satellite missions that rely on visual images, GRACE measured the tiny space-time variations in Earth's gravity field, effectively weighing changes in water mass of large aquifers. Figure 70 illustrates groundwater depletion (-) or replenishment (+) in millimeters of water per year based on GRACE data for Earth's 37 largest aquifers.

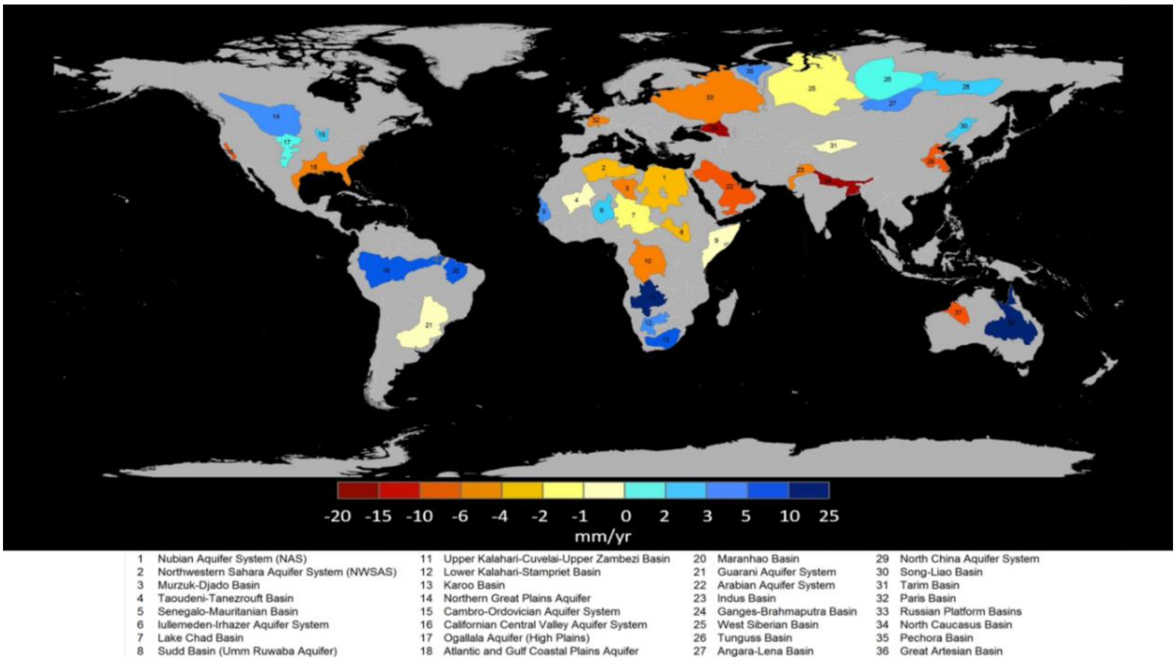

Figure 70 - Groundwater depletion (-) or replenishment (+) in millimeters of water per year for Earth's 37 largest aquifers based on GRACE data from 2003 to 2013 (adapted from NASA/JPL-Caltech, 2015).

The GRACE results are consistent with long-term estimates of groundwater extraction. The estimated evolution of groundwater extraction in India from 1950 to 2010 is shown in Figure 71, together with similar time series for a selected group of countries. India's groundwater extraction rate in 2010 was approximately 251 cubic km per year, equivalent to a quarter of the global rate. The Ganges-Brahmaputra basin suffers aquifer depletion and groundwater pollution stresses including swathes of India, China, Nepal, Bangladesh and Bhutan, which collectively is home to about 10 percent of the Planet's population. Close to 50 percent of the world's aquifers may be "past their tipping point", which means that a natural recovery would require centuries.

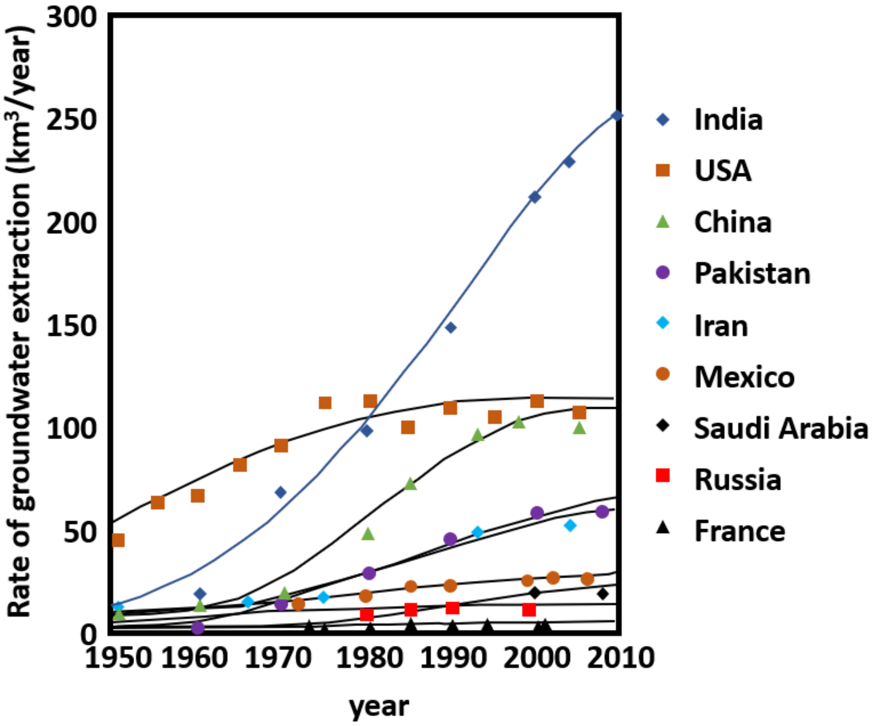

Figure 71 - Estimated national groundwater extraction for selected countries from 1950 to 2010 (adapted from Van Der Gunn 2019, with data from Margat and Van Der Gun, 2013).

The Nubian system, the biggest non-renewable aquifer (fossil water) in the world, occurs under parts of Egypt, Libya, Sudan and Chad. Mostly underlying Egypt and Libya, it is considered under high-stress due to unsustainable withdrawal rates driven by population growth. Libya depends on the aquifer for about 95 percent of its water.

The Nubian system also features one of the few trans boundary aquifer agreements. Worldwide, six trans boundary aquifers exist with specific agreements, and two aquifers with informal accords. The Northwest Saharan aquifer system that underlies 60 percent of Algeria, almost a third of Libya and part of Tunisia is another trans boundary aquifer with high levels of water withdrawals. It also falls under a cooperation pact and is similar to the Nubian system in that it is non-renewable water. The water is used mainly for agricultural irrigation and industry.

Projections based on current water usage, anticipated population increase and economic growth scenarios suggest substantial shortfalls in water availability in the coming decade, including nearly 600 aquifers that cross sovereign borders. The depletion of aquifers is the most evident of the Planet's two groundwater problems, the other problem is groundwater pollution. Pollution diminishes the usefulness of the water that remains after aquifer depletion. The failure to manage Earth's groundwater resources is a threat to the global stability of human society.

9 Challenges in Groundwater Governance

The hundreds of books that are being prepared for inclusion in The Groundwater Project are aimed at bringing knowledge to the many pieces of the "out-of-sight" groundwater puzzle. In order to solve groundwater problems so that groundwater can properly serve its essential role in supporting ecology and humanity, we must have more than deep scientific knowledge about groundwater; in order to stave off the tragedy of the commons we must also have governance (laws, regulations, guidelines) consistent with the nature and complexities of groundwater flow.

Resolving the issues concerning the best form of governance to achieve wise water management must begin with a recognition that water and air are globally-circulating fluids essential to life. Both water and air are finite in quantity and the quantity does not change with time. The same amount of water has been on the earth for hundreds of millions of years. What can change, and must be managed, is the rate of movement of water through the hydrological cycle and the chemical/biological quality of water present at a place and time where and when water is needed to sustain life.

Because water and air are globally-circulating fluids the effects of human activity on these fluids is not limited to the place where the activity occurs, rather the impacts cascade around the world. The expression "Think Globally, Act Locally" is especially relevant to water management.

The most commonly-chosen definition of "local" for water management is a watershed (that is, the portion of the earth's surface from which water could potentially flow downslope on the surface to reach a river channel at a specified outlet location along the channel). Selecting watersheds as management units simplifies measurement of surface water conditions without consideration of the complex groundwater system.

Fortunately, in many cases, particularly in watersheds larger than 1000 km^2, the groundwater flow system has little or no net flow crossing the vertical boundary below the watershed's surface perimeter. In these cases, using a surface watershed unit to manage the underlying groundwater is logical. However, most of the world's largest and most important aquifer systems exceed 100,000 km^2 and underly many different surface watersheds. The management of such large aquifers should encompass the full areal extent of the aquifer.

Many watersheds and aquifers extend across the boundaries of local, regional and national political units. Multi-jurisdictional water management creates major complexity to groundwater governance and is currently the greatest barrier to effective management. There are a few examples of long-term successful multi-national watershed-governance: 1) the Convention for the Protection of the Rhine; and 2) the Great Lakes Water Quality Agreement for the Laurentian Great Lakes are examples of success, but these arrangements are predominantly concerned with surface-water issues not groundwater.

The current scarcity of legal mechanisms for management of trans boundary aquifers is documented by Pateiro (2017). Burchi (2018) lists management agreements for six aquifers that cross international boundaries. The oldest agreement (1977) is between France and Switzerland for management of the Genevese aquifer. The other five agreements are more recent, most post 2007, and most have not been fully implemented.

Groundwater suffers from poor governance in most countries due to a failure to recognize the aspects common to most groundwater problems.

- Groundwater problems typically have a long delay between their cause and the time when the problems are found to be sufficiently acute to draw attention. Too often, the cause-and-effect relations are not clear enough to stimulate corrective actions. This differs from issues common to rivers and lakes where the cause and effect, such as fish kills, are usually clear and occur within a short time period, so corrective action for rapid improvement can be taken.
- For many groundwater problems and especially contamination problems, corrective actions require much time before showing benefits (often decades) so the major benefits from the corrective actions taken by our generation will mostly accrue to future generations. This inhibits corrective actions if there is no broad societal commitment to sustainability.
- Although groundwater problems are a large part of the global water crisis because they are so common, nearly all groundwater problems are local in that each generally pertains to a single aquifer, single community, single well or single family. Because each problem is local and has its own site-specific characteristics, each problem has its own features that must be incorporated into problem solutions. The governance structure for groundwater must be flexible enough to respond to issues at all scales from aquifer wide to individual wells.

The record shows that the conventional approaches to groundwater governance across the globe are performing poorly. This is, in part, due to the lack of synthesized groundwater knowledge, but is primarily due to inadequate approaches to governance. Therefore, The Groundwater Project is aimed not only at elucidating groundwater science, but also examining groundwater governance to identify the limiting factors to good governance of groundwater as well as approaches that have proven to be most effective across the globe.

Establishing effective governance arrangements for water must begin by explicitly recognizing water and air as globally-circulating fluids essential for all life. The result of this recognition is that water and air must be managed as common "goods" not subject to ownership with management entrusted to whatever level of government has constitutional authority. The management of air in the atmosphere as a common good is not questioned, but the classification of water as a common good has been questioned.

In particular, groundwater has been interpreted in some jurisdictions as a "fugitive resource" like oil or natural gas that can be pumped out of a well on a property without regard to the effect of the pumping on the flow of water under surrounding properties or on the surface environment. Governance of groundwater can only be successful if all water, including groundwater, is explicitly recognized in legislation as a common good not subject to ownership. Furthermore, extraction of water from natural systems must be recognized as a usufructuary right (a temporary right of use without damaging or destroying) subject to regulation of the rate of extraction and the water quality when it is returned to the natural system.

Groundwater depletion and contamination are problems we pass on to future generations and there is a need for a better ethical framework for groundwater governance (Abrunhosa et al., 2018). Widely accepted ethical norms arising from principles of intergenerational justice demand that we not make future generations pay for past or present failures at good governance. This is so fundamental as to be at the very heart of the concept of sustainable development, as enshrined in the United Nation's Sustainable Development Goals.

Central to achieving this ethical goal will be the widespread adoption in deed, and not just in word, of the Precautionary Principle. This principle received international attention in 1992, as Principle 15 of the United Nation's Rio Declaration on Environment and Development: "*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*" (Bourguignon, 2015). More recently, the principle has been included either explicitly or implicitly in the majority of international law concerning the physical and biophysical environment, environmental protection, and environmental management. It has been implemented domestically in federal, provincial, and even municipal laws of United Nation's member states. And it is referenced in numerous policies and guidelines both domestic and international, albeit in a variety of different forms (McCaffrey, 2007; Stirling, 2007; Eckstein, 2017; and Jaeckel, 2017). The principle is well known in groundwater governance circles as it pertains particularly to uncertainties regarding management of groundwater extraction and recharge rates (UNESCO, 2012; Foster and Chilton, 2018; and van der Gun, 2018). Less attention has been given to how precaution can guide our governance with respect to the scientific determination of groundwater contamination from anthropogenic causes (Stewart et al., 2020).

Going forward, the Precautionary Principle will demand of the groundwater community—from scientists to policy theoreticians, from local water managers to international law courts—the humility and frankness concerning the challenges we face in governing ourselves and our planet when there is so much we do not know, but when we know enough to be deeply worried. We owe it to future generations to translate that worry into knowledgeable action.

10 Epilogue

Water "lost" by infiltration into the land and losing stream beds does not simply vanish, and water that flows from springs and seeps does not simply appear. Physics governing the flow of water (based on hydraulic head representing the energy per unit weight of water and the principle of mass conservation) "connects the dots" so we know the continuously moving, albeit slow, groundwater flow in the unviewable subsurface, is an integral part of, and the anchor for, the terrestrial portion of the global water cycle (Figure 72).

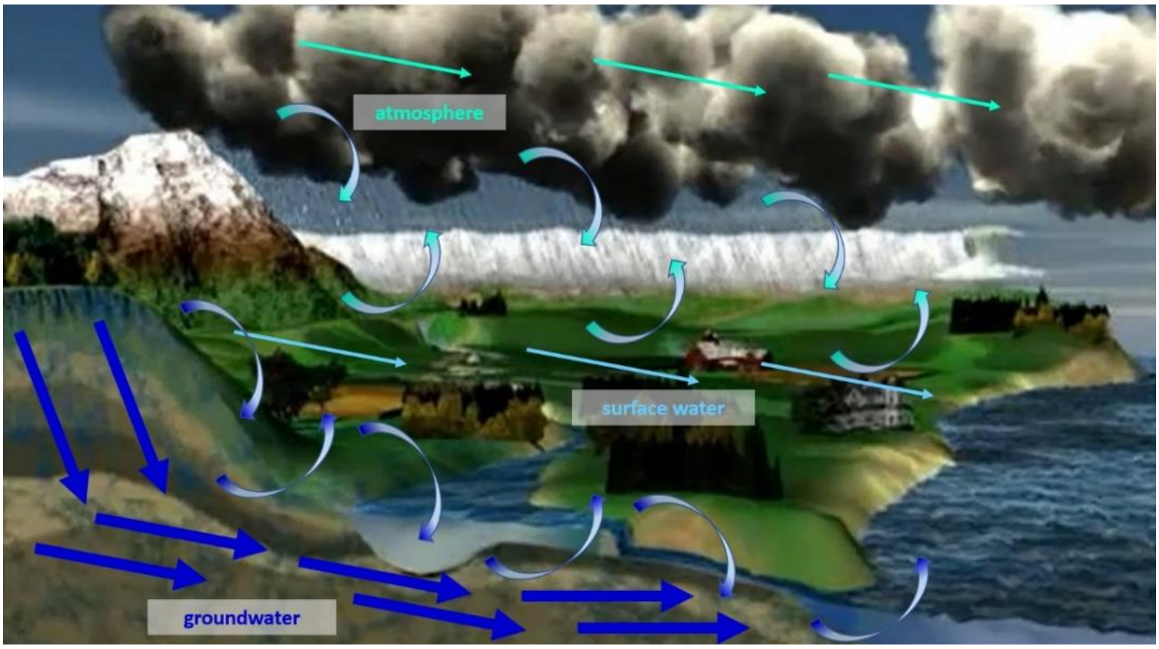

Figure 72 - As illustrated in Figure 37, three continental-scale water transport systems: air circulation in the atmosphere, stream networks on surface, and groundwater in the subsurface are intimately connected and exchange water many times along the way (adapted from NASA, 2020).

The Earth's population of nearly 8 billion in 2020 is expected to reach 11 billion by 2100. Humans will have to learn to produce sufficient food without destroying the soil, water and climate. This has been called the greatest challenge humanity has faced (Bourne, 2015). Sustainable management of groundwater is at the heart of the solution. Scientific understanding and proper management of groundwater is essential, because groundwater can alleviate the problem if we seek its responsible use and replenishment through better governance.

11 Exercises

11.1 Consider the Area Where You Live:

1. What is the type of climate?↴
2. What is the annual precipitation?↴
3. What is the annual evapotranspiration?↴
4. What is the nearest major surface water drainage?↴
5. What is the average discharge of that drainage? ↴
6. Does the stream lose, gain, or sometimes lose and other times gain?↴
7. What is your opinion on the magnitude of the stream discharge (large, moderate, small) and why?↴
8. Where does your drinking water come from?↴
9. What type of geologic formations are present?↴
10. Where do you observe manifestations of groundwater?↴
11. How deep is the groundwater table?↴
12. Where are the groundwater recharge areas?↴
13. Where are the groundwater discharge areas?↴
14. Are both confined and unconfined aquifers tapped by wells?↴
15. Has the groundwater system been pumped at an unsustainable rate?↴
16. Has there been noticeable subsidence?↴
17. What natural constituents occur in the groundwater?↴
18. Is there any groundwater contamination?↴

11.2 Consider General Conditions in All Areas:

1. What is the general pattern of groundwater flow systems?↴
2. Do all precipitation events recharge groundwater?↴
3. How does groundwater occur in the subsurface?↴
4. What happens in a groundwater system when water is pumped from wells?↴
5. What happens if groundwater pumping exceeds recharge?↴
6. What is the difference between a confined and unconfined aquifer?↴
7. Why does the temperature of streams vary less than the air temperature?↴
8. Why is a mediated temperature important for streams?↴
9. Why is water in the vadose zone more acidic than the precipitation?↴
10. What mechanisms contribute to increased Total Dissolved Solids (TDS) of water recharging the table as compared with the precipitation?↴
11. What are common dissolved constituents in groundwater?↴
12. Why does groundwater in areas of old geologic terrain have lower total dissolved solids?↴
13. In general, how do groundwater constituents typically differ between local, intermediate and regional systems?↴

14. What two primary mechanisms increase dissolved constituents along groundwater flow paths?
15. Describe the primary difference between groundwater conveyor belts in dry and wet climates.
16. How is groundwater involved in the global carbon cycle?
17. What are common sources of groundwater contamination?
18. What is the most pervasive groundwater contaminant throughout the world?
19. How can groundwater systems be used in a positive way with respect to contaminants?
20. What endeavor accounts for most of human water use? On average, what percentage of the water used by humans is used for that purpose?
21. What sustains surface water bodies?
22. What makes governance of groundwater so challenging?

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13 Exercise Solutions

13.1 Consider the Area Where You Live:

All of the exercises in Section 11.1 are specific to the area where the reader lives. If these questions are assigned as part of a course, the instructor could develop location specific answers for students to review after attempting to answer. If you are reading this as an independent study, these questions can be answered by a combination of recalling information from the book and searching for information on the internet. Some ideas of where to look are provided below.

1. Considering the area where you live: What is the type of climate?

   Given your observations of the amount of rainfall where you live and information from this book, do you classify your locale as humid, moderate, arid, semi-arid, or extremely arid?

back to exercises↑

2. Considering the area where you live: What is the annual precipitation?

   Search the internet for average annual precipitation for a locale near you.

back to exercises↥

3. Considering the area where you live: What is the annual evapotranspiration?

   Recall estimates of the percentage of precipitation that evapotranspires in various types of climates, and using that percentage along with the amount of average annual precipitation, calculate an estimate of the amount of evapotranspiration.

back to exercises↥

4. Considering the area where you live: What is the nearest major surface water drainage?

   Look at maps of your area for rivers/streams.

back to exercises↥

5. Considering the area where you live: What is the average discharge of that drainage?

   Search the internet for government stream gauge data on that drainage (or a drainage of similar size nearby or in similar climate and terrain with a similar area drained) that reports the volumetric of flow rate (for example, cubic meters per second) as a function of time.

back to exercises↥

6. Considering the area where you live: Does the stream lose, gain, or sometimes lose and other times gain?

   In order to determine this, you need to have at least two locations where the river is gauged to see if the downstream location has a higher or lower discharge. Other inflows and outflows may occur between the gauges so it is difficult to determine this with only a small amount of data. If the gain or loss is large it is possible that you could estimate the condition from visual observations alone.

back to exercises↥

7. Considering the area where you live: What is your opinion on the magnitude of the stream discharge (large, moderate, small) and why?

   This is only an opinion, but you could compare this flow with other famous rivers of the world. Typically typing a simple question like what is the average flow of the Amazon river into the internet will yield a value (e.g. 209,000 cubic meters per second).

back to exercises↑

8. Considering the area where you live: Where does your drinking water come from?

   This might be a well associated with your house or a town water supply that comes from wells or perhaps from a river or reservoir.

back to exercises↑

9. Considering the area where you live: What type of geologic formations are present?

   Look for a geologic summary or geologic map of your area.

back to exercises↥

10. Considering the area where you live: Where do you observe manifestations of groundwater?

    You may see springs. You may see damp river banks. Or perhaps there is a lake or pond where the water table connects to a surface water body.

back to exercises↥

11. Considering the area where you live: How deep is the groundwater table?

    Search for reports about groundwater in your area, or water table maps, or government records about the depth to water in wells (these would be on reports called well logs which are often recorded when wells are drilled).

back to exercises↥

12. Considering the area where you live: Where are the groundwater recharge areas?

    A likely location is in the upland areas. Reports about groundwater in your area will likely discuss recharge areas.

back to exercises↥

13. Considering the area where you live: Where are the groundwater discharge areas?

    A likely location is in the lowland areas. Reports about groundwater in your area will likely discuss discharge areas.

back to exercises↥

14. Considering the area where you live: Are both confined and unconfined aquifers tapped by wells?

    Reports on groundwater in your area are likely to provide this information. Or you might deduce it from geologic information and the depth of wells.

back to exercises↑

15. Considering the area where you live: Has the groundwater system been pumped at an unsustainable rate?

    Reports on groundwater in your area and perhaps news articles are likely to provide this information. Or you might find records of water levels in wells and note a long-term decline.

back to exercises↥

16. Considering the area where you live: Has there been noticeable subsidence?

    Reports on groundwater in your area and perhaps news articles are likely to provide this information.

back to exercises↑

17. Considering the area where you live: What natural constituents occur in the groundwater?

    Reports on groundwater in your area and perhaps news articles are likely to provide this information.

back to exercises↑

18. Considering the area where you live: Is there any groundwater contamination?

    Reports on groundwater in your area and perhaps news articles are likely to provide this information.

back to exercises↑

13.2 Consider General Conditions in All Areas:

1. What is the general pattern of groundwater flow systems?

   Groundwater flows from higher hydraulic head to lower head, typically this is generally from upland areas to lowlands, and from hills slopes to streams and surface water bodies. Some paths are short and local, while others go deeper, bypassing a few drainages before discharging, or making long regional journeys to the lowest drainage in the area.

back to exercises↥

2. Do all precipitation events recharge groundwater?

   No, generally only large and/or extended precipitation events provide sufficient infiltration such that the infiltrated water reaches the water table as opposed to be used by vegetation for transpiration.

back to exercises↥

3. How does groundwater occur in the subsurface?

   Groundwater flows through the spaces between solid particles and within the fractures and caverns in rocks and sediments.

back to exercises↥

4. What happens in a groundwater system when water is pumped from wells?

   Water levels decline.

back to exercises↑

5. What happens if groundwater pumping exceeds recharge?

   Water levels will not equilibrate and eventually the aquifer is depleted. This often results in the disappearance of stream flow and subsidence of the land surface.

back to exercises↥

6. What is the difference between a confined and unconfined aquifer?

   In a confined aquifer the water level is above the top of the aquifer while the water level is within an unconfined aquifer. When water levels decline in an unconfined aquifer, water drains from the pores and fractures, while in a confined aquifer the pores remain full of water but the pressure of the water is lower.

back to exercises↥

7. Why does the temperature of streams vary less than the air temperature?

   Water stores heat better than air and so its temperatures are moderated. This characteristic is enhanced when groundwater discharges to streams because the ground insulates groundwater so the temperatures are less variable than the air (cooler in summer and warmer in winter) thus the stream vary less than the air.

back to exercises↥

8. Why is a mediated temperature important for streams?

   Aquatic life, especially fish, often require a narrow temperature range to support their functions, especially with respect to reproduction.

back to exercises↥

9. Why is water in the vadose zone more acidic than the precipitation?

   Carbon dioxide, produced in the vadose zone by microbial decay of organic matter and by respiration of plant roots, combines with water to produce carbonic acid ($CO_2 + H_2O = H_2CO_3$).

back to exercises↥

10. What mechanisms contribute to increased Total Dissolved Solids (TDS) of water recharging the table as compared with the precipitation?

    Carbonic acid dissolves minerals and the evapotranspiration causes water to be removed from the vadose zone while salts are left behind.

back to exercises↥

11. What are common dissolved constituents in groundwater?

    Ions of sodium, calcium, magnesium, iron, chloride, bicarbonate and sulfate. Many other substances are dissolved in groundwater at lower concentrations.

back to exercises↑

12. Why does groundwater in areas of old geologic terrain have lower total dissolved solids?

    Groundwater flushes soluble minerals from geologic layers after long periods of geologic time.

back to exercises↥

13. In general, how do groundwater constituents typically differ between local, intermediate and regional systems?

    Local flow systems tend to have fewer dissolved solids and are generally bicarbonate ions dominate the chemistry. Intermediate systems have more dissolve solids and typically have more sulfate. Deep systems tend to be saltier and have more sulfate and chloride ions.

back to exercises↥

14. What two primary mechanisms increase dissolved constituents along groundwater flow paths?

    Dissolution of minerals and diffusion of relic salts from low permeability layers.

back to exercises↥

15. Describe the primary difference between groundwater conveyor belts in dry and wet climates.

    In wet climates groundwater discharge flows to the oceans via surface drainages, while in arid climates groundwater often discharges to closed surface systems such that salt deposits build up as a result of evaporation.

back to exercises↥

16. How is groundwater involved in the global carbon cycle?

    Over geologic time the carbon that entered groundwater systems in recharge areas was balanced by the carbon released in discharge areas. In present day there is a net depletion of groundwater and thus a net gain of carbon in the atmosphere because there is more groundwater discharge than recharge.

back to exercises↥

17. What are common sources of groundwater contamination?

    Application of agricultural herbicides and pesticides, seepage from landfills, mines, leaky tanks, disposal of human and animal wastes, among others.

back to exercises↥

18. What is the most pervasive groundwater contaminant throughout the world?

    Nitrate.

back to exercises↥

19. How can groundwater systems be used in a positive way with respect to contaminants?

    Deep geologic repositories can isolate waste from the environment for extended periods of time which can allow for decay of the hazardous aspects of the waste.

back to exercises↑

20. What endeavor accounts for most of human water use? On average, what percentage of the water used by humans is used for that purpose?

    Food production/agricultural irrigation. Approximately 70%.

back to exercises↥

21. What sustains surface water bodies?

    Discharge of water from vast, slow-moving groundwater systems.

back to exercises↥

22. What makes governance of groundwater so challenging?

    1) The effects of groundwater mismanagement are not observed until long after they occur;
    2) once the problem is recognized the remedy requires a long period of time;
    3) although groundwater problems have common aspects throughout the world, each problem is local in nature requiring site-specific solutions.

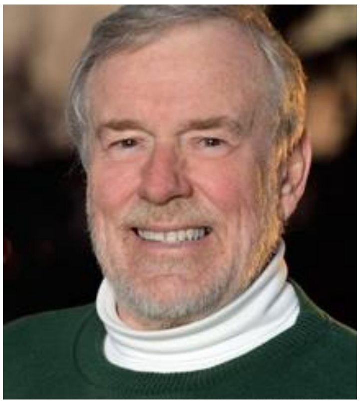
back to exercises↥

14 About the Authors

Dr. Eileen Poeter is an Emeritus Professor of Geological Engineering at Colorado School of Mines, where she taught groundwater courses and advised more than 40 graduate students who worked with her on groundwater system investigations and modeling research projects. She is also Past Director of the Integrated Groundwater Modeling Center; and retired President of Poeter Engineering. With 40 years of experience modeling groundwater systems, she has consulted to attorneys, industries, engineering companies, government agencies, research labs, and citizen groups on groundwater modeling projects for: aquifer storage and recovery; slurry wall performance; drainage at proposed nuclear power plant facilities; regional groundwater management, large-scale regional pumping, dam seepage, contaminant migration, impacts of dewatering, and stream-aquifer interaction. Dr. Poeter is an author of groundwater modeling software including evaluation of model sensitivity, assessment of data needs, model calibration, selection and ranking of models, and evaluation of predictive uncertainty. She was the NGWA Darcy Lecturer in 2006 and received their M. King Hubbert award in 2017 as well as being an NGWA Fellow and Life Member.

Dr. Ying Fan is a professor in the Department of Earth and Planetary Sciences, Rutgers University – New Brunswick. Her research centers on how hydrologic processes modulate global water, energy, and biogeochemical cycles, and in particular how water shapes plant ecology and evolution. She served on National Academy of Science (NAS) Committee on Future Water Resource Needs for the Nation, the editorial board of the journal Hydrology and Earth System Sciences (HESS), the Board of Directors of CUAHSI (Consortium of Universities for Advancement of Hydrologic Sciences, Inc.), and is currently serving on NASA Earth Science Advisory Committee (ESAC), the editorial board of the journal Hydrological Processes (HYP), and the UN commissioned Amazon Science Panel (SPA) on the state of the Amazon.

Dr. John Cherry, after study in the USA and a post-doc in France, joined the University of Waterloo in 1971 for field research on the migration and fate of contaminants in groundwater and their remediation. He co-authored "Groundwater" with R.A. Freeze (1979) and co-edited/co-authored several chapters in the book "Dense Chlorinated Solvents….in Groundwater" (1996). He is the founding Director of the University Consortium for Field-Focused Groundwater Contamination Research. At the G360 Centre for Groundwater Research, University of Guelph, he participates in research on groundwater monitoring technologies and creating safe wells for rural people in remote terrain. He was Chair of the Canadian Expert Panel on Environmental Impacts of Shale Gas development (2012-2014). He is a Foreign Member of the U.S. Academy of Engineering. He received the Lee Kwan Yew Water Prize in 2016, and the Stockholm Water Prize, 2020.



Dr. Warren Wood is currently a Visiting Professor of Hydrogeology in the Department of Earth and Environmental Sciences, Michigan State University and formally the Christiansen Fellow, St. Catherin's College, Oxford University, U.K. and Research Hydrologist U.S. Geological Survey. Warren has published more than 120 research articles on hydrogeology of arid areas and lectured at over 100 universities in North America, China, Botswana, Japan, Oman, UAE, Saudi Arabia, Israel, Jordon, Qatar, U.K. Germany, France, and Mexico. Warren was awarded the Meritorious Service Award by the U. S. Department of Interior; M. King Hubbert Medal by the National Ground Water Association; Distinguished Service Award, Geological Society of America and Elected Fellow of the Geological Society of America. Warren served at Editor-in-Chief of the Journal Ground Water and testified before U.S. congress, briefed the Secretary of Interior, and Chairman of the Nuclear Regulatory Commission on role of hydrogeology in nuclear waste disposal.

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Modifications to Original Release

page i, ii, x, Removed small caps font.

page iii, Removed keywords.

page iii, Added link to Groundwater Project email sign-up.

page iii, Added citation information.

page iii, Changed spelling of Steven Moran to Stephen Moran

pages v-vii, Table of Contents updated

page 8, The AI range for semi-arid areas was changed to 0.2 and 0.5.

page 8, Figure 7, the labels for Arid and Semiarid were reversed

page 16, Figure 14 caption. Revised The Old Pueblo and the Wikimapia citations to be more specific.

page 22, Figure 18 caption. Revised Bailey and Naeinsun citations to be more specific.

page 22, Last sentence. "air temperature" changed to "surface temperature"

page 23, Figure 19 cation. occurrences of "air" changed to "surface"

page 27, Figure 25 caption. Revised Tille citation to be more specific.

page 45, Figure 43 caption. Revised Bunnell citation to be more specific.

page 85, Reference section: numerous small format adjustments to make them consistent with later Groundwater Project Books, and the following page 85, Bailey citation clarified/expanded

page 85, link to web site corrected for both BGS (British Geologic Survey), 2020a and BGS (British Geologic Survey), 2020b

page 86, Bunnell citation clarified/expanded

page 87, Khokhar citation clarified/expanded

page 88, Naeinsun citation clarified/expanded

page 89, The Old Pueblo citation clarified/expanded

page 89, Tille citation clarified/expanded

page 90, Wikimapia citation clarified/expanded

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